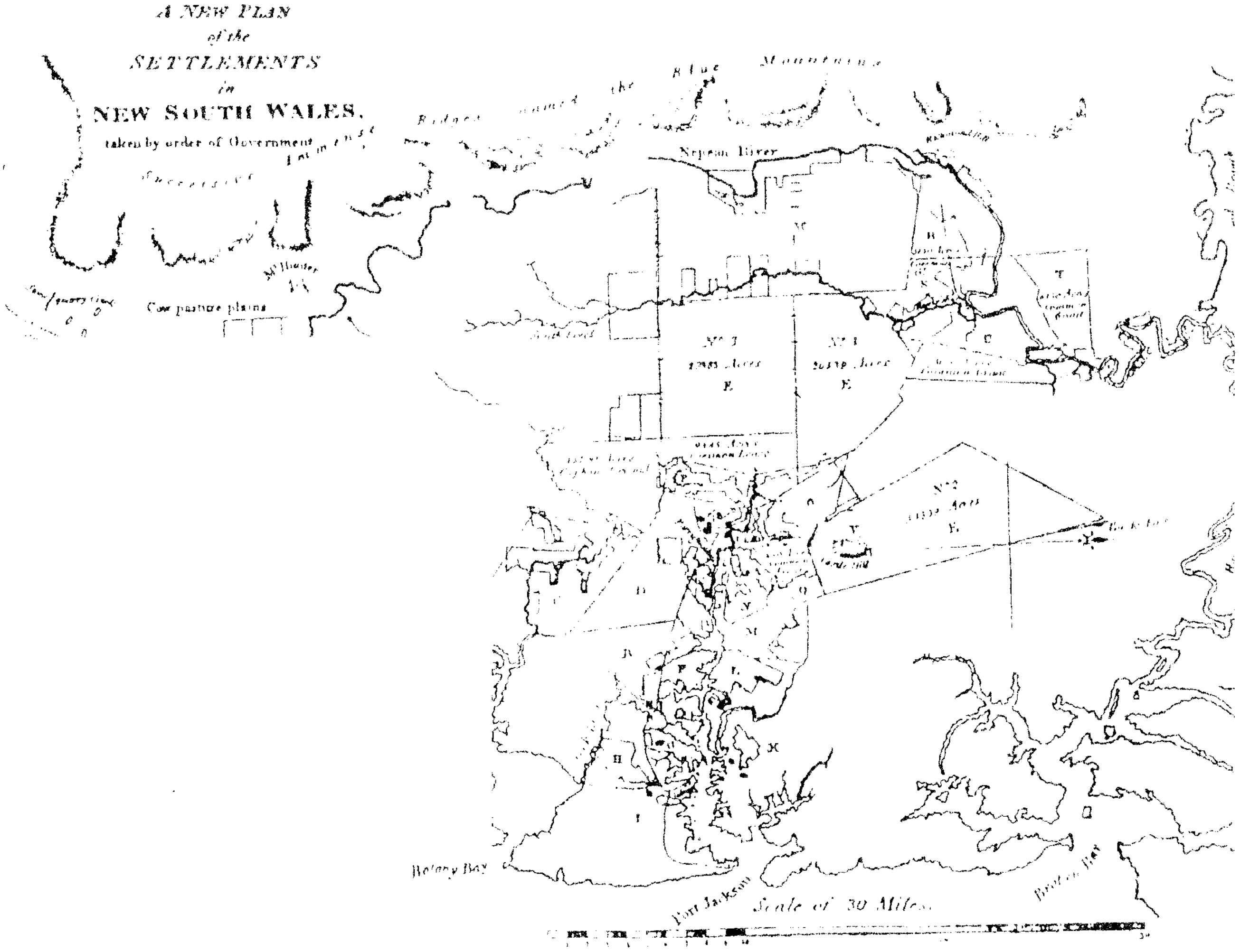
A Model for Establishing the Legal Traceability of GPS Measurements for Cadastral Surveying in Australia

Seng See BOEY



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Editor's Note

The Unisurv-S series has been, since its beginnings in the mid-1960's, the vehicle for publishing research theses and major projects carried out within the School of Geomatic Engineering (formerly Surveying), University of New South Wales.

In recent years there has been an increase in research activity in other Australasian Schools and Departments. In order to assist in the dissemination of this research, this School has decided that, where it is of sufficient quality and relevance, such research will be published within the Unisurv S Series. This report, based upon research for the PhD by Seng See Boey, at the Department of Land Information, Royal Melbourne Institute of Technology, Victoria.
Dr Boey has recently accepted a position of Research Scientist at the Defence Science and and Technological Organisation (DSTO).

A.H.W. Kearsley
Publications Manager
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December, 1999

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ABSTRACT

The Global Positioning System (GPS) technology is a well-established tool for determining spatial relationships between points of interest. Undoubtedly, GPS can provide measurements with accuracies fully commensurate with the requirements of cadastral surveys. This thesis therefore shifts the focus to the highly significant, consequential aspect of legality - the ability of the system to provide measurements which are legally traceable to standards of measurement as stipulated in Australian survey laws. Currently, there is no acceptable means for establishing the legal traceability of GPS measurements either in Australia or in the world. The aim of this thesis is therefore to develop a model for establishing the legal traceability of GPS measurements, pursuant to the provisions of the *National Measurement Act 1960* (Cwlth), for cadastral surveying in Australia.

The conceptual and operational elements of the international and Australian measurement systems are studied in detail in order to determine the principles and means for achieving the legal traceability of measurements. The cadastral survey system is examined in order to elicit statutory requirements for ensuring legal traceability of measurements. The risk factors, and their management, associated with using GPS for cadastral surveying are analysed and described.

This thesis presents two models for establishing the legal traceability of GPS measurements; the first model treats *time* as the most fundamental measurable quantity in GPS, while the second model, currently the more practical of the two, establishes *position* as a physical quantity. Both models, based on the synthesis and application of theories and concepts presented throughout this thesis, extend the traditional concept of *calibration* by providing a method for determining the uncertainty of *each* measurement result, which is specific to the circumstances in which it was obtained. Both models, therefore, provide for the achievement of the requisite traceability *during* a survey. Further, it is shown that only the second model is valid within the provisions of the current legislation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AFN	Australian Fiducial Network
ANN	Australian National Network
AMG	Australian Map Grid
Anon.	Anonymous
APEC	Asia Pacific Economic Co-operation
AS/NZS	Australian/New Zealand Standards
AUSLIG	Australian Surveying and Land Information Group
BIE	Bureau of Industry Economics
BIML	International Bureau of Legal Metrology (*Bureau International de Métrologie Légale*)
BIPM	International Bureau of Weights and Measures (*Bureau International des Poids et Mesures*)
CGPM	General Conference on Weights and Measures (*Conférence Générale des Poids et Mesures*)
CIML	International Committee of Legal Metrology (*Comité International de Métrologie Légale*)
CIPM	International Committee for Weights and Measures (*Comité International des poids et Mesures*)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Cwlth	Commonwealth
DCDB	Digital cadastral database
DoD	U.S Department of Defense
DOP	Dilution of precision
DOSLI	Department of Survey and Land Information, New Zealand
EDM	Electronic distance measurement
FGCC	U.S Federal Geodetic Control Committee
FGCS	U.S Federal Geodetic Control Subcommittee
FIG	International Federation of Surveyors (*Fédération Internationale des Géomètres*)
GATT	General Agreement on Tariffs and Trade
GDA	Geodetic Datum of Australia
GNP	Gross National Product
GPS	Global Positioning System
GPST	Global Positioning System Time
GSD	Geodetic Survey Division of Canada

ICSM	Intergovernmental Committee on Surveying and Mapping
IGS	International GPS Service
ILAC	International Laboratory Accreditation Cooperation
ISO	International Organization for Standardization
ISO/TC	International Organization for Standardization Technical Committee
ITRF	International Terrestrial Reference Frame
LINZ	Land Information of New Zealand
LTO	Land Titles Office
MC	Master Clock
MCS	Master Control Station
NATA	National Association of Testing Authorities, Australia
NAVSTAR	Navigation System Timing and Ranging
NBS	National Bureau of Standards
n.d.	no date
NGS	U.S National Geodetic Survey
NIST	National Institute of Standards and Technology
NML	National Measurement Laboratory
NSC	National Standards Commission
NSW	New South Wales
OCS	Operational Control Segment
OIML	International Organization of Legal Metrology (*Organisation Internationale de Métrologie Légale*)
PSGUC	Public Sector GPS Users Committee in British Columbia, Canada
RAIM	Receiver Autonomous Integrity Monitoring
SI	International System of Units (*Systéme International*)
SLR	Satellite Laser Ranging
TAI	International Atomic Time (*Temps atomique international*)
UNAVCO	University NAVSTAR Consortium
U.S	The United States of America
USNO	United States Naval Observatory
UTC	Coordinated Universal Time (Universal Time Coordinated)
Vic.	Victoria
VLBI	Very Long Baseline Interferometry
WAAS	Wide Area Augmentation System
WGS	World Geodetic System

1. INTRODUCTION

In surveying, the Global Positioning System (GPS) technology is a well-established tool for determining spatial relationships between points of interest. It provides surveyors with accurate and reliable measurements, as well as, arguably, increased efficiency, productivity and versatility. GPS provides positioning accuracies which range from sub-centimetre to less than 100 m. Undoubtedly, as proven by the scientific and surveying communities in numerous publications, GPS can provide measurements with accuracies fully commensurate with the requirements of cadastral surveys. This thesis therefore shifts the focus to the highly significant, consequential aspect of legality - the ability of the system to provide measurements which can be traced to standards of measurement, i.e. its *measurement traceability*.

The GPS measuring system differs in principle from conventional terrestrial measurement technology. Firstly, a vector in three dimensional coordinate space, rather than a direct measurement of length, is determined between a pair of survey marks. Secondly, and more importantly, the user does not control the operation of the system; GPS is both owned and operated by the United States; further, it is not an infallible system. Thirdly, the factors which affect the accuracy of the GPS measurements are not contained within an instrument and are temporal, geographical and spatial in nature; therefore, the philosophy of conventional instrument calibration approach is inapplicable.

In Australia, the primary function of cadastral surveying is to define and demarcate parcel boundaries in support of the processes of alienation of Crown land and the subdivision and conveyance of freehold land. As a result, survey laws have been enacted, essentially, so as to control the quality of surveyors and their work. Cadastral surveyors, when carrying out measurements, have a statutory responsibility, as prescribed in survey legislation, to ensure that the results of the measurement are a matter-of-fact. Furthermore, by law, cadastral surveyors owe a duty of care to their clients and the general public, who may rely and/or act upon the information or advice provided. In this regard, adherence to statutory requirements, such as use of Australian legal units of measurement, calibration of survey equipment, and prescribed accuracy standards for survey measurements, is required. The use of GPS is not an exception to these laws.

In order to ensure that the measurements are what they purport to be, the concept of *legal traceability of measurements* has been implemented in Australia. This concept is embodied in the provisions of the *National Measurement Act 1960* (Cwlth). In particular, s.10 of the Act provides the basis for attaining legal sanction or validity for those measurements carried out for legal purposes, such as agreements, contracts and court proceedings, as well as measurements which are subject to regulation by law or government decree. Essentially, the means for achieving the legal traceability of measurements is by relating the measurements to the appropriate national standards of measurement through a hierarchy of comparisons. Each stage of the comparison process, which is known commonly as *calibration* or *verification*, involves standards of measurement of increasingly higher order of accuracy.

Currently, a surveyor, involved in litigation which concerns questions regarding the matter-of-fact of measurements, can prove the legal status of measurements by simply demonstrating that the measurements have been related to the appropriate standards of measurement pursuant to the provisions of the National Measurement Act. In such a case, the surveyor would typically produce the appropriate certificates as proof of compliance. This course of action has been possible because of the legislative framework and the measurement system for establishing the legal traceability of measurements provided by the National Measurement Act; States and Territories may enact legislation with regard to the verification means of measurements. However, in a deregulated situation, i.e. one in which measurement and survey legislation no longer applies, the onus of proof rests entirely on the surveyor; this may or may not be a difficult task. Ultimately, a court of law would have to judge each such case on its merits.

1.1 Problem statement

Geographically, there are many areas in Australia where the use of the GPS technology for surveying is most suitable and economical. As described in the preceding paragraphs, under existing State and Territory survey legislation, there is a requirement for measurements carried out for cadastral surveys to be legally traceable to Australian standards of measurement. Currently, however, there is no acceptable means for establishing the legal traceability of GPS measurements either in Australia or (possibly) in the world. Regulators and survey authorities are relying on the Intergovernmental Committee on Surveying and Mapping (ICSM) and the National Standards Commission (NSC) to provide a solution.

There are many basic differences between GPS and conventional terrestrial measurement technology which require revisiting some of the fundamental concepts pertaining to traceability and measurements. Further, the verification of the GPS measuring system requires a fundamental shift in the way *instrument calibration* is perceived, because the Global Positioning System is not an *instrument* in the conventional sense.

To date there has been little research into the specific subject of legal traceability of GPS measurements. This is due to mainly two reasons: firstly, legal traceability of measurements is not a requirement in most countries; and secondly, until the advent of real time GPS survey systems, the use of GPS for surveying was considered as limited. This lack of research represents a serious gap in the knowledge required for developing the means for establishing the legal traceability of GPS measurements.

1.2 Aim, hypothesis and research approach

The aim of this thesis is to develop a model for establishing the legal traceability of GPS measurements, pursuant to the provisions of the National Measurement Act, for cadastral surveying in Australia. Based on this aim, the following hypothesis has been formulated:

> *an appropriate model for establishing legally traceable GPS measurements can be developed.*

For the purpose of this thesis, the following research objectives have been set:

- Examine and describe the national measurement system in order to determine the principles for achieving the legal traceability of measurements.
- Examine and describe the cadastral survey system in order to elicit statutory requirements for ensuring legal traceability of measurements.
- Describe and analyse the risk factors, and their management, associated with using GPS for cadastral surveying.
- Based on the foregoing objectives, develop a model for achieving legally traceable GPS measurements.

In order to meet the above objectives, the research methodology shown in Figure 1.1 has been adopted. Existing national measurement and cadastral survey systems have been analysed to identify functions, objectives, and processes pertaining to requirements for the legal traceability of measurements which led to the formulation of general requirements for the research programme. Since the research is concerned with establishing the legal traceability of GPS measurements, a study of the GPS measurement technology was necessary, particularly the factors which affect the accuracy of the GPS measurements. Models were developed based on the general requirements and the ability of the measurement technology to satisfy these requirements.

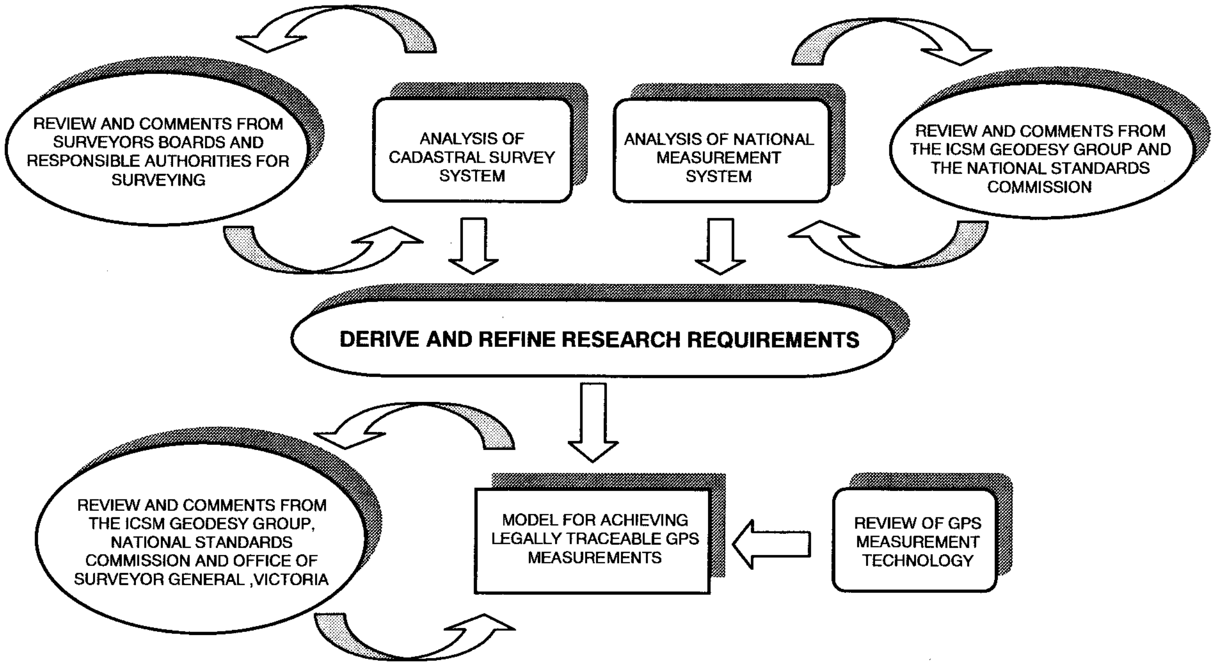


Figure 1.1. Research methodology.

Due to their nature, the models could not be rigorously tested without full implementation. However, during the project, various parts of the model have been subjected to debate and discussion by the various interest groups in order to substantiate the theories presented in this thesis (Figure 1.1). In addition, due to the need to maintain the currency of the research, a majority of the findings have been published in the form of refereed journal articles, conference proceedings and reports to the interest groups. Subsequently, reviews and comments received from individuals and organisations were used to refine the model iteratively.

1.3 Research contributions and thesis organisation

The contributions of this research are both practical and theoretical. From a practical aspect, the research has been conducted in parallel with an ongoing investigation by the ICSM Geodesy Group Working Group on the establishment of the legal traceability of GPS measurements. Many of the concepts and, in particular, the model for achieving the legal traceability of GPS measurements by connecting GPS surveys to the geodetic network, developed in this thesis, have been adopted by the ICSM Geodesy Group. More importantly, significant outcomes, which were produced in a progressive manner throughout the research programme, have provided a focus for meaningful discussion and debate at the annual ICSM Geodesy Group meetings and teleconferences.

This thesis presents two models for establishing the legal traceability of GPS measurements; the first model treats *time* as the most fundamental measurable quantity in GPS, while the second model, which is the more practical of the two, establishes *position* as a physical quantity. Both models have been developed based on the synthesis and application of the theories and concepts presented throughout this thesis. The models extend the traditional concept of *calibration* by providing a method for determining the uncertainty of *each* measurement result, which is specific to the circumstances in which it was obtained. In other words, the traceability of measurements is achieved *during* a survey. The models, and the underlying concepts and assumptions, are considered as significant contributions to the knowledge pertaining to the achievement of the legal traceability of GPS measurements for the purposes of cadastral surveying in Australia.

Apart from the models, the contribution of the research lies also in the unique exposition of the theories and concepts that are required for the development of the models. This has necessitated an extensive gathering of knowledge which lies beyond the traditional bounds of surveying and geodesy literature. The knowledge gathered is a result of the synthesis of elements from cadastral surveying, geodesy, and metrology.

From an academic aspect, the contributions of the research include the following:

Chapter 2 presents a study on the principles of and means for achieving legal traceability of measurements within the international and national measurement systems. In order to gain a clear appreciation of the concept of traceability of measurements and its implications, the elements and structure of a measurement system must be understood. Firstly, an examination and description of the conceptual elements, namely the fundamental concepts of traceability and measurements, is presented. Secondly, the operational elements of the international and Australian measurement systems are described. In particular, the Australian measurement system is discussed with respect to the establishment of legal traceability of measurements pursuant to the provisions of the National Measurement Act.

Chapter 3, firstly, presents an overview of the general cadastral concepts and historical aspects of a cadastral survey system, an understanding of which is necessary to appreciate the reasons and requirements for measurements in cadastral surveys to be given legal validity. Secondly, the chapter presents a review of current survey legislation pertaining to the practice of cadastral surveying in Australia, particularly the statutory requirements for ensuring legal traceability of measurements.

Chapter 4 presents a concise review of the characteristics of GPS. The theory and practice of the GPS relative positioning technique using the carrier phase observable are discussed briefly. In order to appreciate the measurement uncertainties associated with the relative positioning technique, an overview of the factors affecting the accuracy of GPS measurements is presented. An understanding and appreciation of these factors is necessary for the proper design of verification schemes.

Chapter 5 provides a review of some of the available methods, applicable to surveying, for testing and verifying the GPS measurement technology; a comparative analysis of their characteristics is also given. The review and comparative analysis provide an insight into those approaches with the potential to be appropriate for developing a scheme for achieving legally traceable GPS measurements in Australia.

Chapter 6 identifies within GPS the physical measurements, and their associated units of measurement, that are meaningful and practical in the context of cadastral surveying. This chapter presents a discussion on the development of two models for establishing the legal traceability of GPS measurements based on the synthesis and application of the concepts presented in Chapters 2 to 5 inclusive. However, only one is currently tenable within the provisions of the National Measurement Act and is, therefore, recommended for implementation.

Chapter 7 consists of final conclusions and recommendations.

2. THE AUSTRALIAN MEASUREMENT SYSTEM AND TRACEABILITY OF MEASUREMENTS

> *Australia must follow the example of other countries in providing facilities to ensure that measurements are what they purport to be, and in giving legal sanction to its national standards of measurement.*
>
> [Hon. J. J. Dedman, Australia House of Representatives, 1948, p.1788]

2.1 Introduction

This chapter presents a study on the means for achieving legal traceability of measurements within the current *national measurement system*, which can be described broadly as the infrastructure which supports the measurement activities of the country. The traceability of GPS measurements is an issue which must be addressed at the national level. Implementation of any recommendations relating to the issue requires co-operation between national institutions, such as the National Standards Commission (NSC), the Intergovernmental Committee on Surveying and Mapping (ICSM), and the respective States and Territories survey authorities. These organisations are integral components of the *national measurement system*. In order to gain a clear appreciation of the concept of traceability of measurements and its implications, the elements and structure of a measurement system must be understood.

In order to present a rational and meaningful discussion, a framework based on a model presented by Huntoon [1967] is adopted (the model is described in Section 2.5.1), mainly because of its systematic approach in the analysis and description of the basic concepts and functions of a measurement system. Most authors write with specific reference to their fields of expertise; however, the concepts in Huntoon [1967] are discussed in a general sense.

Briefly, according to Huntoon [1967, p.67], a measurement system comprises two interacting systems, namely the *conceptual* and the *operational* systems. The conceptual system provides the basis upon which the operational system is built. This chapter presents, firstly, an examination and description of the conceptual elements, namely the fundamental concepts of traceability and measurements. Secondly, the operational elements of the international and Australian measurement systems are described. In particular, the Australian measurement system is discussed with respect to the establishment of legal traceability of measurements pursuant to the provisions of the *National Measurement Act 1960* (Cwlth).

2.2 Traceability of measurement

The general principles implicit in the concept of traceability are as ancient as civilisation. The need to ensure uniformity and consistency among measurements made at the working level through the use of established reference standards can be observed in the building of the pyramids in ancient Egypt [Glazebrook, 1931, p.417]. Reference standards in the form of marked wooden, metal or stone rods were used to represent the *cubit* – a unit of length derived from the length of the Pharaoh's forearm. One of the oldest reference standards is found on a statue of Gudea, who was a ruler of Lagash in Southern Babylonia *circa* 2300 BC. The statue depicts Gudea seated with a tablet on his lap: on the tablet is engraved a scale showing the Sumerian *cubit* [*ibid.*, 1931, p.413; and Skinner, 1954, p.778]. Historical studies of weights and measures can be found in Glazebrook [1931] and Berriman [1953]. With the rise of the city states and, later, of the early empires, the use of measures in business, their conformity to legal standards, and the struggle against fraud have become the object of technical and juridical regulations. These simple aims, generally, have remained unchanged till modern times.

The concept of *traceability of measurement* has been discussed thoroughly in a number of papers, particularly those relating to general metrology [Cameron, 1975; and Belanger, 1980], ionizing radiation measurements [Heaton II (ed.), 1980], radionuclide medicine [Christmas, 1984], temperature measurements [Nicholas and White, 1994], electrical measurements [Kind and Quinn, 1995], and chemical measurements [Alexandrov, 1996; Thompson, 1997; King, 1997; and De Bièvre and Taylor, 1997]. The dates of some of the papers suggest that the concept of traceability is relatively novel in some disciplines.

2.2.1 The emphasis shift: from instrument to measurement

Prior to the publication of the first edition of the *International Vocabulary of Basic and General Terms in Metrology* in 1984, which formulated a universally acceptable definition of traceability, most authors, for example Cameron [1975] and Eisenhower [1980], approached the issue of traceability from different perspectives and constructed apparently different models. However, these models have provided a framework within which debate can be conducted and, consequently, a generally acceptable concept has emerged.

Belanger [1980], suggests that traceability is an evolving concept; its emphasis has shifted from a focus on the traceability of instrument to the accuracy of the results of a measurement. An interesting note regarding Belanger [1980] is that although the author articulately presents several definitions of traceability, he neither offers nor suggests the adoption of a specific definition. Belanger's observation also is explained lucidly in Eisenhower [1980]. According to *ibid.* [1980, p.4], the main problem with traceability of instrument is *the inability to demonstrate that the measurement made with a traceable instrument is indeed consistent with the national standard.* The consistency of the measurement with a standard is only *implied* if the instrument has been used properly in favourable conditions. However, the consistency of a measurement with a standard can be *demonstrated* when traceability is a characteristic of the measurement itself. To achieve this, the *complete measurement process, including the instrument, the operator and the procedures* must be controlled [*ibid.*, 1980, p.5].

Belanger [1980] and Eisenhower [1980] were not the first authors to note the shift in emphasis; earlier, Cameron [1975, p.195], who was the Chief of Office Measurement Services, National Bureau of Standards, Washington, D.C., had remarked that *it would be better to replace "traceability" of instruments by performance requirements on measurements. ibid.* [1975, p.194] gives the following reasons for the opinion: *There is a valuable lesson to be learned by looking at the measurements related to health, safety, legal regulation, or the myriad of other cases where one can state an allowable uncertainty for the measurement error. Such tolerances reflect the fact that measurement error in excess of the stated amount could create undue risk, lead to results unusable as legal evidence, lead to incorrect diagnosis or similar undesirable consequences. In such cases one needs to insure that individual measurement will "stand up in court," so to speak. It seems quite clear, then, that any requirement about the measurement system has to be a requirement with regard to the uncertainty to be attached to each measurement, and not the instrument with which they are made.* The change in emphasis would be evident in subsequent definitions of the term *traceability.*

2.2.2 Current definitions

The International Organization for Standardization (ISO) has published a second edition of the *International Vocabulary of Basic and General Terms in Metrology*, which defines *traceability* as: *the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties* [ISO, 1993, p.47]. In the Australian context, the NSC [1993, p.2] describes traceability as the *process whereby a measurement may be referred through a chain of calibrations to the appropriate Australian primary standard of measurement.* In addition, *traceability is necessary to ensure that all measurements are derived from and are consistent with the primary standards as well as meet the legal requirements of Section 10* (of the National Measurement Act). The emphasis, in both the ISO and NSC definitions, is on the *result of a measurement*. The fact that traceability is a property of the result of a measurement, and not of an instrument, implies that *each* measurement result has its own associated uncertainty specific to the circumstances in which it was obtained.

There are subtle differences between the definitions given by the ISO and the NSC. The former is defined in a general sense while the latter is more specific, particularly with its reference to national standards. A national standard is a *standard recognized by a national decision to serve, in a country, as a basis for assigning values to other standards of the quantity concerned* [ISO, 1993, p.46]. For the purpose of this thesis, the definition given by the ISO is adopted as a framework for discussion due to its generality and global application. The key issues implied in the ISO definition which require further elaboration are:

- the existence and availability of *stated references* which, in the context of surveying, are the International System of Units (*Systéme International*, SI) of measurement;
- reliable methods of comparison can be established in order to *relate* measurements to *stated references*;
- the requirement for an *unbroken chain of comparisons* which highlights the hierarchical nature of traceability and the requirement for a continuous and demonstrable chain linking the measurements to the *stated references*; and
- the determination and demonstration of *stated uncertainties* (described in Section 2.4.4) which form part of the links in the chain.

An issue that is not apparent in the ISO definition, as well as other definitions studied, is the *temporal* aspect of traceability. Time plays an essential role in terms of the: age of the *result of a measurement*, age of the *stated references*, age of the instruments, definition of an epoch in the *chain of comparisons* and the frequency of *relating* measurements to *stated references*. As mentioned in the preceding paragraph, each measurement result is unique in terms of its uncertainty. One way of identifying such uniqueness is through tagging the result with time. Ehrlich and Rasberry [1997, p.503] argue that both instruments and standards are subject to change, however slight, over time and at different rates. In order to strengthen the integrity of the comparison between a measurement and its standard, i.e. for the determination of the measurement uncertainty, the authors suggest the use of *metrological timelines* in a statement of traceability. This concept is explained in detail in *ibid.* [1997].

With the exception of Rüeger [1980; 1985; and 1991], the concept of traceability of measurement rarely is discussed in detail in surveying literature. Dr Jean M. Rüeger, who has written extensively in the area of the calibration of electronic distance measurement (EDM) devices with the intention of establishing traceability of length to the national standard, explains that the traceability of *the readings of an instrument*, i.e. the results, can be established by comparing the EDM instrument with a *National Standard, a working standard* or *a subsidiary standard* [*ibid.*, 1985, p.149]. This explanation, in general, is consistent with that of the ISO and the NSC.

Apart from Ehrlich and Rasberry [1997], the current definition of traceability has received little critical analysis in the literature reviewed. The underlying assumption in the concept of traceability, presented so far, is that when traceability is achieved through comparisons at the highest level, it will flow down in a straightforward manner to the working level within each country and there will be no need for intercomparisons at other levels of measurements or standards. This concept appears to work well within a jurisdiction or a country. However, in reality, according to Harvey [1998, p.1], there are significant variations between working level measurements made in different countries (e.g. mineral and grain measurements for export). The demands of international trade have imposed a greater emphasis on the need for international traceability of measurements. This has led to a search for a more *horizontal* approach rather than the hierarchical approach that is adopted currently. Section 2.6 discusses some of the present efforts undertaken by the international metrology organisations to address this issue.

2.2.3 Legal traceability

So far, the concept of traceability has been described in a general sense. This section examines the nature of a specific type of traceability, which is of interest to this thesis, namely *legal traceability of measurements.*

In the literature reviewed, a specific definition for the phrase *legal traceability* has not been found. However, extending the definition of *traceability* provided by ISO [1993, p.47] (*vide* Section 2.2.2), *legal traceability,* essentially, refers to the property of the result of a measurement or value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties in accordance with the provisions of the measurement legislation of a nation. Unlike traceability of measurements *per se*, which can be achieved through several routes, legal traceability of measurements can be achieved only under the force of the law. This point, with specific reference to the Australian measurement system, is discussed further in Section 2.7. Legal traceability is a subject covered in legal metrology, which *is the entirety of the legislative, administrative and technical procedures established by, or by reference to public authorities, and implemented on their behalf in order to specify and to ensure, in a regulatory or contractual manner, the appropriate quality and credibility of* *measurements related to official controls, trade, health, safety and the environment* [OIML, n.d.].

In Australia, the main measurement legislation which establishes the requirements for legal traceability is the *National Measurement Act 1960* (Cwlth); in particular, s.10 of the Act, which states:

When, for any legal purpose, it is necessary to ascertain whether a measurement of a physical quantity for which there are Australian legal units of measurement has been made or is being made in terms of those units, that fact shall be ascertained by means of, by reference to, by comparison with or by derivation from:

a. an appropriate Australian primary standard of measurement;
b. an appropriate Australian secondary standard of measurement;
c. an appropriate State primary standard of measurement;
d. an appropriate recognized-value standard of measurement;
e. an appropriate reference standard of measurement;
f. 2 or more standards of measurement, each of which is a standard of measurement referred to in paragraph (a), (b), (c), (d) or (e);
g. a certified reference material;
h. a certified measuring instrument;
i. one or more standards of measurement, each of which is a standard of measurement referred to in paragraph (a), (b), (c), (d) or (e) and a certified reference material;
j. one or more standards of measurement, each of which is a standard of measurement referred to in paragraph (a), (b), (c), (d) or (e) and a certified measuring instrument; or
k. one or more standards of measurement, each of which is a standard of measurement referred to in paragraph (a), (b), (c), (d) or (e) and a certified reference material and a certified measuring instrument;

and not in any other manner.

The four principal requirements for establishing legal traceability in Australia, as contained in s.10 of the Act, are:

- **A measurement must be of a physical (measurable) quantity.**
- **Australian legal units of measurement for the sought-after measurement must be prescribed.**
- **Appropriate Australian standards of measurement must be available.**
- **The methods or means for relating measurements to the appropriate standards of measurement must be available.**

Note the similarities between the above summary and the ISO definition of traceability (*vide* Section 2.2.2). The main point of note is the requirement for measurements to be traceable to Australian standards of measurement. There appears to be no specific provision for traceability to *international standards of measurement*, i.e. either those standards recognised globally as the best approximation of the SI units (*vide* Section 2.6) or equal standards held by other national metrology institutes.

In general, however, there is no requirement for measurements to be traceable to national standards. Legal traceability can be required for measurements carried out for any legal purpose, such as agreements, contracts and court proceedings, as well as measurements which are subject to regulation by law or government decree [NSC, 1993, p.1]. In the context of cadastral surveying, measurements are carried out for legal purposes and are subject to regulation by law, namely survey legislation. Survey measurements are legally required to comply with technical specifications prescribed in survey legislation which include accuracy standards and requirements for the measurements to be made in terms of the SI units of measurement.

The concept of legal traceability and its four principal requirements, within the context of s.10 of the National Measurement Act, form the basis of this thesis. The ensuing discussions presented in this chapter, and subsequently, seek to elaborate and develop this concept, particularly in the context of the Global Positioning System and cadastral surveying.

2.3 Quality systems

Section 2.2 has presented a discussion based on the present situation, i.e. that the requirements for legal traceability of measurements can be satisfied by complying with the provisions of the National Measurement Act. This section examines the situation of a deregulated cadastral survey system and the need for traceability of measurements, if any, in such a circumstance.

Recently, governments have been mounting microeconomic reform efforts, largely aimed at promoting competition and cost reduction, in all sectors of the economy. One such effort concerns the deregulation of the profession, including that of surveying. In a fully regulated system, like that currently implemented in most jurisdictions, survey legislation, as well as supplementary technical publications, provides guidance for the manner in which surveys are to be performed in order to achieve the prescribed minimum standards of accuracy (*vide* Section 3.3). However, in a deregulated environment, survey legislation could be revoked and, possibly, replaced by other means for ensuring the competency of a surveyor and quality of surveys, such as accreditation of surveyors and quality assurance schemes. A set of quality systems that has wide acceptance in Australia, as well as globally, is the ISO series of quality systems standards.

This section provides, firstly, an overview of the current government reform efforts which concern the regulation of cadastral surveyors. Secondly, the requirements for traceability within the ISO series are examined and discussed.

2.3.1 Background

Since the 1970s, in the face of trade liberalisation and increased foreign competition, Australia has embarked on a process of microeconomic reform [Industry Commission, 1998]. Microeconomic reform is concerned with improving *the efficiency of production and allocation of goods and services* in order to raise the national living standards [Forsyth, 1992, p.5]. Thus far, the reforms have involved government efforts to remove barriers to the free flow of market forces, involving, amongst others, programs of deregulation for the private sector and privatisation or commercialisation for the public sector. A framework within which some of the reform aims might be achieved is described in *ibid.* [1992, p.12].

Two initiatives of the microeconomic reform which have impacted directly on the cadastral system are regulatory reforms and the National Competition Policy [Independent Committee of Inquiry into Competition Policy in Australia, 1993], both of which are interrelated. According to the National Competition Policy report (also known as the Hilmer Report) [1993, p.xxix], (t)*he greatest impediment to enhanced competition in many key sectors of the economy are the restrictions imposed through government regulation – whether in the form of statutes or subordinate legislation – or government ownership. Examples include ... licensing arrangements for various occupations, businesses and professions.* Governments, by embracing the principles espoused in the policy, have adopted a minimalist approach towards regulation. In general, the guiding principle is that legislation should not restrict competition unless it can be demonstrated that the benefits of the restriction to the community as a whole outweigh its costs; and that the objectives of the legislation can be achieved only by restricting competition as a whole [*ibid.*, 1993, p.206-208].

Recently, most jurisdictions have moved to review their respective survey legislation as part of the broader microeconomic reform agenda. One of the main issues that has received critical attention is the regulation of cadastral surveyors (see, for example, a report by the Office of the Surveyor General [1995]). Four models for the regulation of cadastral surveyors, namely *full regulation*, *co-regulation*, *self regulation* and *deregulation*, have been mooted by government and the relevant professional bodies. Definitions for each model can be found in

Regulation Review Unit [1990, pp.2-5]. Full government regulation has been, and still is, the model adopted by most jurisdictions. While two jurisdictions, namely South Australia and Queensland, have adopted co-regulation models, Queensland has adopted a co-regulation model as a transitory step to achieving self regulation [McClelland, 1997, p.34].

As the trend towards deregulation of the profession is progressively realised, alternate means of ensuring the integrity and quality of the cadastre have been explored; one which has come to the fore is that of *quality systems*. Boards of Surveyors are actively encouraging the adoption of *quality assurance* principles in the management of the cadastre [Williamson, 1997, p.394-395]. In the Victorian cadastral system, quality systems, recommended by Roberts [1990] and Parker [1990], have been incorporated into the process of registration of surveyors. The impetus for survey firms and organisations to adopt quality systems has come mainly from government business requirements. Firms intending to tender for government contracts are required to have in place fully implemented quality assurance programmes. In addition, quality accreditation is becoming commercially marketable.

2.3.2 Quality systems and traceability

A treatise on the concepts of quality systems is beyond the scope of this thesis. The subject is treated adequately in textbooks, such as Mitra [1993], and the technical publications of the ISO 9000 family. The quality system most widely adopted and implemented in Australia, as well as globally, is the ISO 9000 family of quality systems standards. This comprises those International Standards prepared by the ISO Technical Committee (ISO/TC) 176, which include the ISO 9000 through to 9004, ISO 10001 through to 10020, and ISO 8402. This ISO 9000 family has been reproduced identically and published by Standards Australia and Standards New Zealand as Australian/New Zealand Standards (AS/NZS).

In the context of surveying, introductory material on quality management can be found in Kirchner and Wood [1992]. Rizos [1997] presents an extensive discussion on quality issues and the implementation of quality management principles in relation to GPS surveying. The aim of this section is to examine the role and concept of traceability within the ISO 9000 family.

Collectively, the ISO 9000 family provides guidance for quality management and general requirements for quality assurance [AS/NZS, 1994b, p.vi]. The ISO 8402 or AS/NZS [1994a, p.vi] describes the terms commonly used in quality systems as follows: *In simplified terms,* ***quality control*** *concerns the operational means to fulfil the* ***quality requirements****, while* ***quality assurance*** *aims at providing confidence in this fulfilment, both within the* *organization and externally to* ***customers*** *and authorities. ...* ***Quality management*** *includes both quality control and quality assurance, as well as the additional concepts of* ***quality policy, quality planning*** *and* ***quality improvement****. Quality management operates throughout the* ***quality system****. These concepts can be extended to all parts of an organization.* The phrases shown in bold text are described fully elsewhere in AS/NZS [1994a]. Unless otherwise stated, this thesis adopts the terms and concepts relating to quality systems described in *ibid.* [1994a].

Traceability is described in AS/NZS [1994a, p.8] as the *ability to trace the history, application or location of an entity by means of recorded identifications.* There are three meanings associated with the term, namely those relating to a *product*, *equipment calibration* and *data collection.* In a calibration sense, traceability *relates measuring equipment to national or international standards, primary standards, basic physical constants or properties, or reference materials* [*ibid.*, 1994a, p.8]. Apart from the reference to *measuring equipment*, the gist of the definition is quite similar to that of ISO [1993, p.47] (*vide* Section 2.2).

More detailed quality assurance requirements for measurement are found in AS 3912.1-1993, which is identical with ISO 10012-1:1992. These standards are used to ensure that measurements are made with the intended accuracy and consistency through the implementation of *metrological confirmation systems* [AS/NZS, 1993, p.5]. A *metrological confirmation system* is a set of operations, which includes calibration, adjustment and repair, required to ensure that a piece of measuring equipment is capable of producing results within its specified accuracy standards [*ibid.*, 1993, p.6]. *ibid.* [1993, p.8] adopts the definition of traceability given in ISO [1993, p.47]. Australian users of the standards are referred to the traceability requirements of the National Measurement Act when measurements are made for legal purposes [AS/NZS, 1993, p.2].

This section has highlighted briefly the relevant parts of the ISO 9000 family of quality systems standards which refer to traceability requirements. The examination of the ISO 9000 quality systems has revealed that there are traceability requirements for measuring equipment. The need to ensure pieces of equipment are performing accordingly is an essential part of quality assurance. According to Roberts [1983], quality control will fail when the two main causes of poor quality, poor raw material and lack of equipment calibration, are not under control. Traceability is an integral component of a measurement quality assurance system. The concept of traceability in the standards reviewed is similar to that discussed in Section 2.2. In the context of quality assurance, traceability is the assurance of quality of a measurement.

In summary, if, as appears most likely, the ISO 9000 family of quality systems standards were to be adopted and implemented in a deregulated cadastral survey system, the present requirements for traceability of measurements would still apply. It should be noted that the implementation of quality systems is voluntary. However, Nicholas [1992, p.1447] posits that quality assurance, through the adoption of the appropriate certification process, could be a solution for providing legal sanction for measurements. *ibid.* [1992, p.1445] explains that *for legal force a certifying authority will need to be established in law, otherwise it will need its own status for acceptance, e.g. insurance underwriters.*

2.4 Measurement Concepts

> *Measurements are so common and intuitively understandable that one would think there is no need to identify the prerequisites on which measurements are based. However, a clear understanding of the starting premises is necessary for the development of any science, and for this reason it is desirable to examine the prerequisites of the theory of measurements.*
>
> Rabinovich [1993, p.9]

Fundamental measurement concepts often receive only cursory treatment in surveying and geodesy literature, probably due to the applied nature of those disciplines. Further, as explained by Rabinovich [1993, p.9], there is the perception that the notion of measurements is *intuitively understandable* and pervasive. Consequently, depending on the subject-matter, some authors may have assumed that the concepts associated with measurements are self-evident and, as such, require no in-depth discussion. Measurements are the essence of this thesis; therefore, it is necessary to have a clear understanding of the associated concepts. The most recent re-examination of the meaning of measurements and the interpretation and use of the SI units, which is relevant to geodesy and positioning by space techniques, is a report by the Working Group on the Application of General Relativity to Metrology [Guinot, 1997]. The report concerns very precise measurement of macroscopic quantities for which a correct relativistic treatment is necessary.

Section 2.2.3 has described the concept of legal traceability and its requirements within the context of s.10 of the National Measurement Act. The aim of this section is to provide a background to some of the principal measurement concepts associated with legal traceability. A review of the literature relating to measurements reveals that there are many and varied interpretations of the basic concepts and the associated terms. Most authors tend to define terms according to the context of their subjects of interest. One particular source of reference that has been gaining general acceptance within the international scientific community is the *International Vocabulary of Basic and General Terms in Metrology* [ISO, 1993]. Hence, this thesis adopts the definitions given therein.

2.4.1 Quantity

The ISO [1993, p.11] defines *measurable quantity* as the *attribute of a phenomenon, body or substance that may be distinguished qualitatively and determined quantitatively.* The *value of a quantity* is defined as the *magnitude of a particular quantity generally expressed as a unit of measurement multiplied by a number* [*ibid.*, 1993, p.16]. The adverb *generally* is explained in the following note: *A quantity that cannot be expressed as a unit of measurement multiplied by a number may be expressed by reference to a conventional reference scale or to a measurement procedure or to both.* In a general sense, implicit in these definitions is the notion that quantities, which can be defined unambiguously, are measurable. In other words, there are no non-measurable quantities, only quantities which are undefined. In physics, measurable quantities are also known as *physical quantities* such as time, mass and length.

An interesting point to note is that most surveyors and geodesists adopt a realist view of the ontological status of quantities, the same as that implied in the above ISO definitions. The assumption in such a view is: quantities are inherent in the objects or phenomena that possess them and they must pre-exist prior to measurement. To some, such a concept may appear to be obvious; however, there are authors, like Dingle [1950], who refute the realist conceptions of pre-existing quantities. *ibid.* [1950, p.7] opines that *instead of supposing a pre-existing 'property' which our operation measures, we should begin with the operation and its result and then, if we wish to speak of a property..., define it in terms of that.* According to this opinion, there are no quantities in nature, only various sorts of precisely specified operations which yield numbers. This implies that there could be several different concepts of a quantity based on the different ways of measuring it. For example, the notion of length between two marks can be described differently depending on whether it has been measured directly using a ruler or indirectly using triangulation.

An important concept that is implied in the above definitions is the *relational character* of quantity which is discussed in Ellis [1966]. *ibid.* [1966, p.38] states that the *existence of a quantity is logically dependent upon the existence of a set of linear ordering relationships.* This view is almost a compromise between the realist and the Dingle propositions. This thesis accepts that quantities of objects or phenomena can be determined only by means of comparison which is the basis of *measurement.*

2.4.2 Measurement

According to the Concise Oxford Dictionary [1990, p.736], *measurement* can be either *the act or an instance of measuring* or *an amount determined by measuring.* The former refers to a *process* or an *operation* while the latter refers to the *result* of the operation. These two meanings are often used interchangeably in literature. Certain disciplines, such as surveying and geodesy, as will be discussed in the following paragraphs, attempt to differentiate between the process and the result by adopting different terms. The ISO [1993, p.19] defines *measurement* as a *set of operations having the object of determining a value of a quantity.* This definition concentrates on the process aspect of measurement.

In the context of general science, Campbell [1920, p.267], who is considered to be one of the pioneers in the philosophy of measurement science, defines measurement as the *assignment of numbers to represent properties.* This assignment is made according to certain *laws*, some of which are based on basic mathematical and experimental laws [*ibid.*, 1953, p.119 & p.133]. Eisenhart [1963] expands on Campbell's definition by incorporating the *relational character* of quantity. According to *ibid.* [1963, p.163], *Measurement is the assignment of numbers to material things to represent the relations existing among them with respect to particular properties. ... In practice the assignment of a numerical magnitude to a particular property of a thing is ordinarily accomplished by comparison with a set of standards, or by comparison either of the quantity itself, or of some transform of it, with a previously calibrated scale.* In essence, this concept is consistent with the definitions provided by the ISO [1993]. Eisenhart [1963, p.163] also gives two reasons for measurement: *first, symbolic representation of properties of things as a basis for conceptual analysis; and second, to effect the representation in a form amenable to the powerful tools of mathematical analysis.*

In the parlance of geodesy, measurement is considered as the process of assigning a number to a quantity by means of an instrument or sensor [Vanícek and Krakiwsky, 1986, p.177]. A physical or geometrical quantity that can be measured or observed is known as an *observable* and the number that is assigned to an observable is known as an *observation.* In the field of satellite geodesy, in particular GPS, Langley [1993, p.52] explains that the term *observable* refers to the *measurable parameters of a system.* It is used *to distinguish the quantity being measured (the observable) from the measurement process itself (the observation).* Langley's explanation of *observable* is consistent with that of Vanícek and Krakiwsky [1986]; however, the authors differ in their opinions regarding the description of *observation.* Inconsistency in the usage of terms also is evident in the field of surveying; for example in Mikhail and Gracie [1981] the authors use the nouns measurement and observation interchangeably. *Measurement (observation)* refers to a set of operations undertaken to assign a numerical value to the sought-after quantity [*ibid.*, 1981, p.1]. In addition, the same terms also are used to describe the result of applying the set of operations.

The preceding discussions have shown that concepts are defined and used to suit the context of the subject-matter. The inconsistency caused by this approach has presented a certain degree of difficulty, particularly in the context of this thesis, which seeks an amalgamation of concepts from three different fields, namely cadastral surveying, satellite geodesy and measurement science. Semantic consistency is important, especially when there is a possibility that the concepts and recommendations presented may contribute to the amendment of existing measurement and survey legislation. Hence, the definitions provided by the ISO are adopted for the general case and, in more specific instances, the appropriate definitions of terms are provided according to the context in which they are presented.

2.4.3 Unit of measurement

> *When man became a measuring animal he naturally took as his standards the parts of his own body; the cubit, the length of the forearm from the elbow joint to the tip of the middle finger, was his unit of measurement.*
>
> [Glazebrook, 1931, p.413]

As mentioned in Sections 2.4.1 and 2.4.2, quantities of objects or phenomena can be determined by means of comparison. The basis of comparison is the *unit of measurement* which is a *particular quantity, defined and adopted by convention, with which other quantities of the same kind are compared in order to express their magnitudes relative to that quantity* [ISO, 1993, p.13]. Similarly, s.3 of the National Measurement Act defines a *unit of measurement* as *any word or expression that is used in conjunction with numerical values in order to describe the magnitudes of physical quantities.* Essentially, the process of measurement is about establishing a relationship, by experiment, between the value of a quantity and the appropriate unit of measurement. The result of a measurement is always a *ratio* of the value of the quantity to the value of the unit.

The most important characteristics of a unit are that it is *universally agreed*, *readily available*, and *may be easily measured*, or *reproduced*, or *realised* [Huntoon, 1965, p.171; Mills, 1997, p.104]. An internationally agreed system of units is the International System of Units (*Systéme International*, SI), the details of which are well documented in many publications, especially in National Physical Laboratory [1993] and Quinn [1994/95]. The SI is based on a choice of seven well-defined units, called *base units*, which by convention are regarded as dimensionally independent: the *metre* (symbol m), the *kilogram* (kg), the *second* (s), the *ampere* (A), the *kelvin* (K), the *mole* (mol), and the *candela* (cd) [*ibid.*, 1993, p.2]. Also, there is a set of *derived units*, which are units expressed algebraically in terms of base units (for example, area (m^2) and velocity (m/s)). The choice of the base units, their definitions and maintenance is the responsibility of the International Committee for Weights and Measures (*Comité International des poids et Mesures*, CIPM).

Units of measurement evolved from *unit-standard* to *conceptually defined unit* [Huntoon, 1965, p.170-171]. *Unit-standards* are based on pre-existing standards: physical objects, such as the cubit rod (*vide* Section 2.2), and physical processes, such as the movement of clocks. *Conceptually defined units* are units which can be realised or reproduced independently without access to the original sample. These units are defined based on some natural phenomena, such as *physical constants*, *physical situations* and the *properties of specified substances* [Barrell and Essen, 1959, p.209]. An example of a unit of measurement that has been defined in terms of both a physical standard and a physical constant is the *metre* (Table 2.2). Table 2.1 shows two units of measurement that are used most commonly in surveying and geodesy, namely the units of length and time, being the *metre* and the *second* respectively. (Angles are not a concern in this thesis since their traceability to a standard of measurement is unnecessary - *vide* Section 3.3.4.2). Also described in Table 2.1 is the relationship between a physical quantity and its conceptually defined unit of measurement.

Physical quantity	SI Unit of measurement	Definition of the SI unit
Length	metre	The metre is the length of the path travelled by light in a vacuum during a time interval of 1/299 792 458 of a second (adopted at the 17th CGPM in 1983 [National Physical Laboratory, 1993, p.5] and used in r.5 of the National Measurement Regulations).
Time	second	The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom (adopted at the 13th CGPM in 1967 [National Physical Laboratory, 1993, p.6] and used in r.21 of the National Measurement Regulations).

Table 2.1. Relationship between physical quantity, unit of measurement and its definition.

A fundamental physical constant that is adopted for defining units of measurement is the speed of light in vacuum (c). The exact value for the speed of light, being 299 792 458 m/s, was adopted in 1975 by the 15th General Conference on Weights and Measures (*Conférence Générale des Poids et Mesures*, CGPM) [National Physical Laboratory, 1993, p.45]. Detailed treatment on the role of fundamental physical constants in metrology can be found in Petley [1985]. Briefly, fundamental physical constants have two main roles: *first, they provide an invariant quantity whose measurement provides valuable information concerning the reproducibility, dissemination, and stability of the SI units; and second, they are, explicitly and implicitly, either incorporated into the definition of an SI base unit or used to maintain a* *reproducible secondary unit* [*ibid.*, 1992, p.96]. Long-term stability does not necessarily imply high precision in the unit's practical realisation [Quinn, 1994/95, p.518]. For example, the previous definition of the *metre*, based on the wavelength of the radiation corresponding to the energy between the specified transitions in the krypton-86 atom, had limited reproducibility due to the broad spectral line width of the krypton atom.

The definition of units, in terms of physical constants and atomic or quantum phenomena, implies the possibility of realising or reproducing the units without recourse to conventional hierarchical comparison means. Results of measurement which can be linked directly to the realisation of the appropriate unit would not require comparison in order to determine the uncertainties of the measurement. This implication is important in the context of establishing traceability for GPS measurements and is discussed in greater detail in Section 6.4.

2.4.4 Standard of measurement

As remarked in Section 2.4.3, units of measurement are abstract conceptions; as such, they cannot be used as practical bases of measurement until they have been reproduced or realised by reference to either arbitrary physical objects or natural phenomena. A *standard of measurement* is the practical or physical realisation of a unit of measurement. The ISO [1993, p.45] defines a *standard of measurement* as a *material measure, measuring instrument, reference material or measuring system intended to define, realize, conserve or reproduce a unit or one or more values of a quantity to serve as a reference.* Section 3 of the National Measurement Act adopts a similar meaning with the inclusion of *a formula designed or intended to define the magnitude of a physical quantity.* The provision of standards of measurement is necessary for maintaining consistency in the measurement of physical quantities. Standards of measurement should be readily available (ubiquitous), easily reproducible, and invariable (stable) [Barrell and Essen, 1959, p.210].

Standards of measurement do evolve according to the demands of practicalities and advancement of science and technology. The *metre* is a typical example (Table 2.2).

Date	Definition	Realisation	Reasons for abandonment
1791	10^{-7} part of the arc of meridian from the equator to the north pole through Paris	*Mètre des Archives*, an *end standard* being the distance between two flat and parallel end-surfaces of a platinum bar	Not easily accessible, difficult to reproduce
1889	Length between two lines on a specific platinum-iridium bar kept under controlled conditions	*International Prototype Metre*, a *line standard* being the distance between two parallel lines marked on a bar of platinum-iridium	Accuracy improvement, difficult to reproduce
1960	1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels 2p and 5d of the krypton-86 atom	Wavelength of radiation in vacuum	Accuracy improvement, difficult to reproduce
1983-present	Length of the path travelled by light in a vacuum during a time interval of 1/299 792 458 of a second	There are three recommended methods for realising the metre, the most popular being the wavelength of iodine stabilised laser radiation	Currently in use

Table 2.2. The evolution of the *metre* compiled from Klein [1974], Wilkie [1983] and National Physical Laboratory [1993].

The standard for each unit is unique and is realised practically using laws applicable to the appropriate fields of physics and technology. The *second* is defined explicitly in terms of quantum phenomena (Table 2.1) and is realised by physical standards in the form of caesium atomic clocks. The current definition of the *metre* is dependent on both the speed of light, a constant, and on the definition of the *second* (Table 2.2). Hence, the realisation of the *metre* cannot be more accurate than that of the *second*. The relative uncertainties (u) in the realisations of the *second* and the *metre* are about 3 parts in 10^{14} and a few parts in 10^{11} respectively [Quinn, 1994/95, p.521]. The relative uncertainty associated with the realisation of the *second* is now in the order of 10^{-15}, due to improvements in atomic frequency standards and GPS time transfer techniques (*vide* Section 6.1).

By implicitly adopting an exact value for the speed of light, the *metre* can be realised by any source of electromagnetic radiation whose frequency is known or can be measured. In 1983, the CIPM recommended three methods for realising the *metre* [Documents concerning the new definition of the metre, 1983, p.164-165]:

a) by means of the length l of the path travelled in vacuum by a plane electromagnetic wave in a time t; this length is obtained from the measured time t, using the relation $l = c \cdot t$ and the value of the speed of light in vacuum c = 299 792 458 m/s;

b) by means of the wavelength in vacuum λ of a plane electromagnetic wave of frequency f; this wavelength is obtained from the measured frequency f, using the relation $\lambda = c/f$ and the value of the speed of light in vacuum c = 299 792 458 m/s;

c) by means of one of the radiations from the list below whose stated wavelength in vacuum, or whose stated frequency, can be used with the uncertainty shown, provided that the given specifications and accepted good practice are followed ...

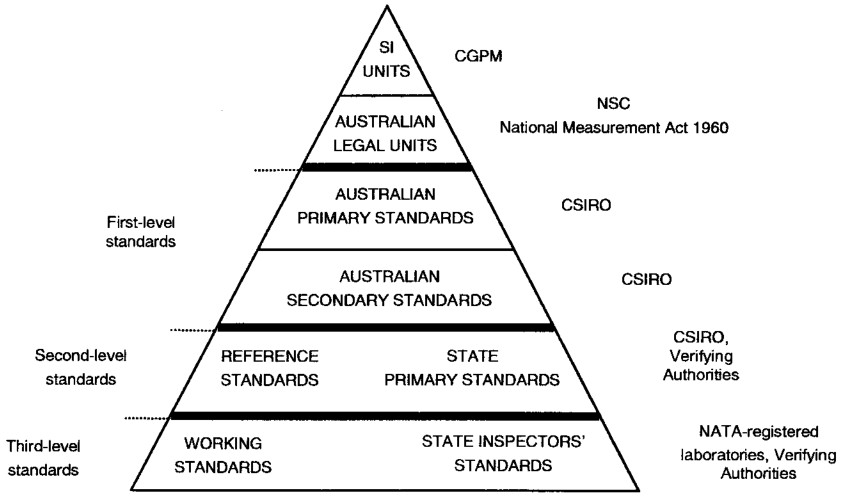
The choice of the method is determined by the magnitude of the sought-after length, the desired accuracy, and the facilities available. The first method, the most direct implementation of the current definition of the *metre*, is implemented currently in space based positioning techniques, like the Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). For very precise measurements, this method requires accurate measurement of very small time intervals. According to the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [1996], *it is not yet technically possible* to use the method for very precise measurements at the sub-millimetre level. Issues relating to precise measurement of macroscopic quantities, in particular the influence of relativity or gravitation, have been the subject of a study by Guinot [1997], which in part, was prompted by improvements in the accuracy of atomic time standards. The second and third methods for realising the *metre* involve the use of interferometry to measure the desired length in terms of the wavelength of a light beam. Currently, these methods, as shown in Table 2.2, are the preferred means for laboratory realisation of the *metre*, employing rules adopted by the CIPM, known as the *mise en pratique* (practical realisation) of the definition of the *metre* [Quinn, 1993/94]. In Australia, iodine stabilised laser devices constitute the primary standard of length [CSIRO, 1996]. Ciddor and Sim [1984] and CSIRO [1996] describe in detail the nature of the standards of length and their dissemination in Australia.

Generally, in order to transfer the sizes of units into ordinary measurement practice, a hierarchical system of standards is implemented (Figure 2.1 and Figure 2.2). The path from the definition in the SI down to the user is represented by a series of three basic operations [Kind and Quinn, 1995, p.85]:

- *Realization* of the internationally agreed conceptual definition of the unit;
- *Maintenance* of the results of realisation of the unit by means of a *primary standard of measurement*; and
- *Dissemination* of the unit to the user.

At each level, except the highest, the standards will have been compared against those in the level above. At the apex of the hierarchy is the *primary standard* which is a *standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity* [ISO, 1993, p.46]. Commonly, the primary standard constitutes the national standard, embodying the realisation of the relevant SI unit. The terms for the standards at each level of the hierarchy shown in Figure 2.1 are defined in ISO [1993] and s.3 of the National Measurement Act.

Another feature of the hierarchical system is the progressive increase in *measurement uncertainties* as the standards move further away from the apex. The uncertainty of measurement is *a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the* *measurand* [ISO, 1993, p.25]. Figure 2.2 illustrates an existing structure of standards used for transferring the SI unit of length to a surveying tape. Also shown in Figure 2.2 are the measurement uncertainties (*italicized*) associated with each level of the hierarchy.



Abbreviations:
CGPM - Conférence Générale des Poids et Mesures
NSC - National Standards Commission
CSIRO - Commonwealth Scientific and Industrial Research Organization
NATA - National Association of Testing Authorities, Australia

Figure 2.1. Australia's hierarchy of physical units and standards. Note: This figure is an amended version of the original figure shown in NSC [1993, p.2] following advice from Harvey [1998, p.2].

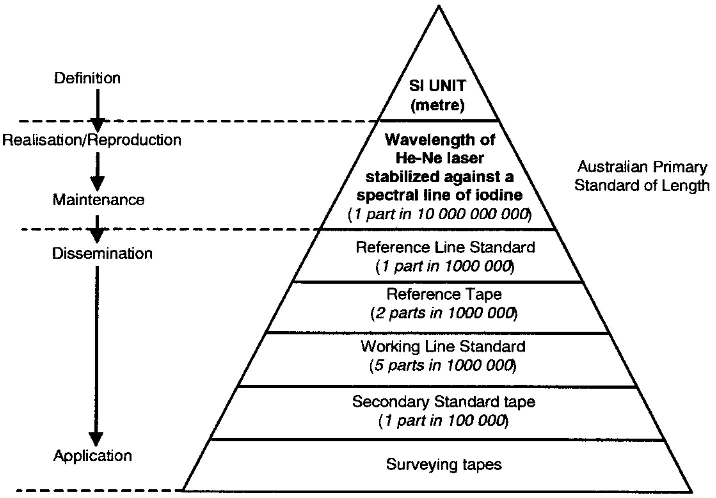


Figure 2.2. The hierarchy of reference standards by which a measurement of length from a surveying tape is related to the unit of measurement [adapted from Rüeger, 1985, p.152].

Finally, the term *standards* is used in two quite separate but related meanings. Firstly, in the sense described previously in this section. Secondly, in the sense of *specification or documentary standards*, i.e. published criteria by which a product or a service or a test may be assessed as to quality or performance. Such an assessment usually involves measurement; hence, the second category of standards relies on the existence of the first. Examples of documentary standards are the ISO 9000 family of quality systems standards (referred to in Section 2.3.2) and the Standards and Practices for Control Surveys (SP1) published by the ICSM [1994].

2.4.5 Calibration

The transfer of units of measurement into ordinary measurement practice is achieved through the process of *calibration*, which is *a set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards* [ISO, 1993, p.48]. The relationship is often expressed in terms of *measurement uncertainties* (depicted in Figure 2.2).

In the context of surveying, the calibration of EDM instruments is a typical example. Rüeger [1990, p.186] describes the *calibration of a distance meter as the determination of its instrument constant and associated precision*, i.e. the measurement uncertainties. The determination is made by comparing the measured lengths against a *working standard of length* [*ibid.*, 1990, p.188].

The term *calibration*, and other terms having the same connotation, such as *standardisation*, *comparison*, *verification* and *test*, are found commonly in measurement and survey legislation in Australia. Some of these terms, such as *calibration* and *standardisation*, are used because of their association with particular types of equipment. *Standardisation* is often associated with surveyors tapes and bands, while *calibration* is used in relation to EDM instruments. Modern legislation, which is less prescriptive, avoids using both terms by adopting terms like *comparison* and *verification* (*vide* r.5 of the Surveyors (Cadastral Surveys) Regulations 1995 (Vic.) and c.14 of the Survey Practice Regulation 1990 (as amended 1 October 1994) (NSW) respectively). All the aforementioned terms have one particular object, that is to ensure that results of measurement are made in terms of the Australian legal units of measurement in accordance with s.10 of the National Measurement Act. This objective is achieved by establishing a relationship between the results of measurement and the equivalent standard of measurement, i.e. via the process of calibration. The operation of relating physical measurements to the standard of measurement, through a hierarchy of continuous chain of calibrations, in fact constitutes the establishment of traceability for these measurements (*vide* Section 2.2.2, Figure 2.1 and Figure 2.2).

The term *calibration* also can be found in GPS textbooks to describe a process which correlates the values of instruments with specified or known values which are not necessarily standards of measurement. This term and that defined in ISO [1993, p.48] do not share the same meaning. Typical examples are: *receiver calibration* in order to eliminate inter-channel biases, *calibration of antenna phase centres* and *receiver self-calibration* [Hofmann-Wellenhof *et al.*, 1997, p.82, 145, 163].

2.5 Measurement system

The following sections present a study of the operational elements of a measurement system. A review of the concepts of such a system, as well as the justification for its establishment in terms of its economic worth, are described. Overviews of organisational networks and links of both the international measurement system, specifically the Convention of the Metre, and the Australian measurement system are presented. Finally, the elements of the national measurement system which have direct impact on the subject-matter of this thesis are reviewed, namely the achievement of legal traceability of measurement within the present measurement system.

2.5.1 Concepts of a measurement system

More than two thousand years ago, weights and measures were developed to meet the requirements of trade among individuals and city states. Nowadays, the role of measurement systems in world trade cannot be overemphasised - a fact which was reiterated recently in Professor Jean Kovalevsky's address as President of the CIPM [Kovalevsky, 1997].

The recent World Trade Agreement, which is a successor to the General Agreement on Tariffs and Trade (GATT) 1994, recognises that national standards and conformance assessment systems can threaten international trade by erecting technical barriers to all but preferred or locally manufactured products. The World Trade Agreement on Technical Barriers to Trade aims to reduce discriminatory standards by establishing international rules governing the procedures by which national standards are prepared, adopted, and applied, and by which products are tested for conformity [World Trade Organization, 1997]. At the regional level, the GATT principles were adopted by members of the Asia Pacific Economic Co-operation (APEC). Consequently, APEC has sought the assistance of the Asia Pacific Metrology Program, a specialist organisation, to identify means of eliminating technical barriers to trade by the year 2020 [Standards & Measurement, 1995, p.18]. In 1994, in the light of the global and regional developments and the government's own microeconomic reform agenda, the Federal government formed the Committee of Inquiry into Australia's Standards and Conformance Infrastructure [1995] to identify the impediments in the *national* *measurement system*. The establishment of such a national inquiry highlights the important role the national measurement system has in the economic growth of the nation.

The purpose of a national measurement system is to enable the accomplishment of national objectives by providing: a *quantitative basis in measurement for (i) interchangeability and (ii) decisions for action in all aspects of daily life - public affairs, commerce, industry, science, and engineering. As soon as we have a measurement system with a set of established units and standards, we have a firm basis for the interchange of goods and services in the mass markets of modern commerce, of machine parts and devices in industry, and of scientific and technical information* [Huntoon, 1967, p.68]. Similarly, the CSIRO, in its submission to the Committee of Inquiry into Australia's Standards and Conformance Infrastructure [1995, p.3], states that the purpose of a *national standards and conformance infrastructure* is to provide *the technical basis for orderly commerce, national and international trade, technical harmony between manufacturers, and governmental regulatory activities. Fundamental to the achievement of this is an effective infrastructure for physical measurement, standards writing, testing, trade measurement, competency assessment and compliance certification.*

Phrases such as *measurement system*, *measurement support system* and *measurement infrastructure* are commonly found in literature related to metrology. With the exception of a few authors, like Huntoon [1967], Eisenhower [1980] and Nicholas and White [1994], a majority of authors, such as Sydenham [1982, p.85] and Sydenham *et al.* [1989, p.16], rarely provide an adequate exposition on the underlying concepts of the measurement system, especially its elements and structure. The understanding of the composition of a measurement system, either international or national, is necessary in order to appreciate the organisational and institutional networks which provide the paths and links for which traceability of measurement is established.

Arguably, the first attempt to analyse and describe the concept of a measurement system was made by Dr Robert D. Huntoon [1967], a former Director of the Institute for Basic Standards, the National Bureau of Standards (NBS) (renamed in 1988 to the National Institute of Standards and Technology (NIST)). Dr Huntoon adopted a *systems approach* to examine the components and structure of the measurement infrastructure in the United States. He described the infrastructure as comprising two interacting systems, namely the *conceptual* and *operational systems*. The *conceptual system* is *a rational, ordered structure of rules, definitions, laws, conventions, or procedures which provides the fundamental basis upon which the operational system can be built*. The *operational system* is *an ordered structure of functional elements - that is, organizations of people - interacting with one another under central guidance to perform a function. It is national in scope; it assumes a* *character suited to the nation it serves, and one that is consistent with the requirements of the conceptual system* [*ibid.*, 1967, p.67]. A *conceptual system* which is adopted internationally, by virtue of an international agreement (Convention of the Metre), is the International System of Units (*Systéme International*, SI). It provides a comprehensive set of rules and specification for the definition and realisation of units of measurement. The *operational system* is that part of the system which implements the conceptual elements and is usually manifested as a country's national measurement infrastructure.

Different models of measurement systems have been presented by various authors. In general, most existing national measurement systems have adopted, either partially or wholly, the basic elements and structure of the model presented by Huntoon [1967]. A good treatise on the operational elements of a measurement system can be found in Eisenhower [1980] which is written with respect to ionizing radiation measurements. *ibid.* [1980, p.7-8] describes the United States *measurement support system* as consisting of basically three different levels labelled as *primary*, *intermediate* and *user* levels (Figure 2.3).

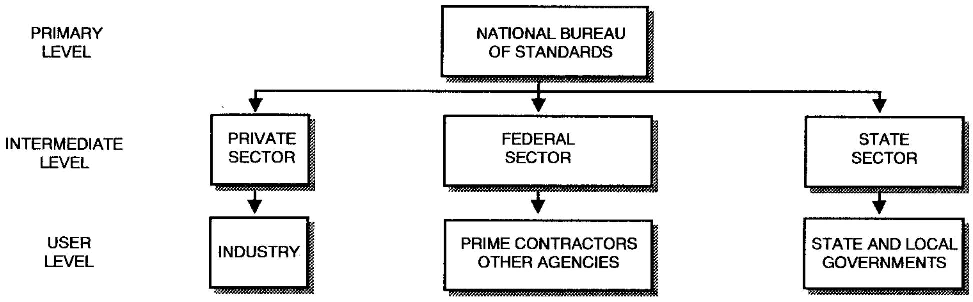


Figure 2.3. The three-level concept of a national measurement support system [from Eisenhower, 1980, p.7].

Interaction between the levels is supported by *technical* and *institutional* elements. The technical elements are:

- *measurement standards* which include the national standards and transfer standards used at the intermediate level;
- *calibrations* of transfer standards by the NBS and field instruments by intermediate laboratories;
- *measurement quality assurance programs*, including performance testing services provided by the NBS or an intermediate laboratory;
- *field instruments* used to make measurements at the user level;
- *procedures* used for measurements, calibrations and measurement quality assurance (MQA);
- *training of personnel* who perform measurements, calibrations, and MQA; and
- *records* which document specific actions that have been undertaken.

The institutional elements are:

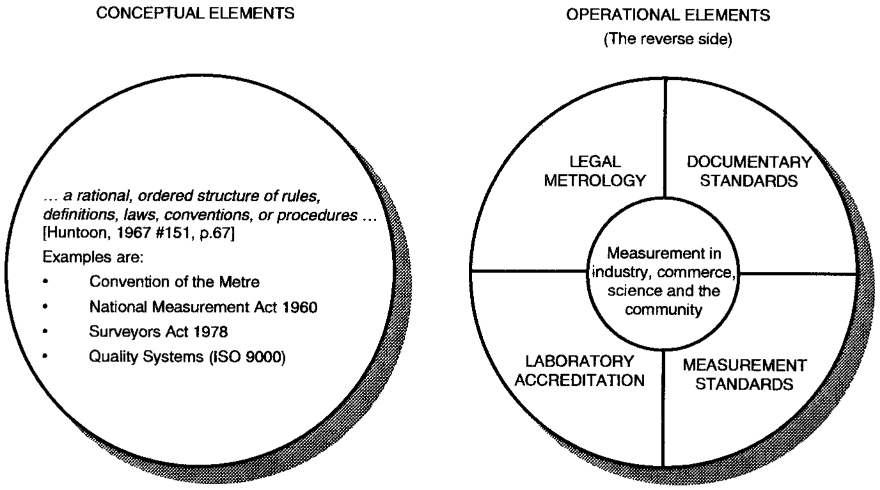
- *national standards laboratory* that maintains the national standards and provides related services;
- *intermediate standards laboratories* that use transfer standards as the basis of calibrations and other services provided by them;
- *field level entities*, such as laboratories, companies, or individuals that perform measurements; and
- *voluntary standards-writing organizations and professional societies* that define, develop, and document various traceability interactions.

Nicholas and White [1994: p.25], in the context of temperature measurements, consider a National Measurement System as comprising *services* such as

- *training of staff in measurement techniques*
- *supply of measuring instruments*
- *repair and servicing of instruments*
- *calibration of instruments*
- *specifications and procedures for measurements*
- *certification of measurement results*

Implicit in the above description is the existence of resources and infrastructure which can provide and support the services.

Generally, the aforementioned elements are evidenced in most measurement systems and can be grouped into three major categories: *measurement standards*, *laboratory accreditation* and *documentary standards*. Laboratory accreditation provides a means of determining the competence of laboratories to perform specific types of testing, measurement and calibration. Huntoon [1967, p.68-69] classified a similar set of elements as *data*, *instrument* and *techniques networks*, while the CSIRO, in its submission to the Committee of Inquiry into Australia's Standards and Conformance Infrastructure [1995, p.3], categorised them as *infrastructure for physical measurement, standards writing, testing, trade measurement, competency assessment and compliance certification.* One important category that has not been mentioned in the literature cited above is *legal metrology*. For a majority of applications, particularly those for legal purposes, legal metrology is a requirement. In the context of this thesis, legal metrology is a major issue. In general, a combination of the four categories of elements constitutes the basis of a measurement system (Figure 2.4).



... a rational, ordered structure of rules, definitions, laws, conventions, or procedures ... [Huntoon, 1967 #151, p.67]

Examples are:

- Convention of the Metre
- National Measurement Act 1960
- Surveyors Act 1978
- Quality Systems (ISO 9000)

Figure 2.4. Main components of a measurement system.

2.5.2 The economic dimension of the national measurement system

As remarked previously, measurement systems have an important role in world trade as well as in the economic growth of a nation. However, justification for the need of any infrastructure is often made on economic terms; and the national measurement system is no exception to this rule. This section presents a brief discussion on some of the attempts at quantifying the economic worth of the measurement system.

From the literature perused, actual data on the economic value of a national measurement system is scarce. As stated by Huntoon [1967, p.67], a reason for this could be due to its *all-pervasive nature*, which renders almost impossible the performance of an economic evaluation of such a system. The study by *ibid.* [1967], albeit conducted 30 years ago, provides a rough estimation of the economic value of the measurement system in the United States. It estimated that, in 1965, the value of measurement related services was in excess of US$15 billion, which was 3.75% of the Gross National Product (GNP) (US$400 billion) [*ibid.*, 1967, p.67].

Between 1972 and 1975, the NBS, based on the concepts proposed by Dr Robert D. Huntoon, undertook an in-depth study to identify the various elements of the National Measurement System [NBS, 1974, p.38]. One of the initial tasks of the study was to quantify the economic value of the measurement system. In 1973, based on data provided by the Department of Labor, measurement-related activities were calculated conservatively to be in excess of US$70 billion or approximately 6% of the GNP [*ibid.*, 1974, p.39]. Sydenham *et al.* [1989, p.16], citing the findings of other authors, suggest that the economic value of the national measurement system lies in the range of between 0.1% and 5% of a nation's GNP. Using a similar approach, Kose [1994/95, p.457] suggests a value which lies in the range of between 3% and 6% of the GNP. Kind [1997, p.436] estimates that measurement and measurement-related operations in industrialised countries account for up to 6% of the GNP.

In 1992, the Bureau of Industry Economics (BIE) conducted a study to establish an economic assessment methodology for evaluating resource allocation for the CSIRO. The study concluded that *the benefits of the National Measurement System far exceeded its costs. However due to the intangible and indirect nature of the benefits and the interconnectedness of the contributions of its constituent organisations, a benefit-cost ratio could not be quantified for the National Measurement Laboratory* [BIE, 1992, p.7]. In 1995, the Committee of Inquiry into Australia's Standards and Conformance Infrastructure did not conduct an economic evaluation of the National Measurement System. However, it recapitulated the conclusions relating to the economic value of the National Measurement Laboratory reached by the BIE 1992 study [Committee of Inquiry into Australia's Standards and Conformance Infrastructure, 1995, p.35].

The foregoing paragraphs have demonstrated that it is very difficult, if not impossible, to quantify the economic worth of a measurement system. However, extrapolation of the figures estimated by Huntoon [1967] and NBS [1974] into present day terms would lead to the inescapable conclusion that the national measurement system contributes significantly to a nation’s economic growth and wealth.

2.6 International measurement system

As described in Section 2.5.1, a measurement system comprises those elements which pertain to measurement standards, legal metrology, documentary standards and laboratory accreditation. In this regard, the international measurement system is composed of, respectively, four main organisations, namely the General Conference on Weights and Measures (*Conférence Générale des Poids et Mesures*, CGPM), the International Organization of Legal Metrology *(Organisation Internationale de Métrologie Légale*, OIML), the International Organization for Standardization (ISO) and the International Laboratory Accreditation Cooperation (ILAC) (Figure 2.5). Jensen and Thor [1994/95] provide a lucid description of the organisational network that forms the international measurement system.

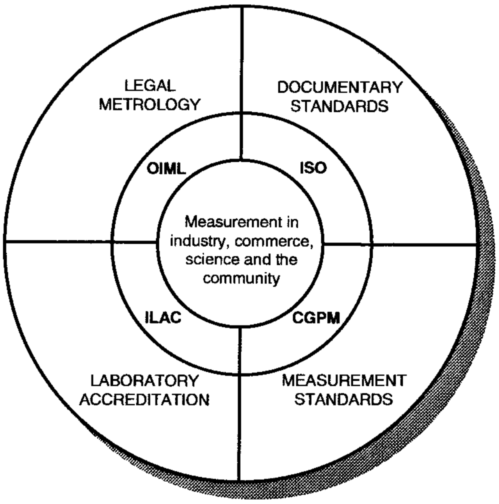


Figure 2.5. Components of the international measurement system.

The origin of the international measurement system can be attributed to the signing of the Convention of the Metre (*Convention du Mètre*), an international treaty signed in 1875 by 17 countries in recognition of the benefits to be derived from the universal adoption of a single, rational system of units of measurement, particularly the Metric System, based on the *metre*, the *second* and the *kilogram*. The Metric System has since evolved into its modern counterpart known as the International System of Units (*Systéme International*, SI). Forty-eight nations (December 1996), known as Member States, including Australia, conform to the treaty. A permanent organisational structure of the Convention of the Metre has been established for Member States to act in common accord on all matters relating to units of measurement (Figure 2.6).

The supreme authority on units of measurement is the CGPM which comprises delegates from all Member States and is responsible: for ensuring the propagation and improvement of the SI units, for reviewing and endorsing new fundamental metrological developments, and for adopting decisions about the organisation and the activities of the International Bureau of Weights and Measures (*Bureau International des Poids et Mesures*, BIPM) [BIPM, 1995, p.12]. The CGPM controls the BIPM through the International Committee of Weights and Measures (*Comité International des Poids et Mesures*, CIPM). The CIPM, which comprises 18 individuals elected by the CGPM, and is responsible for supervising the work of the BIPM and preparing proposals for consideration by the CGPM, operates through a number of Consultative Committees consisting of scientists and technical experts from around the world.

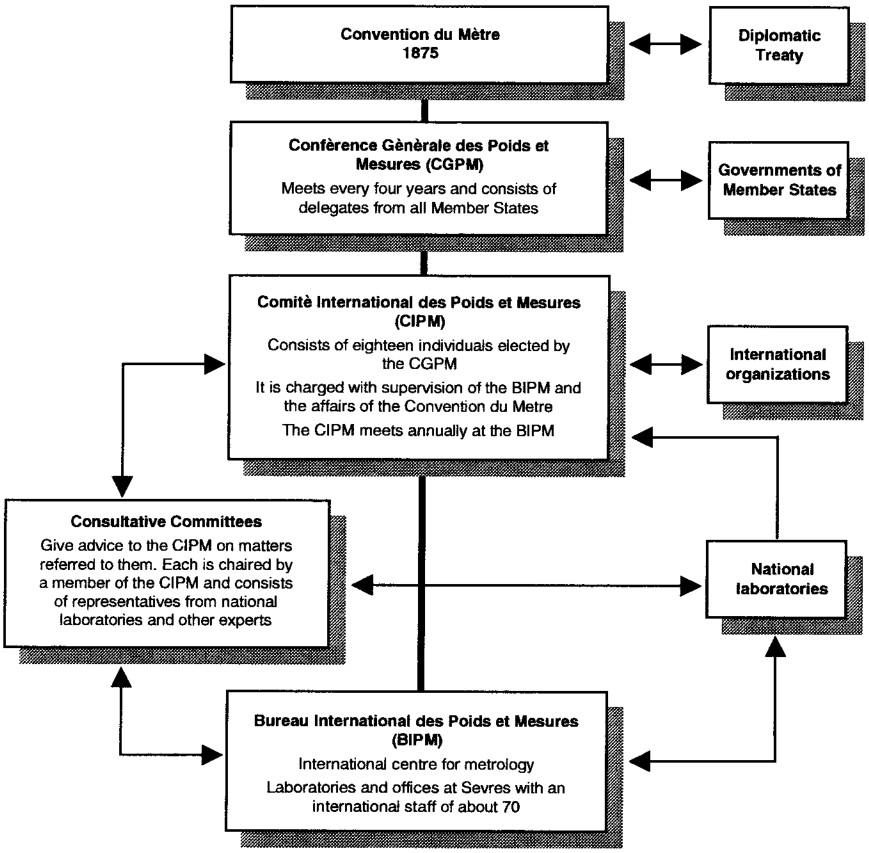


Figure 2.6. The organisational structure of the Convention of the Metre. The thick line indicates the line of responsibility while the thin lines indicate interactions between organisations [from BIPM, 1995, p.6].

The BIPM is the focus of a network of scientific and technical links between industrialised nations. Under the authority of the Convention of the Metre, the BIPM is entrusted with the task of ensuring world-wide uniformity of measurements and their traceability to the SI. The principal activities of the BIPM include:

- the maintenance and dissemination of the unit of mass, the calculation of the International Atomic Time (*Temps atomique international*, TAI) and its dissemination through Coordinated Universal Time (Universal Time Coordinated, UTC) [Quinn, 1994/95, p.515];
- the organisation of, and participation in, international comparisons of national measurement standards; and
- the performance of calibrations for Member States.

The international organisation responsible for the legal aspects of measurements is the OIML, which is an intergovernmental organisation based on an international convention signed in 1955 by 37 countries. Its organisational structure is similar to that of the Convention of the Metre (Figure 2.6), but differs from it in having no laboratories or technical equipment.

The OIML cooperates closely with the BIPM and has a general secretariat named the International Bureau of Legal Metrology (*Bureau International de Métrologie Légale*, BIML).

The main objective of the OIML is to promote the global harmonisation of legal metrology procedures in order to reduce barriers to international trade. To achieve this objective, OIML develops model laws and regulations, known as International Recommendations, which provide the Member States with an internationally agreed upon basis for the establishment of national legislation pertaining to measurements used in industry, commerce and science. The International Recommendations are formulated by technical secretariats formed under the International Committee of Legal Metrology (*Comité International de Métrologie Légale*, CIML). The recommendations are submitted to the International Conference of Legal Metrology (*Conférence International de Métrologie Légale*) for approval. The International Conference of Legal Metrology is also responsible for formulating general policy and organisational issues. More detailed information regarding the OIML can be obtained from the OIML internet site (www.oiml.org).

The international organisation responsible for developing documentary standards is the ISO, a non-governmental world-wide federation of national standards organisations from 130 countries, whose objective is to promote the development of standardisation and related activities in the world, with a view to facilitating the international exchange of goods and services, and to developing cooperation in the spheres of intellectual, scientific, technological and economic activity [ISO, 1998].

The ISO develops, over almost the entire range of technology, international documentary standards which are *documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics, to ensure that materials, products, processes and services are fit for their purpose* [ISO, 1998]. ISO standards are developed by international consensus among experts drawn from the industrial, technical or business sectors. The technical work of the ISO is carried out in a hierarchy of 2850 technical committees, subcommittees and working groups. In these committees, qualified representatives of industry, research institutes, government authorities, consumer bodies, and international organisations from all over the world come together as equal partners in the resolution of global standardisation problems.

The adoption of ISO standards is voluntary. An example of ISO standards widely adopted in surveying is the ISO 9000 family of quality systems standards. Information regarding the ISO can be obtained from the ISO internet site (www.iso.ch).

The ILAC is the *world's principal international forum for the development of laboratory accreditation practices and procedures, the promotion of laboratory accreditation as a trade facilitation tool, the assistance of developing accreditation systems, and the recognition of competent test facilities around the globe* [ILAC, 1997]. Currently, laboratory accreditation is not a link adopted in Australia to establish *legal* traceability of measurements (*vide* Section 2.7 for further elaboration). Therefore, this particular element is not a main concern in this thesis; interested readers may refer to the ILAC internet site (www.ilac.org) for more information on laboratory accreditation.

As remarked in the opening paragraphs of Section 2.5.1, the demands of international trade, particularly that of the removal of technical barriers to trade, have placed greater emphasis on the need for international traceability of measurements. This is, however, a relatively recent issue and the concepts discussed here are still embryonic in nature. Discussions relating to the interdependence of international trade and international metrology can be found in Quinn [1997a]. One of the biggest *technical barriers* is the need to relate measurements or standards of measurement of one country to those of another country. A traditional way of overcoming this problem is by proving that the accuracy of the realisations of the SI units in a national metrology institute is consistent with that of other national metrology institutes. According to Kind and Quinn [1995, p.88], confidence in such accuracy comes from two sources only: first, *from the internal consistency and visible quality of the work*; and, second, *from the comparisons with similar but independent realizations made elsewhere*. For years, the BIPM has been organising and participating in international comparisons of national measurement standards. International comparisons also can be organised and carried out by the Consultative Committees and, at the regional level, by the national metrology institutes. The details for performing international comparisons are described in BIPM [1998a]. Most comparisons carried out by the BIPM involve the following [BIPM, 1995, p.22]:

- national primary standards are brought to the BIPM and compared with standards from the BIPM; and
- BIPM travelling primary standards are taken to a national metrology institute for comparison with those of that institute.

International comparisons are not trivial exercises. The experiments, conducted with utmost care by experts in the field, cannot be performed regularly without incurring high costs and demands on technical and human resources. In addition, as mentioned in Section 2.2.2, the underlying assumption that traceability will flow down in a straightforward manner to the working level measurements in a country, following comparisons at the highest level, is not always correct, because significant variations between working level measurements made in different countries can be found.

Recently, in order to meet the increasing demands of international traceability, the CIPM proposed the concept of *international equivalence of national measurement standards* [Quinn, 1997b, p.188; and Quinn, 1997a]. *Equivalence* is a term used to link measurements or standards at the same level. Unlike the concept of traceability, there is no hierarchical relationship between equivalent measurements or standards. Equivalence of national measurement standards can be achieved through *key comparisons* [Quinn, 1997b, p.188; and Kind, 1997, p.439]. Key comparisons are not dissimilar to the international comparisons carried out by the BIPM, according to Quinn [1997b, p.188]; the novelty lies in *the process of making the comparisons systematic, covering all the essential measurement quantities and using a common format to describe the published results*. The published results of the key comparisons provide a set of internationally agreed reference values which, together with an associated uncertainty (± ε), can be used to represent the best approximation of the SI value [Kind, 1997, p.439]. This can be used to form the basis of *international standards* (Figure 2.7). Quinn [1997b, p.188] anticipates that the publication of the results of key comparisons will, over the course of time, provide a solid technical basis for agreements on equivalence of national standards between national metrology institutes. Also, Kind [1995, p.438] suggests that a general agreement on the required *structures* and *procedures* for key comparisons should be formalised in order to achieve international recognition of the equivalence of national measurement standards. The concept of international equivalence of national measurement standards and its proposed implementation is also described in BIPM [1998b].

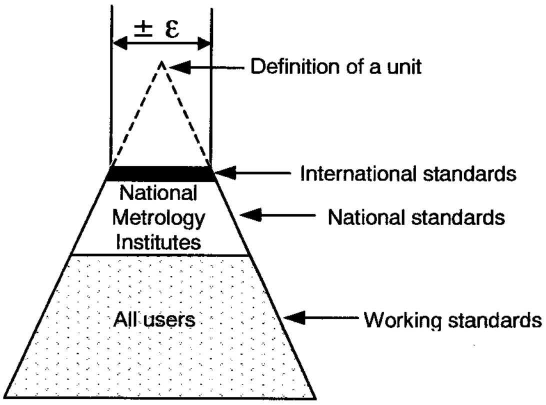


Figure 2.7. Hierarchy of measurement standards: International standards established by intercomparisons between primary laboratories, coordinated by the BIPM and Consultative Committees of the CIPM [from Kind and Quinn, 1995, p.89].

2.7 Australian measurement system

Information relating to the Australian measurement system can be found in a series of information leaflets produced by the NSC [1992; 1993; 1994b; 1995b; n.d.] as well as in publications by Ciddor and Sim [1984] and Rüeger [1985]. Dr Jean M. Rüeger [1985] is arguably the first author in Australia to have described the composition of the Australian measurement system and its relevance in the context of surveying, particularly for the measurement of length. However, since that publication, several new developments in the measurement system have occurred, including:

- the publication of the cited NSC information leaflets which provide additional insight into the national measurement system; and
- the recent review of the national measurement system by the Commonwealth-appointed Committee of Inquiry into Australia's Standards and Conformance Infrastructure [1995].

It should be noted that Rüeger [1985] examined the *Weights and Measures (National Standards) Act 1960*, which was amended when its name was changed to the *National Measurement Act 1960* (Cwlth). This Act is the subject of this thesis, and ensuing paragraphs present a discussion on the aforementioned developments. More importantly, the discussion concerns the means for achieving traceability of measurements, particularly *legal traceability*, in the present national measurement system. Since the Global Positioning System is an international system, the links between the national and international measurement systems are discussed briefly.

The discussion pertaining to the Australian measurement system is similar to that of the international measurement system, i.e. identification of the relevant organisations and institutions responsible for *measurement standards*, *legal metrology*, *documentary standards* and *laboratory accreditation*. In this regard, Figure 2.8 illustrates the organisational networks and links between the international and national measurement systems. The various institutions are linked through legislation, voluntary undertakings and treaties or agreements. Some of the links, for example the link to the BIPM by virtue of the Convention of the Metre, provide important paths for establishing traceability at the international level. For the purpose of clarity, Figure 2.8 delineates only the important links; however, in reality, there are several lesser cross-links between the institutions, the nature of which will become clear in the following paragraphs. As will be discussed later, the NSC is responsible for coordinating the national measurement system – a point which is not apparent in Figure 2.8. Links between institutions or national metrology laboratories, in themselves, do not provide traceability of measurements. By definition, traceability is the property of the result of measurement (*vide* Section 2.2.2), and not the property of an instrument, an organisation or a laboratory.

Institutions and laboratories provide the means for establishing traceability, such as standards of measurement, verification procedures and voluntary or legislated regulations.

Laboratory accreditation is shown in Figure 2.8, despite its comparative irrelevance in the context of this thesis, in order to provide a complete picture of the national measurement system. Information regarding the National Association of Testing Authorities, Australia (NATA) can be obtained from the NATA internet site (www.nata.asn.au). The relevance of *documentary standards* has been discussed briefly in Section 2.3. The components of *measurement standards* and *legal metrology* are discussed in greater detail in the following paragraphs.

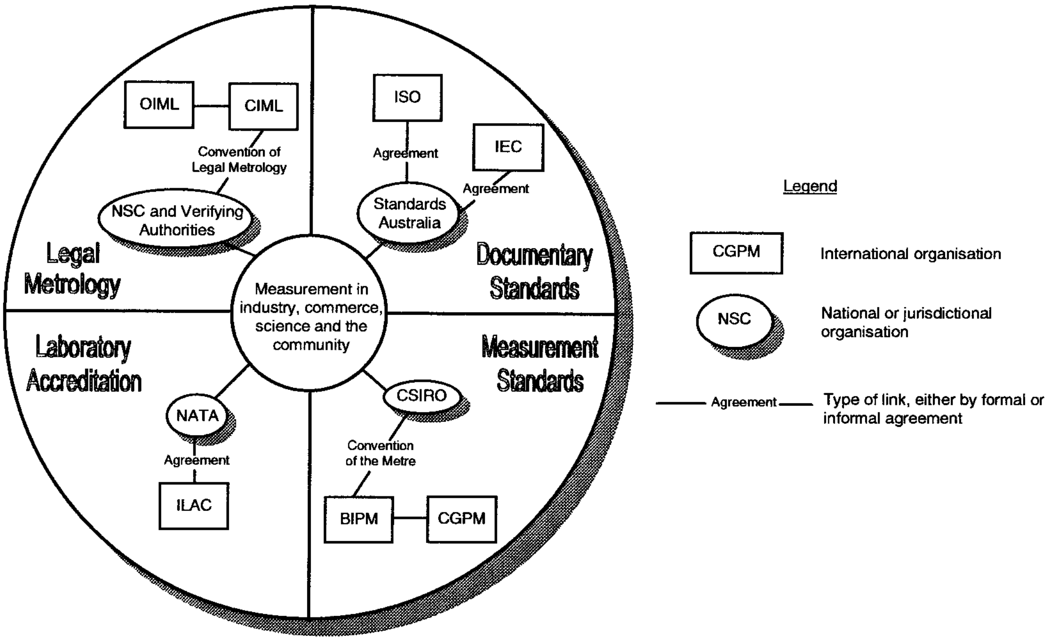


Figure 2.8. Principal links between the international and Australian measurement systems [adapted from NSC, n.d., p.10; and Ciddor and Sim, 1984, p.130].

The Australian Measurement System is described as that *infrastructure which ensures consistent and internationally recognised basis for measurement throughout Australia* [NSC, 1995a, p.1]. The Committee of Inquiry into Australia's Standards and Conformance Infrastructure [1995, p.23] describes the National Measurement System as *all the activities and mechanisms in industry, government and the community that provide physical measurement data and is the foundation of the standards and conformance infrastructure.*

The responsibility for the measurement system in Australia is shared between the Commonwealth and the States and Territories. According to s.51(xv) of the *Commonwealth of Australia Constitution Act 1900*, the Federal parliament is responsible for enacting laws pertaining to *weights and measures*. In this respect, the main piece of national measurement legislation is the *National Measurement Act 1960* (Cwlth). Its administrator is the NSC which is a Commonwealth Statutory Authority. Essentially, the National Measurement Act provides for a uniform system of measurement throughout Australia to be administered through the existing States and Territories instrumentalities. States and Territories may enact legislation with regard to the verification of means of measurements. Such legislation must be consistent with s.10 of the National Measurement Act, which stipulates the means for attaining legally traceable measurements [NSC, 1995c, pp.1-3]. Examples of verification requirements can be found in survey regulations (*vide* Section 3.3). It is interesting to note that when the Weights and Measures (National Standards) Bill 1948, the predecessor to the National Measurement Act, was introduced by the Hon. John Dedman, one of the main reasons given for the purpose of the bill was the need to provide legal sanction to the national standards of measurement of all physical quantities which concern commerce, industry and science. In particular, the standards were necessary for those measurements required for, *inter alia*, the sale of land [Australia House of Representatives, 1948, p.1788]. Hence, s.12(A)(1) of the National Measurement Act stipulates the following: *every contract, dealing or other transaction made or entered into with respect to an interest in land that refers to any measurement of a physical quantity (including a reference to a measurement of a physical quantity for descriptive purposes only) shall refer to Australian legal units of measurement of that physical quantity.*

As mentioned previously, the most recent study of the Australian measurement system is that conducted by the Committee of Inquiry into Australia's Standards and Conformance Infrastructure [1995]. There were two reasons for the review:

- government's microeconomic reform policy; and
- business concerns that the infrastructure, in particular the standards and conformance components, was not meeting industry's needs adequately [*ibid.*, 1995, p.vii & p.xi].

The Committee set the following aims: *This report seeks to provide a clear picture of the infrastructure today, analyses why it appears to be failing to meet industry and community expectations, identifies challenges in the future for industry and government and explores what changes are necessary to ensure that the infrastructure and its institutions serve Australia well in the future* [*ibid.*, 1995, p.vii]. As a result of the review, the Committee suggested sixty recommendations which would form the basis of a model for Australia's Standards and Conformance Infrastructure. However, not all the recommendations were adopted by the Federal government. One of the most controversial recommendations, which has direct implications to the object of legal traceability, was that pertaining to the dissolution of the NSC [*ibid.*, 1995, p.55]. The recommendation was made based on the dubious rationale that the NSC lacked specialist personnel in the field of measurement and that many of its functions could be assumed by other government departments [*ibid.*, 1995, p.53].

However, the recommendation was rejected by the government, mainly because of the perceived need to maintain the NSC as an authority in legal metrology [Department of Industry Science and Technology, 1995, pp.7-8]. In particular, the government recognised as significant the role NSC plays in the international measurement system, through its membership and involvement in the OIML.

The specific functions of the NSC are defined in s.18 of the National Measurement Act. In general, the Commission is responsible for coordinating the operation of the national measurement system and advising the government on the scientific, technical and legislative requirements of the national measurement system. The CSIRO is also a Commonwealth Statutory Authority and its role in the national measurement system is defined in two pieces of legislation. Section 9(g) of the *Science and Industry Research Act 1949* stipulates that the CSIRO is *to establish, develop and maintain standards of measurement of physical quantities* ... . Similarly, s.8 of the National Measurement Act requires the CSIRO to *maintain, or cause to be maintained*, Australia's primary standards of measurement. A majority of the primary standards of measurement, which include length and time, are realised, maintained and disseminated by the National Measurement Laboratory (NML) of the CSIRO Division of Telecommunications & Industrial Physics (CTIP). Essentially, the NSC provides the legislative base, in the form of the National Measurement Act, which relates the standards of measurement realised by the CSIRO to the day-to-day control by State and Territory governments of measurement in industry, commerce, science and the community. Most importantly, this relationship provides a basis for achieving *legal traceability* of measurement in Australia.

International traceability of measurements, as discussed in Section 2.6, is achieved through the NML's participation in *international comparisons* of national measurement standards organised by the BIPM. International equivalence of national measurement standards also can be achieved through *key comparisons* carried out by the BIPM, Consultative Committees of the CIPM, and regional metrology institutes. International traceability is important because the Global Positioning System is owned and operated by the United States. In other words, Australia has no control over the performance and operation of the system. The measurement standards used in the Global Positioning System, specifically those for time, are realised and maintained by the United States and are related to those at the BIPM through international comparisons. In principle, GPS measurements carried out in Australia could be traceable to the *international standards* based on the recently mooted concept of *international equivalence of national measurement standards* (*vide* Section 2.6). There is a possibility that the National Measurement Act would need to be amended, because there is no provision within the Act which gives legal sanction to measurements traceable to *international standards*. The topic relating to the traceability of GPS Time is discussed in detail in Section 6.4.

In order to satisfy Australia's international obligations, for example those framed in the Convention on Legal Metrology and World Trade Agreement, as well as the Australian law, the NSC has implemented a *metrological control system* for measuring instruments. In order to provide traceability of measurement, a metrological control system should be implemented [NSC, 1994a, p.1]; it should comprise the following elements:

- national pattern approval of measuring instruments;
- verification of measuring instruments;
- re-verification of measuring instruments on a periodic basis;
- accreditation of measurement laboratories, including measurement skills and training of personnel; and
- ideally measurements should be made by an independent third party.

The above elements are described in detail in *ibid.* [1994a]; the first three are those of particular relevance in this thesis. Pattern approval is *the process whereby an impartial body examines the design of an instrument prototype against a set of national or international metrological specifications* [*ibid.*, 1994a, p.1]. Its aim is to ensure that the instrument, once calibrated, is capable of retaining its calibration over a range of environmental and operating conditions. Re-verification is a *test of accuracy of measuring instruments that have been in use for some time* [*ibid.*, 1994a, p.2]. This process is akin to the process of calibrating EDM devices in surveying. Some of the aforementioned requirements can be found in survey legislation (*vide* Section 3.3).

Australia has two formal methods of disseminating standards of measurement throughout the country in order to prove traceability to national standards, namely through NATA and by the appointment of *verifying authorities* by the NSC. Measurements traceable to the national standards through the NATA link (Figure 2.8) cannot be given legal sanction, because the link has no force under the provisions of the National Measurement Act. As mentioned in Section 2.2.3, legal traceability of measurements can be established only when the measurements have been related appropriately to the national standards in accordance with the provisions of s.10 of the National Measurement Act.

The NSC appoints verifying authorities according to the provisions of r.77 of the National Measurement Regulations in force under the National Measurement Act. According to r.77, a verifying authority is a person or a body corporate holding, or performing the duties of, a specified office of the Commonwealth, a State or a Territory, or a body corporate authorised in writing by the NSC to verify specified *reference standards of measurement*. A *reference* *standard of measurement*, according to s.3 of the National Measurement Act, is *a standard of measurement (other than an Australian primary standard of measurement, an Australian secondary standard of measurement, a recognized-value standard of measurement, State primary standard of measurement) that has been verified in accordance with the regulations* ... . Verifying authorities *are appointed where there is a need for legally traceable measurement, such as measurements that form the basis for government regulation, agreements, contracts and court proceedings* [*ibid.*, 1994b]. To be appointed as a verifying authority under r.77, the applicant must satisfy the following conditions [*ibid.*, 1988, p.6]:

- there is a reasonable need to verify standards of measurement for the purposes of administering a State or Federal law;
- adequate test facilities are available;
- competent staff are employed;
- valid standards of appropriate accuracy are held and maintained;
- adequate records are maintained; and
- test procedures follow accepted practice.

Under r.80(6), verifying authorities are empowered to issue certificates that attest to the verification of a standard of measurement. Such a certificate, according to r.80A(1), *is evidence of the matters stated in it* and is admissible as evidence in legal proceedings [*ibid.*, 1995c, p.4]. The proof of legal traceability of measurements to the national standards is through certificates issued by the verifying authorities following the appropriate verification process. Approved methods of verification are prescribed by the NSC in the Verifying Authorities Handbook [*ibid.*, 1994b].

In the field of surveying, Surveyors General are the appointed authorities for the verification of reference standards of measurement of length. Presently, Surveyors General calibrate survey tapes, levelling staves and EDM devices. Figure 2.9 illustrates the manner in which a length measured using a surveyor's EDM device can be traced to the national standards in a scheme which involves verifying authorities and certificates issued under the provisions of r.80.

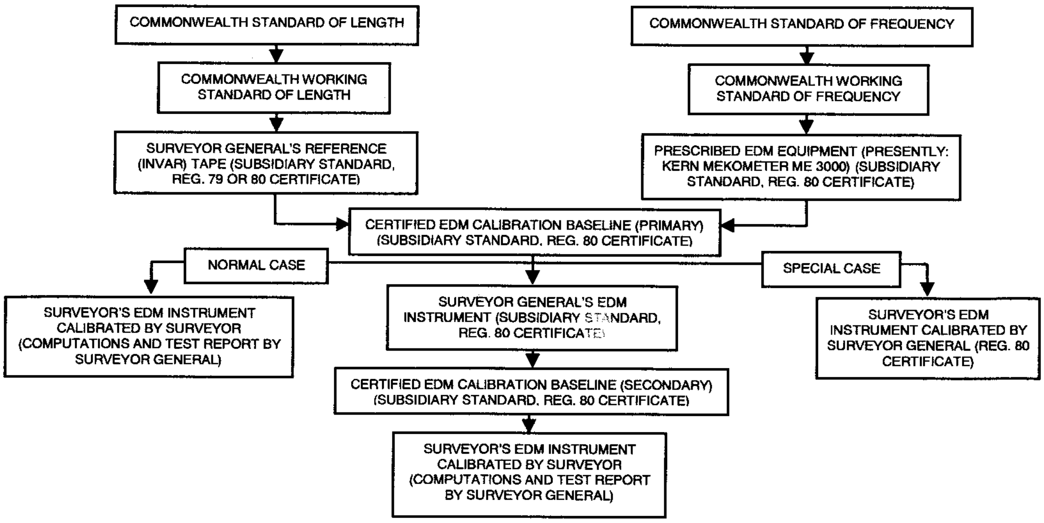


Figure 2.9. Traceability of electronic distance measurement to the national standards [from Rüeger, 1985, p.154].

2.8 Summary

The foregoing sections have examined and described the means for establishing traceability of measurements within the current national measurement system. In order to provide a meaningful discussion, the measurement system has been conceptualised as comprising conceptual and operational elements.

The conceptual elements, namely the concepts of traceability and measurement concepts, form the fundamental basis upon which a measurement system is built. The concepts of traceability were discussed within the context of the present measurement system as well as in the context of a deregulated system. In both situations, it was established that the requirements for legal traceability of measurements can be achieved only by complying with the provisions of the National Measurement Act, particularly those of s.10 of the Act.

Principal measurement concepts were examined in order to gain an appreciation of the underlying principles of a measurement system. Where possible, the legal, as provided in the National Measurement Act, and metrological, as provided in the *International Vocabulary of Basic and General Terms in Metrology*, meanings were described and compared. Apart from subtle differences, which are peculiar only to the national measurement system, the terms used in the legislation are generally compatible with those recommended by the ISO.

Of particular theoretical significance, in the context of this thesis, is the possibility of directly reproducing units of measurement without recourse to conventional hierarchical means of calibration. The conventional hierarchical means of calibration is also important because it presents a possible practical solution for establishing traceability of GPS measurements. Both approaches, theoretical and practical, are explored and expanded further in Chapter 6.

The operational elements of a measurement system implement the requirements of the conceptual elements. The operational elements are composed of organisations, laboratories, people and regulations. A model of a measurement system which comprises four major components, namely *measurement standards*, *legal metrology*, *laboratory accreditation* and *documentary standards*, has been used as a basis for reviewing the international and national measurement systems.

International traceability of measurements can be achieved by way of *international comparisons* and *key comparisons* of national measurement standards. The concept of international traceability of measurements has been reviewed because of its importance in the context of the Global Positioning System. The standards of measurement, specifically that of *time*, used in the Global Positioning System are realised and maintained in the United States. However, the recently mooted concepts of *international equivalence of national measurement standards* and *international standards* could be implemented to provide traceability for GPS measurements carried out in Australia. The implementation may require the National Measurement Act to be amended because, according to s.10 of the Act, legal traceability can be achieved only by reference to the *national standards*.

In Australia, legal traceability can be required for measurements carried out for any legal purpose, such as agreements, contracts and court proceedings, as well as measurements which are subject to regulation by law or government decree. Traceability of measurements can be achieved via several components of the national measurement system. However, legal traceability of measurements can be established only when the measurements have been related appropriately to the *national standards* in accordance with the provisions of the National Measurement Act, particularly those of s.10 of the Act.

3. THE CADASTRAL SURVEY SYSTEM AND TRACEABILITY OF MEASUREMENTS

3.1 Introduction

As described in Section 2.2.3, legal traceability of measurements can be required for measurements carried out for any legal purposes, such as agreements, contracts and court proceedings, and for measurements which are subject to regulation by law or government decree. In the context of cadastral surveying, measurements are carried out for legal purposes and are subject to regulation by law, namely survey legislation. Survey laws are enacted, essentially, to control the quality of surveyors and their work. Cadastral surveyors, when carrying out measurements, have a statutory responsibility, as prescribed in survey legislation, to ensure that the results of the measurements are what they purport to be. By law, cadastral surveyors owe a duty of care to their clients and the general public, who may rely and/or act upon the information or advice provided. In this regard, adherence to statutory requirements, such as use of Australian legal units of measurement, calibration of survey equipment, and prescribed accuracy standards for survey measurements, is required. In the case of a deregulated cadastral survey system (*vide* Section 2.3), however, quality assurance principles, in place of statutory requirements, can be adopted.

The *National Measurement Act 1960* (Cwlth) provides the statutory framework which relates the standards of measurement realised by the CSIRO to the day-to-day control by State and Territory governments of measurement in industry, commerce, science and the community (*vide* Section 2.7). States and Territories enact survey legislation, consistent with the provisions of s.10 of the National Measurement Act, regarding the verification of survey instruments. This thesis postulates that the establishment of the legal traceability of measurements extends beyond the instrument. The concept of traceability, adopted in this thesis, is a characteristic or property of the *result* of a measurement (*vide* Section 2.2). To achieve this, the whole *measurement process*, which includes the surveyor, the instrument and the procedures, must be considered. It is this holistic approach which ensures the legal traceability of measurements in cadastral surveying. In principle, existing survey legislation includes all the aforementioned elements.

The first part of this chapter presents an overview of the general cadastral concepts and historical aspects of a cadastral survey system, an understanding of which is necessary to appreciate the reasons and requirements for measurements carried out in cadastral surveys to be given legal validity. In addition, since the existence of legal rules or laws presupposes a source from which those rules originate, the overview provides an insight into the source of the present laws and codified survey practices. The second part presents a review of the survey legislation pertaining to the practice of cadastral surveying in Australia, particularly the statutory requirements for ensuring the legal traceability of measurements.

3.2 Overview of cadastral concepts

The aim of this section is to provide an overview of the basic concepts which underpin the cadastral system. An overview, by definition, is general in nature; more in-depth discussions can be found in the cited references.

The subjects of *cadastres* and *cadastral systems* are well documented in Dowson and Sheppard [1956], Simpson [1976], Dale [1976], Williamson [1983] and Bullock [1984]. A majority of the discussion in this chapter is based on Williamson [1983] which is considered to be one of the most comprehensive documentation of a cadastral system, that of New South Wales. In general, there is little variation between the Australian cadastral systems because of the similarities in the title registration systems adopted by the respective jurisdictions [Bullock, 1984, p.41]. Hence, the Australian cadastral systems can be adequately reviewed, as a generality, by describing that of one jurisdiction.

A *cadastre*, in general terms, is a *public register usually recording the quantity, value and ownership of land parcels in a country* [Dale, 1976, p.xx]. Originally, cadastres were established in Europe for fiscal purposes, i.e. valuation and taxation; however, modern cadastres, such as legal and multi-purpose types, serve several purposes. A multi-purpose cadastre may also be known as a land information system. The role of the cadastre in a land information system is described in Williamson [1983], Bullock [1984] and McLaughlin and Nichols [1987]. Recently, the relationship between the cadastre and land information system has been re-emphasised in the International Federation of Surveyors (*Fédération Internationale des Géomètres*, FIG) *Statement on the Cadastre*, which defines the *cadastre* as *a parcel based and up-to-date land information system containing a record of interests in land. It usually includes a geometric description of land parcels linked to other records describing the nature of the interests, and ownership or control of those interests, and often the value of the parcel and its improvements* [FIG, 1995, p.1]. This definition regards the terms *cadastre* and *land information system* as synonymous.

A *cadastral system* is that basic infrastructure which is necessary for the creation, development and operation of a cadastre. Bullock [1984, p.1] describes the elements of a cadastral system as *those agencies concerned with:*

- *the recording of basic descriptive information concerned with the valuation and assessment of land parcels*;
- *the registration of ownership of rights in land*; and
- *the delimitation and mapping of land parcels.*

Essentially, the above has outlined three systems, namely the *valuation*, *land registration* and *cadastral survey* or *mapping systems* (the relationship between these systems is shown in Figure 3.1 and Figure 3.2). Williamson [1983, pp.15-18] identifies the *land registration* and *cadastral survey systems* as central elements of the Australian cadastral system. The same opinion is shared by several other authors, including Dale [1976, p.201] and Toms [1976, p.188]. The *land registration* and *cadastral survey systems*, particularly their inter-relationship, are the main focus of this thesis.

Land registration is described broadly as *the process whereby various rights in defined units of land are officially recorded* [Dale and McLaughlin, 1988, p.12; and FIG, 1995, p.7]. The information component of a land registration system is the cadastre. According to Dale and McLaughlin [1988, p.25], land registration cannot operate effectively without a cadastre. This view is supported by the FIG [1995, p.2] because the cadastre, as defined by the FIG [1995, p.1], is considered to be the primary means of providing information about property rights.

Cadastral surveying is the *definition, identification, demarcation, measuring and mapping of new or changed legal parcel boundaries* [FIG, 1995, p.4]. Traditionally, in Australia, the primary role of cadastral surveying has been *to describe and mark on the ground, parcels of land for alienation and conveyancing* [Williamson, 1983, p.63; and Bullock, 1984, p.17]. However, this role, increasingly, is expanding to include cadastral mapping and the compilation of digital cadastral databases (DCDB). Some Australian jurisdictions have embodied both, traditional and expanded, roles of cadastral surveying in their respective survey legislation (see for example, s.5 of the *Surveyors Act 1977* (Queensland), s.3 of the *Surveyors Act 1978* (Vic.), and s.4 of the *Survey Act 1992* (South Australia)). Statutory definitions are employed to provide unambiguous meaning to words used in the legislation. Inappropriate definitions, however, can inadvertently impose unnecessary restrictions on the intentions of the legislation; for example South Australia has adopted a very general approach in its definition of a cadastral survey, which, according to s.4 of the *Survey Act 1992*, is *any process of determining the boundaries of land by the measurement of distances and angles...or by photogrammetry.* This definition, unlike any other in Australia, actually states the types of measurement that are to be used for determining the boundaries of land. The South Australian aspirations of implementing the concepts of a legal co-ordinated cadastre are widely documented in Porter [1990, p.118], Nisbet [1992, p.1] and Kentish and Porter [1992, p.215]. The current definition, however, does not appear to reflect such aspirations since it seems to preclude the use of coordinates for determining boundaries of land. According to Nisbet [1996], similar concerns were expressed by the surveying fraternity when the legislation was being drafted. Based on advice given by the Parliamentary Draftsperson, the definition was never altered. However, like any piece of legislation, the Act should be read as a whole: it is then clear that the main thrusts of the Act provide for a coordinated cadastre.

Dale [1976, p.36] describes a *cadastral survey system* as a *set of connected parts which relate to the collection, processing and presentation of land information.* In addition, this system operates within certain *considerations and constraints* as shown in Figure 3.1. Similarly, Williamson [1983, p.18] describes the Australian cadastral survey system as referring to *the control and methods of carrying out cadastral surveys* which include *the legal and administrative controls and framework, the personnel involved at a government or private enterprise level, the professional and educational institutions, and the methods and equipment used to carry out such surveys.*

Dale [1976, p.37], adopting a systems approach, postulates a model of a cadastral system which comprises *external factors, central components, output elements* and *feedback factors* (Figure 3.1). Later, using the same approach, Dale [1979] modified and expanded the model to include additional interactions with the environment (Figure 3.2), so providing a broader, generalised perspective of the cadastral system. These models illustrate that cadastral systems are influenced and shaped by the environment in which they serve. Hence, cadastral systems are unique to the respective jurisdictions in which they exist and operate. In Australia, cadastral systems are administered independently by the States and Territories, but as mentioned previously, there is in fact little variation between the various versions. Further discussions on the effects of changing environments and constraints on the cadastral system are provided in Dale [1976], Toms *et al.* [1988] and Smith [1990].

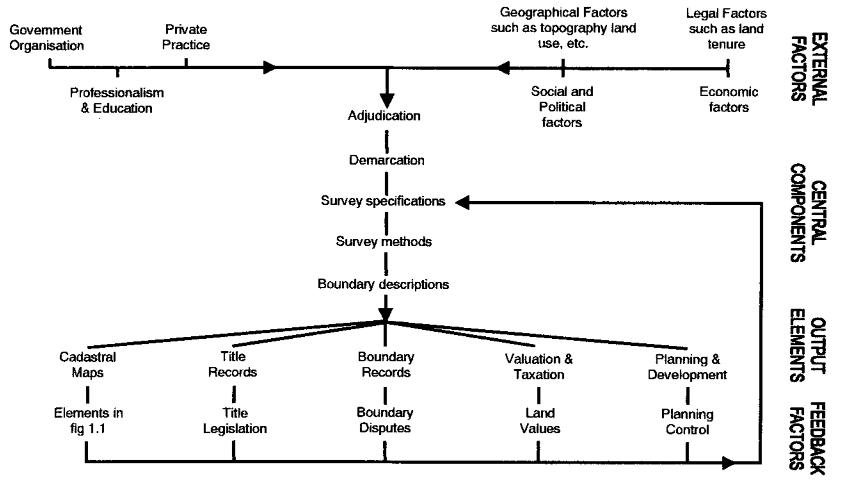


Figure 3.1. Elements in a cadastral system [from Dale, 1976, p.37].

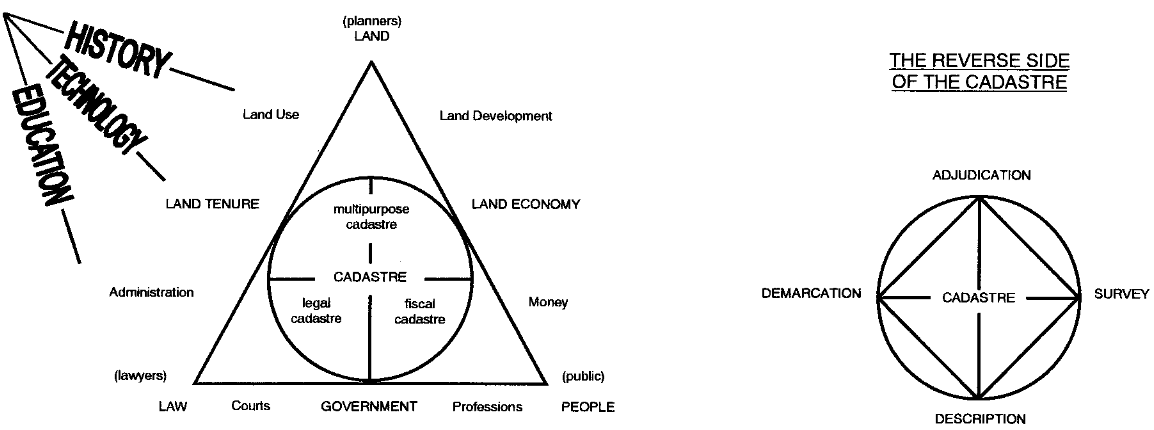


Figure 3.2. Conceptual model of a cadastral system [from Dale, 1979, p.29 & 30].

Other authors, such as McLaughlin [1971], have also used a systems approach to study and analyse the cadastral system, and the models presented by these authors have been developed specifically to suit the subject-matter. Dale's models, however, are comprehensive and, as such, can provide a good general basis for understanding the structure and operation of a cadastral system. As Dale [1979, p.32] aptly puts it; *the systems approach to the cadastre not only permits an understanding of the way things are but where change is postulated or introduced, allows the consequences to be examined and moderated.* Several authors have adopted Dale's model as a basis for analysing a country's cadastral system (see for example Toms *et al.* [1988] and Toms and Cross [1990]); this thesis also adopts Dale's models as providing a framework for discussion relating to the cadastral system in Australia.

In Dale's models, the cadastral survey system has a central and integral role within the overall cadastral system. The components of the cadastral system which are relevant to this thesis are the land registration and cadastral survey systems. Figure 3.1 shows that the cadastral survey system has a dynamic character, since it is influenced by the *external factors* as well as by the evolving requirements of the *feedback factors*. These factors and their influence on the cadastral survey system are discussed in the following sections. In particular, Section 3.2.1 provides a review of the land registration system and examines its requirements for survey measurements. Section 3.2.2 provides a review of the cadastral survey system and examines the circumstances which have shaped the system into its present state.

3.2.1 The land registration system and its requirements for survey measurements

> *In order to examine a cadastral survey system it is necessary to consider why it exists and what purpose it serves. ... Central to the operation of our cadastre is the system of title registration.*
>
> Williamson and Holstein [1978, pp.35-36]

Traditionally, in Australia, the primary role of land registration has been to facilitate property conveyancing and registration of proprietary interests in land. In such an instance, the cadastre is termed as a *legal* or *juridical cadastre* which serves as a legally recognised record of land tenure [Williamson, 1983, p.3; and Dale and McLaughlin, 1988, p.13]. There are two main types of land registration system operating in Australia: *title registration system* and *deeds registration system*. The present system of registration of titles to land, which is known also as a *Torrens system*, was introduced in 1858 to South Australia by its instigator, Sir Robert Richard Torrens, with the main purpose of simplifying the process of conveyancing. This title registration system gained wide acceptance and was adopted in the remaining Australian States between 1858 and 1874. Prior to the introduction of the title registration system, conveyancing was based on an English deeds registration system, which is known also as the *old law system* or *general law system*.

The fundamental difference between the title registration and deeds registration systems is the *unit of registration*: the unit in the former is the *land parcel*, while the unit in the latter is the *deed*, which essentially is a record of transaction. The evidence of title in a deeds registration system is dependent on the complete collection of documents held in the registry. In a title registration system, the primary evidence of title is the *title register* itself. The deficiencies of the deeds registration system and the advantages of the title registration system are well documented in Simpson [1976, pp.19-23], Whalan [1982, pp.13-23] and Stein and Stone [1991, pp.6-8].

Due to the increased security and simplicity provided by the title registration system, owners of land with titles held under the old system are usually advised to convert their titles to it. The procedure is referred to as *bringing land under the Act*, the *Act* being the statute enacted for the purposes of the title registration system (for example, the *Transfer of Land Act 1958* (Vic.) and *Real Property Act 1900* (NSW)).

Upon the enactment of a Torrens statute, all land alienated from the Crown is subject to the provisions of the statute when the grant is recorded in the title register at the Land Titles Office (LTO). The act of registration confers on the registered proprietor an absolutely secure title. A certificate of title is prepared, recording the details of ownership, rights and other conditions affecting the land. In the past, the description of the land comprised a map, located in the margin of the certificate, showing its dimensions, usually, as plane distances and bearings. The modern cadastre, generally, comprises two types of records, textual and graphical, linked by a unique parcel identifier. The former comprises proprietary information while the latter constitutes spatial information which is derived from the maps and plans prepared by cadastral surveyors. Changes in the status of the title are recorded on the face of the certificate, subject to examination of supporting documents by the LTO. These documents include instruments of transfer, lease, mortgage and any other dealings with land, as well as maps and plans. All transactions which result in mutation of a parcel are also recorded on the appropriate map or plan and the graphical database. All registered documents, including maps, plans and certificates of title, are open to public inspection.

One of the cardinal features of the Torrens system is the concept of *indefeasibility of title* which is based on the conclusive nature of the title register. A registered proprietor's title to an estate or interest in the land comprised in the title register is considered legally to be conclusive or *indefeasible* [Baalman, 1955, p.143; Hallmann, 1973 p.142; and Butt, 1980, p.288]. The integrity of the title register is guaranteed financially by the government by means of a statutorily created *assurance fund*. Under certain circumstances, registered proprietors deprived of land or any estate or interest in land through the operation of the Torrens statute can claim compensation from the fund [Baalman, 1955, p.144; Hallmann, 1973 p.142; and Butt, 1980, p.305].

Whether indefeasibility of title extends to *title boundaries* has been a moot point. *Title boundaries* are the limits of the title which are described numerically on a map or plan and defined physically on the ground with the aid of monuments. As mentioned previously, the maps and plans are part of the title register. Many authors, including Hallmann [1973, p.184], Simpson [1976, p.137], Dale [1976, pp.24 & 202] and Williamson [1983, pp.153-157], have argued strongly that indefeasibility of title does not include the measurements used to describe title boundaries. Simpson [1976, p.137] states that *none of the Torrens statutes ... expressly guarantees boundaries.* In contrast, Brown [1980, p.46], following a study of all the Australian Torrens statutes, opines that *title to land is ... guaranteed as to all particulars, including boundaries, and indefeasible except on certain enumerated grounds.* This difference of opinion, according to Williamson [1983, pp.156], could be due to different interpretations of the word *boundary*; Simpson [1976, p.137] is referring to the mathematical measurements used for describing the boundary, while Brown [1980, p.46] is referring to the *bounds* of the title as described by roads, parcels and monuments. Williamson [1983, p.157], after studying the prevalent views on the matter, including those cited in the foregoing discussion, concludes that it is the *bounds of a title* rather than *the mathematical dimensions which describe cadastral boundaries and appear on a plan of survey,* that are guaranteed by the State. Hence, the bounds must be determined accurately.

One of the main reasons for the prevailing opinion that indefeasibility of title does not include boundaries is the fact that survey measurements used to describe title boundaries are prone to error; therefore, no legislation can provide a guarantee that survey measurements are exact [Toms and Lewis, 1974, p.256; and Dale, 1976, p.25].

The need to define parcels unambiguously in the title registration system is recognised by several eminent authors. Whalan [1982, p.19] states that, *To complement the land unit base of the Register it is necessary to have accurate surveys which precisely define parcels of land.* Also, *ibid.* [1982, p.19] claims that the register and survey are the *twin pillars of the Torrens system.* According to Simpson [1976, p.131], *It is obvious that it is impossible to make and maintain a register of parcels of land and warrant titles to them unless it is possible to identify each parcel without ambiguity or, in other words, to say where its boundary lies.* These authors, together with several others, including Dale [1976, pp.205 & 272], Williamson and Holstein [1978, p.36] and Williamson [1983, p.147], opine that, because the land parcel is the basic unit in the Torrens system, it is necessary for the parcel to be defined in an unambiguous manner, either in the register or on the ground. As the government guarantees the indefeasibility of title to land, the guarantee is only meaningful if the subject of the title, being the land, is identifiable beyond reasonable doubt. The need to define parcel unambiguously is not a requirement of the Torrens statutes but one that stems mainly from administrative and historical reasons [Williamson, 1983, p.157].

In summary, this thesis adopts the opinion that indefeasibility of title does not extend to title boundaries and there is no legal requirement for precise mathematical dimensions within the title registration system. However, for expediency, the title registration system requires a means for relating the land parcel, as described in the register, to the ground, in a unique and unambiguous manner; this is the primary concern of the cadastral surveyor.

3.2.2 The cadastral survey system – a historical perspective

> *There are many lessons to be learned both from looking at a subject historically, through time, and geographically, through space, assessing how and why systems differ throughout the world.*
>
> Dale [1985, p.354]

History, technology and education have a significant impact on the development of a cadastral survey system (Figure 3.2). The aim of this section is to provide a historical overview of the circumstances which have shaped the Australian cadastral survey system into its present state. Since cadastral surveys in Australia are currently regulated by law, an historical overview provides an insight into the source of the laws and codified survey practices.

The present system of boundary definition in Australia is described as an *isolated survey system*, based on a *fixed boundary* concept [Toft, 1967, p.118; Dale, 1976, pp.25 & 203; Williamson and Holstein, 1978, p.36; and Bullock, 1984, p.17]. A system of isolated or sporadic surveys is a system whereby *individual surveys are regarded as independent units; are only connected to each other if convenient; and are unconformed to an ordered whole* [Toft, 1967, p.132]. A fixed boundary in Australia is a boundary *which is determined by straight lines between turning points whose positions are established at the time of alienation of the land. When a plot is originally demarcated it is marked by pegs and, once these pegs are emplaced in the ground, then the position established on the ground at that point in time is for ever the fixed position* [Dale, 1976, p.25]. There are two exceptions to this principle, namely *natural boundaries*, such as rivers, lakes and cliffs, and *artificial boundaries*, such as walls and fences. A comprehensive account of both types of boundary is given in Hallmann [1973, pp.23-27]. In the Australian boundary survey system, boundaries are defined to a high relative accuracy and monuments, placed precisely to delineate the parcel boundaries, are related mathematically to one another by measurement. The whole boundary definition system is based on precise measurement. However, the underlying principle of *monuments over measurements* or *pegs are paramount to the plan* prevails, because measurements are considered to be most prone to error. The principle is embodied in legislation (see for example, s.268 of the *Property Law Act 1958* (Vic.) – this Act applies to Crown land surveys only).

The main reasons for the development of the isolated survey system are the sporadic nature of early land settlement and lack of natural features in the Australian landscape. Williamson [1983, p.66] states that the system of granting land was one of the greatest factors that encouraged the development of the isolated survey system during the early Colonial period. Hallmann [1973, p.4], Simpson [1976, p.132] and Williamson [1983, p.66] present a good account of the manner in which land was alienated by the Crown and the pattern of its occupation by the early settlers. Toft [1967, p.118] provides a list of the circumstances which have led to the development of the isolated survey system. An in-depth discussion of the evolution of the isolated survey system in New South Wales can be found in Williamson [1983, pp.63-87].

Williamson [1983, p.85] suggests that the *isolated survey system, using fixed boundaries, developed for good reasons.* And, according to Hallmann [1973, p.5], circumstances of the early settlement of the Colony *made it expedient to adopt rough and ready methods.* Barrie [1976, p.16] aptly states that: *The guiding principle behind most early surveys – in fact, most title surveys until well past the middle 19th century – was to measure and demarcate land holdings by the cheapest and most rapid means possible. In the short term this was really the only rational and possible method which could be justified, having regard to the pressing logistic difficulties and the value of the land. For so sparse a population spread over such a large territory, the introduction of a sophisticated and expensive system could not have been justified – nor would it have been tolerated.*

As a result of the government's desire to properly control the alienation of land to the public, the early surveyors had to perform their work as rapidly as possible. The topography of the land and shortages of resources and skilled labour compounded the problems which they faced. Authors, such as Arter [1960], Toft [1967], Chappel [1974], Barrie [1976] and Toms [1976], when describing the history of cadastral surveys during the early settlement of Australia, agree that the early surveys were performed in a very unreliable fashion. During late last century, several Royal Commissions were appointed to inquire into the poor standard and practice of cadastral surveys, as well as into problems relating to the title registration system. These reports, together with the minutes of evidence, provide one of the best insights into the survey system up to that time. The Victorian Royal Commission on Land Titles and Surveys [1885], in particular, is filled with testimonies relating to imperfect instruments, inexperienced surveyors and poorly prepared descriptions of land. Based on the testimonies from *several skilled surveyors*, the Commissioners drew the following conclusions regarding the state of the *territorial surveys*: *the surveys made in the early days of the colony were, for the most part, extremely faulty and unreliable, and that, as a rule, the dimensions of allotments, as marked out by the surveyors on the ground, differ from the* *dimensions of the same as given in the grants* [*ibid.*, 1885, p.x]. The Commission made several recommendations for improving surveys, and emphasised that the Registrar of Titles should be empowered to call for surveys as a basis of title [*ibid.*, 1885, p.iii]. Many of the recommendations, particularly those relating to boundary definition principles, standards of accuracy for cadastral surveys and survey methods, were later embodied in a number of statutes in Victoria, such as the *Property Law Act 1958*, *Transfer of Land Act 1958*, *Survey Co-ordination Act 1958* and *Surveyors Act 1978*.

Apart from the poor standard of surveys, the main problem associated with the isolated survey system is that individual surveys do not correlate to each other due to the absence of uniformity and connection between surveys. As a consequence, hiatuses and overlaps were created between abutting parcels. In Victoria, to overcome some of the problems of non-uniform surveys, the Royal Commission on Land Titles and Surveys [1885, p.xi] recommended: *That a skeleton survey, establishing permanent marks near the corners of all public streets and roads in Melbourne and suburbs, should be undertaken forthwith, so as to supply data for the accurate definition of properties and for the preparation of proper record plans for the use of the Titles Office, as well as for the alignment of streets. And it is the general opinion of the experts examined that such surveys should be made at once, and should be based, as regards to principal lines, on the trigonometrical survey of the colony, so as to ensure accuracy and uniformity in the work, and render the surveys valuable for sanitary, water supply, and all other public purposes.* This recommendation, essentially, was a precursor to the principles of *survey coordination* in Victoria; however, there was to be a delay of almost fifty five years before the introduction of the *Surveys Co-ordination Bill* into Parliament on 1st May 1940 [The Australian Surveyor, 1940, p.164]. Later, the principle of the Victorian *Survey Co-ordination Act* was adopted by several other Australian jurisdictions. The delay in the response to the recommendations could be due to the widespread use of the theodolite and band in the late 1880's, which led to a marked improvement in the accuracy attained in surveys [Toft, 1967, p.124].

Survey coordination, generally, has not been a success [Toft, 1967, p.119; Fletcher, 1971, p.491; Williamson, 1983, pp.100-110; and Bullock, 1984, p.55]. Toft [1967, p.119] opines that the Survey Co-ordination Acts *do not destroy the basic principle of an isolated system: that of working from the part to the whole. They do attempt to modify this principle by introducing a system of correlated surveys. That is, the parts of the whole may be connected to an unconformed whole. The Acts do not facilitate the diversification of survey methods because a plane co-ordinate system for general use has not been introduced with them. The Acts do not perceive the various fields of survey operations as comprising an integrated and systematised whole. Rather they maintain these fields as mutually exclusive and provide for* *connection between them. The full exploitation of a horizontal network of control is not possible if it is used only as an aid to connecting surveys rather than as an essential for survey.* An account of the circumstances which have led to the failure of survey coordination is presented in Williamson [1983, pp.100-110].

Prior to the introduction of survey coordination, several measures were introduced to control the quality of the surveyors as well as the surveys themselves, with the particular intention of facilitating the operation of the title registration system. Some of the measures, still extant, include:

- examination, licensing and discipline of surveyors;
- regulations for controlling survey practice, survey methods, standards of accuracy, marking of boundaries and plan preparation;
- introduction of new measurement technology, such as advancement from circumferentors to theodolites; and
- survey examination.

Many of the measures were recommended in the Royal Commission on Land Titles and Surveys [1885] and have since been enacted as survey laws; for example, the *Surveyors Act 1978* and *Surveyors (Cadastral Surveys) Regulations 1995* in Victoria. The first *Land Surveyors Act* came into operation on 1 January 1896. Prior to this Act, the first Victorian Act relating to surveyors was the *Transfer of Land Statute 1866* [Middleton and Culliver, 1989, p.15].

The introduction of some of these measures, particularly in regard to the increase of survey precision, has attracted critical attention from some authors. Ruoff [1952, p.196] claims ... *that nowhere is it more evident that modern surveying is near to being an exact science than in the several Australian States where a standard of extraordinary accuracy, surely second to none in the world, is maintained. Nevertheless, there is a point beyond which practical exactitude neither can nor need be carried. If the degree of perfection that is sought is such that the amount of public time and public money expended are out of all proportion to the results achieved, it may be questioned whether the surveyor is fulfilling his most useful function in the community, ...* . Arter [1960, p.115] suggests that the *passionate yearning for supreme accuracy when it is not necessary is uneconomic and should be discouraged.* In addition, the showing of unnecessarily precise measurements on surveyors' plans and field notes is *a form of inverted superiority indoctrinated with an accuracy complex that goes far beyond the personal capacity and ability of the surveyor ...* [*ibid.*, 1960, p.116].

As mentioned in Section 3.2.1, precise survey is not an inherent requirement of the Torrens statutes but one that has evolved mainly for administrative and historical reasons. The requirement for precise measurement was a direct consequence of the isolated survey system. Bullock [1984, p.54] claims that *precise measurement was originally introduced so that (in the absence of a control network) a uniform cadastral charting series could be built up "from the part to the whole."* Importantly, in the absence of a control network, precise measurement was necessary to control the propagation of errors in individual surveys, particularly in any survey system which required the adoption of reference marks of adjacent surveys as a datum. In this regard, Barrie [1977, p.257] states that *the motivation to impose increasingly stringent standards on surveys for land description has been based upon the need to inhibit the growth of errors in surveys and not upon the inherent demands of parcel description.* Other factors which have contributed to the demands for precise measurements in cadastral surveys include:

- The uncertainty characteristic of crude measurements of earlier surveys. *The unsatisfactory nature of the original surveys led to an over-reaction in which high precision surveys were carried out in order to prevent the kinds of defect that had existed in the past* [Dale, 1976, p.203].
- The manner in which land was originally alienated. All land that was alienated from the Crown was granted by area which required accurate demarcation [Williamson, 1983, p.149]. Simpson [1976, p.133], quoting from the Report on Registration of Title in Lagos (1957), states that in *Crown grants measurement, not title, is the dominant factor, and so survey takes on a specially important role.*
- The introduction of survey examination. *There has, throughout, been undue emphasis on measurements as evidence as to the position of the original boundaries, in part because of an insistence by most Registrars General that they must examine surveys. Since, in general, they have had no survey background, they have had to rely on the most basic and obvious form of evidence, namely, that of measurement ...* [Dale, 1976. pp.203-204].

The isolated survey system has had a profound influence on the nature of survey laws. Following an analysis of the survey laws in New South Wales, Williamson [1983, p.141] opines that *survey legislation and procedures ... are designed to support an isolated survey system using fixed boundaries.* Due to the similarities in the cadastral survey systems, the comments are equally applicable to survey laws in other jurisdictions. One of the measures used in the legislation to control the quality of surveys is the specification of *permissible error of traverse closure*, which, according to Toft [1967, p.121]:

- *only tests the self-consistency of the closed traverse. It does not verify the accuracies of the individual angular and linear measurements.*
- *does not test for systematic errors.*
- *does not test for the absolute accuracy of traverse points.*

- *does not uncover compensating errors.*

ibid. [1967, pp.116-117] describes some of the reasons for the popularity of traversing. The systematic error in linear measurement is verified by means of *standardisation of bands* [*ibid.*, 1967, p.121]. According to Williamson [1983, p.82], the first known set of regulations which specified the requirement for verifying lengths by means of comparison against a standard of measurement can be dated back to 1848. The following evidence given by Robert Russell, an architect and surveyor, to the Victorian Royal Commission on Land Titles and Surveys [1885, p.48] on the 7th October 1884, provides an indication of the use of standard of measurement during the early surveys:

> *1042. By Mr Madden – Purposefully kept longer? – Purposefully kept longer, four or five inches longer.*
>
> *1043.By the Chairman – Had they a standard laid down in the camp to which this chain was referred at any time? – I brought down the standard from Sydney, and used it; but when Mr. Hoddle came he used a chain four or five inches longer than 66 feet.*
>
> *1044. Would you tell us what the standard was: was it a chain? – It is nearly fifty years ago, and I am not certain. A standard was brought down, but I think that it is a brass rod about 8 feet long; ...*

The evidence appears to indicate that a standard of measurement was used for surveying in the Colony even prior to 1840.

With regard to the quality of surveys, in particular, requirements pertaining to calibration of equipment and independent verification of individual measurements, several enhancements have been introduced into the present survey laws. The composition of current survey legislation is reviewed in Section 3.3.

The main consequence of inaccurate survey measurements is the disagreement between legal and equitable titles. Such inaccurate measurements also cause problems in the creation of *survey-accurate* digital cadastral databases (DCDB), since they result in mis-matching of adjacent parcels. Several legal principles have been introduced so as to overcome these problems; see, for example, the *Transfer of Land Act 1958* (Vic.) and *Property Law Act 1958* (Vic.). Essentially, these principles are based on the premise that long-established occupation takes precedence over measurements (see earlier discussions on this matter in this section).

In summary, the foregoing paragraphs have discussed in a general manner the historical factors which have led to the development of the present cadastral survey system. In order to preserve its integrity, administrative requirements for stringent survey standards and precise survey were introduced. Regulation of cadastral surveying has been necessary in order to reduce risk and uncertainty to the public. According to Arter [1960, p.114], *In any title, ... the*

Crown ... can guarantee that the survey has been made in accordance with the regulations, that the parent title has been re-established with some degree of certainty and that the alignments are reasonably acceptable. The survey laws, together with the Torrens statutes, provide the registered proprietor *not only a guarantee of title ... , but also, in a large measure, a guarantee of the accuracy in the recording of the position of his boundaries relative to those of his neighbour* [Simpson, 1976, pp.367-368].

3.3 Review of current survey legislation in Australia

Survey laws have two main objectives: to control the quality of surveyors and their surveys (*vide* Section 3.2.2). Currently, the quality of surveyors is controlled through a licensing or registration scheme, whereby cadastral surveyors are required to possess certain levels of qualifications and training. The quality of surveys, which is the focus of discussion in this section, is ensured through compliance with measurement requirements stipulated in survey legislation. Essentially, the measurement process must be carried out in accordance with the provisions of the survey laws: measuring instruments are required to be calibrated and standardised, survey methods must conform to those prescribed in the legislation and survey results must meet prescribed accuracy standards.

Surveyors have traditionally used an assortment of survey equipment such as: survey bands and tapes, theodolites, EDM equipment and total stations for measuring angles and lengths. In most jurisdictions, survey equipment used for cadastral surveys is required to be calibrated and standardised for two main reasons: the ascertainment of the uncertainties in the measurements, and the establishment of the legal traceability for measurements pursuant to the provisions of the National Measurement Act. The calibration and standardisation of equipment, through the uniform use of units and standards of measurement, also ensures that measurements are of a common high quality.

While new and more efficient instruments have been introduced progressively into surveying, survey methods, such as traversing, have remained relatively unchanged. Most survey legislation in Australia requires, whenever possible, surveys to be performed using direct measurements in a closed loop traverse. Some legislation requires measurements to be independently verified. Consequently, accuracy standards are prescribed according to the capabilities of contemporary equipment technology and associated survey techniques.

Equipment technology continues to be developed and improved, offering surveyors greater flexibility, efficiency and productivity. Position-based measuring technology and techniques will become more prevalent as new technologies, such as GPS, gain wider acceptance. The mathematical basis of GPS measuring technology and associated survey techniques is different from that of conventional surveying (*vide* Chapter 4). The intention of survey legislation should be not to exclude any specific or valid measuring technology, nor should it be technology-dependent. In the case of GPS, there is a possibility that outmoded and inappropriate statutory requirements may inhibit use of the technology for cadastral surveying.

Section 3.2 has presented an overview of the general cadastral concepts and historical aspects of a cadastral survey system. This has been necessary in order to understand the circumstances and philosophical reasons which have shaped the composition of the present survey legislation. This section presents a review of the current legislation pertaining to the practice of cadastral surveying in Australia. In particular, requirements relating to the calibration and standardisation of survey equipment, survey methods and accuracy standards are examined. It should be noted that the review was undertaken in 1996; since then, some legislation may have been amended. A substantial part of the review has been published in Boey and Parker [1996].

3.3.1 Review criteria

One of the primary tasks of a cadastral surveyor is that concerned with the making of measurements in order to determine and mark title boundaries. In making the measurements, the surveyor is constrained by the type of survey equipment and methods which may be used so as to achieve the results which would comply with prescribed accuracy standards. The surveyor's confidence in the measurements is dependent on a combination of the following factors:

- using verified and well maintained equipment;
- adopting appropriate survey methods;
- adopting correct reference marks;
- implementing the correct verification techniques; and
- employing the assistance of appropriately educated and trained personnel.

The above requirements are used as criteria for reviewing the current survey legislation.

In most jurisdictions, survey equipment used for cadastral surveys is required to be calibrated and standardised for the following reasons:

- ascertainment of the uncertainties in the measurements; and
- establishment of the legal traceability for measurements.

According to s.10 of the National Measurement Act, measurements are legally sanctioned only when they are traceable to the national standards of measurement (*vide* Section 2.7).

Presently, in Australia, the means for establishing traceability is through a hierarchy of calibration processes of increasingly higher accuracy (*vide* Section 2.4.4). Some States and Territories enact legislation relating to the verification of survey equipment consistent with the provisions of s.10 of the National Measurement Act. The means for achieving the legal traceability of GPS measurements is yet to be established [Department of Land Administration, 1994; Boey and Hill, 1995; and Surveyor-General of Victoria, 1995].

Section 3.2.2 has discussed some of the reasons which have caused the adoption of certain survey techniques and accuracy criteria. Well proven survey methods, such as those of traversing and radiation, are used widely by surveyors as part of the measurement process. Traditionally, a closed traverse has been the preferred method because of the nature of the available measurement technology (the theodolite and band), lack of low order horizontal control and the suitability of the Australian terrain [Toft, 1967, pp.116-117]. A traverse closure, however, may not indicate possible existence of systematic errors, which can be caused by a number of factors including faulty equipment, environmental conditions and observers' idiosyncrasies. Therefore, it is important that calibrated survey equipment and appropriate field verification techniques are used during a survey.

Accuracy standards are used to control the quality of measurements by ensuring that the measurement errors are within stipulated tolerances. Accuracy standards for lengths are commonly prescribed as *relative tolerances* which comprise two parts: a constant error and a value proportional to the distance measured. Accuracy standards for angles are also quoted in two parts: a constant error and a formula which relates a fraction of the smallest graduation of a theodolite and the number of observed angles. Originally, these accuracy standards were prescribed to suit the isolated survey system, i.e. precise measurement of lengths and angles between monuments. The shortcomings of relative tolerances are well documented in Berthon Jones [1971, p.420], Angus-Leppan [1973, p.44] and Ghilani [1994, p.163]. These authors favour the use of statistically-based positional tolerances. Essentially, relative accuracy standards limit the use of position-based survey equipment and techniques.

In order to determine whether the accuracy standards prescribed in the existing legislation are able to accommodate the use of GPS, a comparison between the statutory accuracy standards and a typical GPS manufacturer's accuracy specification for a real time kinematic GPS system is undertaken. Boey *et al.* [1996a] present an assessment of the accuracy of real time kinematic GPS positions for the purposes of cadastral surveying in Victoria.

3.3.2 Survey legislation reviewed

In Australia, the practice of cadastral surveying is controlled by States and Territories legislation in the form of Acts of Parliament and regulations, made pursuant to them, which define the administrative detail. Table 3.1 lists the legislation and complementary publications reviewed for the purposes of this thesis. As shown in Table 3.1, the nomenclature for the legislation varies between the jurisdictions.

Jurisdictions	Legislation	Complementary Publications
Australian Capital Territory	*Surveyors Act 1967* (Reprinted as at 28 February 1995). *Survey Practice Directions 1995* (Gazette No. S42, 13 February 1995).	Handbook for Calibration of Electronic Distance Measuring Equipment. Quality Manual LO/7.
New South Wales	*Surveyors Act 1929* (Reprinted as at 7 March 1996). *Survey Practice Regulation 1990* (as amended 1 October 1994).	Surveyor General's Directions for Survey Practice (November 1993).
Northern Territory	*Licensed Surveyors Act 1983.* *Survey Practice Directions 1986.*	None.
Queensland	*Surveyors Act 1977* (Reprinted as at 20 July 1993). *Surveyors Regulations 1992* (Reprinted as at 12 October 1994).	Surveyors Operations Manual (Revision 4, January 1996).
South Australia	*Survey Act 1992* (No.10 of 1992). *Regulations under the Survey Act 1992* (1 October 1992). Surveyor-General's Directions Number 1 issued pursuant to Regulation 29 of the Survey Act 1992.	Manual of Survey Practice Volume 2 (September 1995).
Tasmania	*Land Surveyors Act 1909* (Reprinted as at 1 December 1985). *Land Surveyors (Survey Practice) By-Laws 1982.*	None.
Victoria	*Surveyors Act 1978.* *Surveyors (Cadastral Surveys) Regulations 1995.*	Survey Practice Handbook - Victoria Part 2 EDM Calibration Handbook. Survey Practice Circular - August 1995.
Western Australia	*Licensed Surveyors Act 1909.* *Licensed Surveyors (Guidance of Surveyors) Regulations 1961.* *Licensed Surveyors (Guidance of Surveyors) Amendment Regulations 1986.*	Guidelines for Urban Subdivisions Under Regulations 55A-55F of the Licensed Surveyors (Guidance of Surveyors) Regulations 1961.

Table 3.1. Survey legislation and complementary publications in Australia.

The evolution of survey legislation in Australia has been influenced by general historical factors (*vide* Section 3.2.2), as well as by localised cadastral issues, which, in turn, depend upon variables such as: the manner in which a jurisdiction was first settled, land development policies, government of the day and, to a certain extent, availability of surveying resources and infrastructure. Further, post-World War II developments such as: survey co-ordination, survey integration, multipurpose cadastres, creation of digital cadastral databases (DCDB) for spatial information systems and prospects of deregulation have dominated many cadastral reform initiatives. As a consequence, various jurisdictions have been either proactive or reactive to these initiatives in their implementation, *inter alia*, of appropriate statutory changes. Discussions on some of the cadastral reform initiatives undertaken by the Australian jurisdictions can be found in the Proceedings of the National Conference on Cadastral Reform 1990 [Jeyanandan and Hunter, 1990]. In the context of wider microeconomic reform initiatives (*vide* Section 2.3), survey legislation is being regularly revised; even when this review was undertaken, some jurisdictions were in the process of either updating or introducing new legislation for reasons already mentioned.

3.3.3 Summary of statutory requirements

A summary of the statutory requirements pertaining to calibration and standardisation of survey equipment, survey methods and accuracy standards is presented in Table 3.2 and Table 3.3. Included in Table 3.2 are additional matters relating to discretionary powers and requirements for the verification of measurements. A full account, i.e. jurisdiction by jurisdiction, of the statutory review is presented in Boey [1996].

Jurisdictions	Calibration and standardisation of survey equipment (see Table 3.4 for full requirements)	Survey methods for boundary determination	Verification of measurements	Powers to give survey practice directions	Discretionary powers to waive certain statutory requirements
Australian Capital Territory	Required	Most direct method. Closed traverse for survey connection.	Required	Surveyors Board	No express provision
New South Wales	Required	Most direct method. Closed traverse for survey connection. Remote sensing methods.	Required	Governor	Surveyor General can waive certain requirements.
Northern Territory	Required	Non-specific	No express provision	Surveyors Board	Surveyor General can waive the requirements of the Directions if there are good and sufficient reasons to do so.
Queensland	Required	Subject to approval, non-traditional methods can be used.	No express provision	Surveyors Board	No express provision
South Australia	No express provision. Equipment must be capable of complying with the prescribed accuracy standards.	Closed traverse. Coordinate-based techniques. Verified radiations.	Required	Surveyor-General	Surveyor-General may grant exemptions from compliance with the regulations of directions.
Tasmania	Required	Non-specific	Required	Surveyors' Board	No express provision
Victoria	Required	Non-specific. Methods other than direct determination of directions and distances must be described in the Surveyors Report.	Required	Surveyors Board	Surveyor-General can waive certain requirements.
Western Australia	Required for steel and invar bands. Surveyor General to approve use of electronic instrument.	Surveyor General can approve survey performed by other methods.	No express provision	Land Surveyors' Licensing Board	Surveyor General has discretionary powers on matters relating to survey equipment, methods and accuracy standards.

Table 3.2. Summary of statutory requirements.

Jurisdictions	Standards of accuracy *				
	Closure		Measurements		
	Angular	Linear	Angular	Length	Position
Australian Capital Territory	$30'' + 20''\sqrt{n}$ or 3'	1:8000 (level) 1:6000 (undulating) 1:4000 (steep) 1:3000 (mountainous)	Nil	1:12000 (level) 1:9000 (undulating) 1:6000 (steep) 1:4500 (mountainous)	Nil
New South Wales	$30'' + 20''\sqrt{n}$ or 3'	15mm + 100ppm (level & undulating) 15mm + 150ppm (steep & mountainous)	Nil	6mm + 30ppm	Nil
Northern Territory	$30'' + 20''\sqrt{n}$ or 3' (rural) & 2' (urban)	$\frac{\sqrt{\Delta E^2 + \Delta N^2}}{x} + 0.01\text{m}$ where: For rural land: x = 5000 (<4° slope) x = 3500 (>4° slope) For non-rural land: x = 10000 (<4° slope) x = 5000 (>4° slope)	Nil	Nil	Nil
Queensland	$2.5\sigma\sqrt{n}$ or 2'	10mm + 1/5000 (for the total distance traversed) 20mm + 1/2500 (for rough and broken terrain) 20mm + 1/2000 (including another surveyor's work) 20mm + 1/1000 (including pre 1890 surveys)	$\sigma < 10''$	10mm + 1/10000	Nil
South Australia	$15'' + 0.02\text{m}^A$ $20'' + 0.02\text{m}^B$ $20'' + 0.03\text{m}^C$ $40'' + 0.10\text{m}^D$	$0.02\text{m} + 1/15000^A$ $0.02\text{m} + 1/10000^B$ $0.03\text{m} + 1/10000^C$ $0.10\text{m} + 1/5000^D$	Nil	Nil	0.02m^A 0.03m^B 0.05m^C 0.15m^D
Tasmania	$25''\sqrt{n}$ or 2.5' (urban) $30''\sqrt{n}$ or 3' (rural)	1:8000 (urban) 1:4000 (rural)	$\sigma < 20''$	$\sigma <$ 10mm or 1:10000 of the distance	0.03m (urban) 0.06m (rural)
Victoria	Nil	15mm + 100ppm (level & undulating) 15mm + 150ppm (steep & mountainous)	Nil	10mm + 60ppm (for both measured and determined)	Nil
Western Australia	1' (city & suburban) 3' (rural)	1:8000 (city & suburban) 1:4000 (rural)	10" (city & suburban) 15" (rural)	Nil	$F\sqrt{(0.04 + S^2)}$ see notations for F & S

Notations:

* The tabulated standards of accuracy are those obtained from the cadastral survey legislation, other supporting legislation (not included in this review), such as the Survey Co-ordination legislation, may also prescribe additional accuracy standards for the appropriate purposes.

n - number of angles

σ - standard deviation

ΔE - misclosure in easting

ΔN - misclosure in northing

^{A} - Adelaide City Core District

^{B} - Commercial and Adelaide City Frame & Residential Districts

^{C} - Urban

^{D} - Rural

F - either 50 or 140 depending on the type of marks compared.

S - the distance between 2 marks.

Table 3.3. Summary of accuracy standards.

3.3.4 Discussion

From the summary of statutory requirements presented in Table 3.2 and Table 3.3, several observations can be made regarding survey legislation in Australia. Common threads running through the overall body of legislation are: discretionary powers to make and waive survey practice directions, calibration and standardisation of survey equipment, survey methods and accuracy standards. There are, however, differences and similarities in the manner in which such details are prescribed.

3.3.4.1 Discretionary powers

Usually, there is an express provision within the legislation that empowers the Surveyors Board, Surveyor General or other responsible authority to give directions relating to the practice of cadastral surveying (an exception is the *Surveyors Act 1929* (NSW) which does not empower either the Board of Surveyors or the Surveyor-General to give survey practice directions). In most instances, the Surveyors General or other responsible authorities are also given discretionary powers, to waive certain statutory requirements, which must be exercised within the ambit of the legislation. Such powers allow greater flexibility in the administration of the legislation by the issuing of survey practice directions. Survey practice directions prepared in this manner are not required to be laid before Parliament, therefore obviating lengthy debate and consequent delay.

Published directions relating to the practice of cadastral surveying are usually in the form of manuals, handbooks and guidelines which complement the statutes (Table 3.1). Generally, the publications are prepared with statutory authority and within the provisions of the legislation; therefore, they do carry legal force. Publications, such the ISO technical publications (*vide* Section 2.3), prepared without the authority of legislation may have some degree of legal significance if they are perceived as the recommended and accepted standard of professional practice. Complementary publications have the following functions:

- to set out the requirements of the legislation in greater detail;
- to clarify any ambiguities that may appear in the legislation; and
- to recommend best practice procedures and guidelines for matters relating to cadastral surveying.

While a means for establishing the legal traceability of GPS measurements is not yet available, a responsible authority can use discretionary powers to waive certain requirements, particularly those relating to equipment calibration, in order to accept cadastral surveys carried out using GPS. In such a situation, the surveyor must convince the responsible authority that all the measurements have been adequately verified using sound survey methods.

3.3.4.2 Calibration and standardisation of survey equipment

Calibration of survey equipment establishes a relationship between the results of measurement and the equivalent standard of measurement, the relationship being known as measurement uncertainty (*vide* Section 2.4.5). Relating physical measurements to standards of measurement through a hierarchy of a continuous chain of calibrations does, in fact, amount to the establishment of traceability for the measurements concerned. Calibration has one main objective, that is to ensure that results of measurement are made in terms of the Australian legal units of measurement, pursuant to s.10 of the National Measurement Act. Calibration ensures that a measuring system:

- can comply with the required accuracy specifications; and
- can retain its calibration during its operating life.

Jurisdictions	Legislation	Requirements
Australian Capital Territory	c.10 of the *Survey Practice Directions 1995* (Gazette No. S42, 13 February 1995).	(1) In making a survey, the surveyor shall ensure that all equipment used in the survey is in accurate adjustment, standardised and properly calibrated. (2) Steel and invar bands and electronic distance measuring equipment must be verified at least once every 12 months and immediately after repairs on a standard base established by or acceptable to the Chief Surveyor. (3) The method of verification must be in a manner approved by the Chief Surveyor, details and results of which are to be supplied to the Chief Surveyor on request.
New South Wales	c.14 of the *Survey Practice Regulation 1990* (as amended 1 October 1994).	(1) A surveyor must make every survey with appropriate equipment. (2) Before using any measuring equipment, a surveyor must know the accuracy obtained by use of the equipment in relation to: (a) the Australian primary standard of measurement of length, within the meaning of the National Measurement Act 1960 of the Commonwealth; or (b) the State primary standard of measurement of length, within the meaning of that Act, that standard being under the control of the Surveyor General. (3) Steel and invar bands must be verified at least once every 2 years and immediately after repair. (4) All electronic distance measuring equipment is to be verified against the State primary standard of measurement, in the form of Pillared Testlines, at least once each year and immediately after service or repair. (5) The accuracy and method of verification must be as approved.
Northern Territory	c.5 of the *Survey Practice Directions 1986.*	A surveyor shall ensure that all distance measuring equipment and theodolites used by him or under his supervision are in correct adjustment before use and that distance measuring equipment has been checked within the previous 12 months against a standard acceptable to the Surveyor-General
Queensland	r.31 of the *Surveyors Regulations 1992* (Reprinted as at 12 October 1994).	(1) This section applies to angular and linear measurement only. (2) A surveyor must calibrate and standardise survey equipment used on a cadastral survey to ensure that the standard deviation – (a) in the case of angular measurement – does not exceed 10 seconds of arc; or (b) in the case of distance measurement – does not exceed 10 mm plus 1 part in 10 000 of the distance. Maximum penalty – 6 penalty units.
South Australia	r.18 of the *Regulations under Survey Act 1992* (1 October 1992)	(1) A surveyor must, in carrying out a cadastral survey - … (b) use equipment and techniques that will enable the required standard of accuracy to be met.
Tasmania	By-law 5 of the *Land Surveyors (Survey Practice) By-laws 1982*	(1) A surveyor shall carry out surveys with such equipment and by such methods as are capable of readily achieving the purpose of the survey and satisfying the requirements prescribed by these by-laws. (2) A surveyor shall apply such checks and tests to his work as to ensure that the requirements prescribed by these by-laws are achieved. (3) To maintain the standards of survey accuracy required by these by-laws, a surveyor shall ensure that all equipment used in carrying out a survey is kept in good order and adjustment and that it is regularly calibrated or standardized in accordance with procedures approved by the Board.
Victoria	r.5 of the *Surveyors (Cadastral Surveys) Regulations 1995*	(1) A licensed surveyor - (a) must use survey equipment which has been compared to a standard of measurement in units of measurement specified in Part A of Schedule 6 to the Survey Co-ordination (Surveys) Regulations 1992; and (b) must ensure that - (i) the process of comparison; and (ii) the basis of comparison – are adequate to obtain the accuracy for a cadastral survey required under these regulations. Penalty: $1000.
Western Australia	r.21 of the *Licensed Surveyors (Guidance of Surveyors) Regulations 1961*	Field measurements shall be made with a steel or invar band, tested at frequent intervals with the surveyor's standard. Tension shall be applied by using a tested spring balance. Provided that with the prior approval of the Surveyor General measurements may be made with an electronic instrument.

Table 3.4. Calibration and standardisation requirements in Australia.

In general, most survey legislation in Australia requires survey equipment to be calibrated and standardised (Table 3.2 and Table 3.4). In addition, the equipment is required to be maintained routinely, *inter alia*, in order to preserve the validity of the calibration. Table 3.4 shows that there is very little uniformity in the manner in which the requirements are prescribed, since they vary from the specific, such as those of New South Wales, to the non-prescriptive, such as those of South Australia. Queensland and Victoria have prescribed penalties for non-compliance. The requirement in Western Australia, in particular, is outdated, since the use of electronic instrument still requires the approval of the Surveyor General.

The legislation in the Australian Capital Territory, New South Wales, Northern Territory, Queensland and Western Australian stipulates the type of equipment, such as steel and invar bands and EDM instruments, that should be calibrated and standardised. Since such legislation prescribes requirements specific to length measuring devices, it inhibits the use of any new technology which is based on a different principle. In South Australia, Tasmania and Victoria, however the legislation, by being technology independent, is non-prescriptive. This approach has the flexibility to accommodate any type of measurement technology, provided that the equipment can be calibrated.

In general, there is no requirement for the measurement of angles to be traceable to a standard of measurement. However, there is a requirement for angular measurements, particularly in a closed traverse (Table 3.3), to be verified. Until the advent of the EDM instruments, measurements of length, compared to angular measurements, have been considered as the more unreliable, due to the limitations of available technology. Plane angles are geometric quantities: angles can be established by appropriate subdivision of a circle. According to Ciddor and Sim [1984, p.137], calibration of reference and working standards of angle depends on *the ability to perform such a subdivisional procedure and not on the possession of, or ability to realize (sic) or relate to, a primary standard.* Hence, it has not been necessary for angular measurements to be traceable to a standard of measurement.

In most jurisdictions, approved calibration and standardisation procedures and facilities are available to the surveyors. Generally, these are specified in complementary publications (Table 3.1). South Australia, being an exception, has adopted a non-prescriptive approach, recommending that surveyors should exercise professional discretion regarding the quality of the survey equipment. According to r.18(1)(b) of the *Regulations under the Survey Act 1992*, the surveyor is responsible for ensuring and proving that the survey equipment used is capable of complying with the required standard of accuracy. However, r.18(2) allows the Surveyor-General to seek evidence of compliance.

In the case of GPS, both Western Australia [Department of Land Administration, 1994] and Victoria [Surveyor-General of Victoria, 1995, p.2] have stated that currently there is no acceptable means for establishing the legal traceability of GPS measurements. Surveyors in Western Australia are advised not to use GPS *as the sole method for measuring distances that would appear on land titles* [Department of Land Administration, 1994].

Some jurisdictions, like the Northern Territory [West, 1996, p.1], Queensland [Higgins, 1996, p.2] and South Australia [Nisbet, 1996, p.1], are accepting cadastral surveys performed with GPS. The extent and manner of the use of GPS in those surveys is, however, unclear. There is always a possibility that the legal validity of measurements made by surveyors could be questioned either in a court of law or by the authority responsible for controlling the practice of cadastral surveying. On such occasions, proof of traceability is most likely to be required (*vide* Section 2.2.3).

3.3.4.3 Survey methods

Survey methods, such as closed traverses, are still prevalent in almost all legislation. South Australia provides for coordinate-based and radiation techniques. In most jurisdictions, the use of *non-traditional* methods, such as GPS, is subject to approval either by the Surveyors General or the responsible authorities.

New South Wales, Queensland, South Australia and Victoria publish manuals and handbooks which set out detailed procedures and methods for surveys performed in various situations. However, none of the publications have guidelines for using GPS. Western Australia has prepared a set of guidelines [Department of Land Administration, 1994] to facilitate surveys performed for the purposes of early preparation of certificates of title. The guidelines address matters relating to the practice of cadastral surveying such as accuracy standards, survey methods, data lodgement standards and survey marking procedures. The survey methods recommended in the guidelines include both GPS and conventional terrestrial survey techniques.

Since May 1996, the Intergovernmental Committee of Surveying and Mapping (ICSM) has published the *Best Practice Guidelines Use of the Global Positioning System (GPS) for Surveying Applications*. These guidelines, similar to those of Western Australia, are issued with the intention of setting out general principles by which GPS results of the appropriate quality can be achieved, but in themselves, however, *do not represent legal traceability of measurement* [ICSM, 1997c, p.1].

Almost all legislation requires survey measurements to be verified. Only Victoria has a specific requirement that measurements must be independently verified (r.10(1)(g) of the *Surveyors (Cadastral Surveys) Regulations 1995*). Surveyors must use their discretion when applying measurement verification methods. In Victoria, such methods must be described in the *Abstract of Field Records* (Sections 7.8.2(b) and 7.8.2(j) of the *Survey Practice Handbook - Victoria Part 2*).

In the case of GPS, particularly real time kinematic GPS, several methods can be used to provide independent verification, two of which are to:

- re-occupy either all or some of the points of interest [Rizos, 1997, p.202]; and
- perform an independent survey using either conventional terrestrial techniques or other GPS techniques.

For cadastral surveying, both of these methods could be considered to be uneconomical. Consequently, reliable and efficient field verification techniques for the detection of errors in a GPS survey during the measurement process must be developed.

The introduction of GPS provides an opportunity for surveyors and regulators to explore new survey methods. Current methods, as evident in the legislation, are inhibiting the use of new technologies unless they can be used in the same manner as the *theodolite-band* combination, i.e. closed loop traverses.

3.3.4.4 Accuracy standards

As shown in Table 3.3, there is very little uniformity in the manner in which accuracy standards are prescribed in the various Australian survey legislation. This is despite the fact that current survey measuring technology and methods can provide similar results, regardless of jurisdictional boundaries. During the mid eighties, several cadastral survey systems, including New South Wales, South Australia and Victoria, underwent major reviews (see Toms *et al.* [1988], Toms *et al.* [1986] and Review Working Party [1985] respectively). As a result of the reviews, some jurisdictions subsequently either amended or introduced new legislation to reflect the recommendations; survey legislation in those jurisdictions has since become less prescriptive.

In most legislation, the *permissible error of traverse closure* (*vide* Section 3.2.2), for both linear and angular components, is prescribed. Accuracy standards for linear closures are prescribed according to two criteria, namely land values and nature of terrain. As shown in Table 3.3, South Australia, Tasmania and Western Australia have adopted accuracy standards based on land values, while the Australian Capital Territory, New South Wales and Victoria used standards based on the nature of terrain. The Northern Territory prescribes accuracy standards based on a combination of the two criteria, whilst Queensland has used a combination of different criteria.

Victoria is the only jurisdiction that does not explicitly prescribe accuracy standards for angular misclosure and angular measurement. It is implied that, in order to satisfy the accuracy standard prescribed for *determined lengths* (Table 3.3), angular measurements used to derive the lengths must be of satisfactory quality.

Apart from the Northern Territory and South Australia, accuracy standards for measurements of length and angle are prescribed generally. The methods of determination usually rely either on calibration or standardisation of survey equipment or methods that must be approved by the responsible authority.

South Australia, Tasmania and Western Australia have prescribed positional accuracy standards.

In order to determine whether the accuracy standards prescribed in the existing legislation are able to accommodate the use of GPS, a comparison between the statutory accuracy standards, particularly those for the measurement of length, and a typical GPS manufacturer's accuracy specification for a real time kinematic system has been performed (Figure 3.3). The GPS manufacturer's accuracy specification is 10 mm + 2 ppm at the 67% confidence interval [Trimble Navigation Limited, 1994; Leica, 1996b; and Allen Osborne Associates, 1998]. The existing accuracy standards for the measurement of length, which are specified at the 95% confidence interval, are those shown in Table 3.3. These range from the least stringent, that prescribed by the South Australian legislation for the linear closure in a rural survey, to the most stringent, that prescribed by the Australian Capital Territory legislation for the measurement of length on level terrain. As shown in Figure 3.3, GPS baseline lengths must be at least 120 m to comply with the majority of the existing accuracy standards.

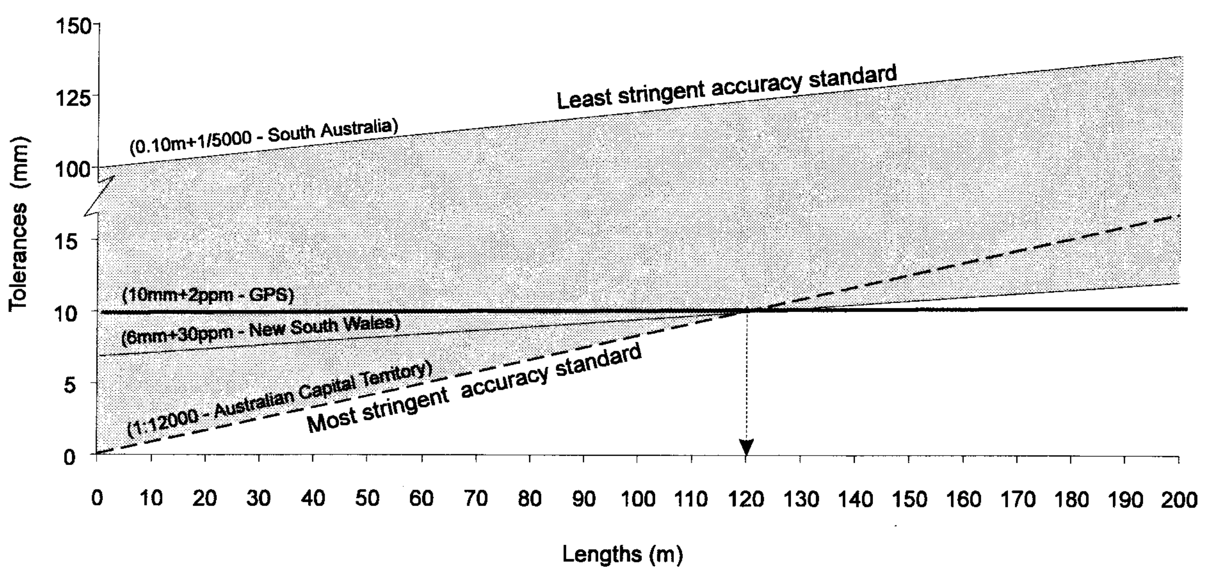


Figure 3.3. The relationship between existing accuracy standards (enclosed in the shaded area) and the accuracy of GPS baseline lengths.

Boey *et al.* [1996a, p.114], in an attempt to assess the accuracy of real time kinematic GPS positions for the purposes of cadastral surveying, found that the relative accuracy standards specified in the Victorian legislation were difficult to comply with, particularly for short lengths. The authors [*ibid.*, 1996a, p.119] contend that the reason was due to the radial nature of GPS survey techniques. In addition, for that particular investigation, positional tolerances were recommended for assessing the accuracy of GPS surveys [*ibid.*, 1996a, p.119].

The problems associated with the inability of short lengths to comply with prescribed accuracy standards are well documented in Toft [1967, p.120], Berthon Jones [1971, p.420], Angus-Leppan [1973, p.44], Ghilani [1994, p.163] and Williamson [1983, pp.212-213]. The Australian Capital Territory survey legislation has included a provision which states that short lines, which cannot comply with the prescribed accuracy standards, must be measured with the *best possible standard* (Direction 43(2) of the *Survey Practice Directions* 1995).

Boey *et al.* [1996a] state that the mathematical basis of most modern measuring technology and survey techniques is fundamentally different from that of conventional surveying. The appropriate accuracy standards for measuring technology, such as GPS, can only be recommended following proper investigation and analysis of the technology and the associated survey techniques. Most importantly, however, the recommendations must be practical and based on community expectations.

3.4 Summary

This chapter has presented a two part discussion. The first part is an overview of the history which has shaped the cadastral survey system, particularly the circumstances which have led to the requirement for survey laws, whose main functions are to control the quality of surveyors and surveys in order to preserve the integrity of the cadastral system. However, the goal of the laws is to minimise the financial risk to the public. Part of the risk management scheme is the requirement for survey measurements to be traceable to national standards.

The second part is a review of the current survey legislation, particularly the statutory requirements for ensuring the legal traceability of measurements. It is a contention of this thesis that to achieve the legal traceability of measurements, the whole *measurement process*, which includes the surveyor, the instrument and the procedures, must be considered. These elements, which are evident in the current survey legislation, formed the criteria for the review.

The legislation review revealed that there are common themes in the various States and Territories survey legislation. However, the manner in which the requirements are prescribed, particularly those related to calibration and standardisation of survey equipment and accuracy standards, varies between jurisdictions. Observations made in this regard may be summarised as follows:

- Generally, survey equipment used for a cadastral survey is required to be calibrated and standardised in order to establish the legal traceability of measurements. Western Australia and Victoria have advised surveyors that, currently, there is no acceptable means for establishing the legal traceability of GPS measurements.
- In most jurisdictions, detailed survey methods are usually outlined in complementary publications, such as manuals and handbooks. The use of non-traditional methods, such as GPS, is subject to approval either by the Surveyors General or the responsible authorities.
- Almost all survey legislation requires survey measurements to be verified. Current verification methods for GPS surveys could be considered as uneconomical.
- In most survey legislation, accuracy standards are prescribed in the form of relative tolerances in favour of traverse-based surveys and direct measurements (angles and lengths). In addition, some of the existing accuracy standards for cadastral surveys may be too stringent for GPS baseline lengths to comply with. Only South Australia, Tasmania and Western Australia have prescribed positional accuracy standards.

Currently, there are statutory requirements which would preclude the use of satellite-based technology, such as GPS, in a cadastral survey. In particular, these requirements relate to the need to:

- calibrate and standardise survey equipment;
- verify survey measurements; and
- comply with accuracy standards that may be inappropriate.

The first requirement is the focus of the research in this thesis while the second and third requirements could possibly form the basis for future research. Undoubtedly, acceptable means for establishing the legal traceability of measurements, appropriate survey methods, particularly reliable and efficient field verification procedures, and suitable accuracy standards must be developed in order to ensure that surveys performed with modern measuring technology are of acceptable quality.

4. THE GPS MEASURING SYSTEM FOR CADASTRAL SURVEYING

> *It will be incumbent upon civil GPS users to match the known capabilities and limitations of the global positioning system with the degree of risk associated with the activity they are undertaking.*
>
> Spradling [1990, p.51]

4.1 Introduction

The application of GPS technology to cadastral surveying is well documented (see for example, Gerdan and Talbot [1990], Gerdan [1991], Duffy [1991], Sumpter and Asher [1994] and Boey *et al.* [1996a]). Undoubtedly, GPS can be applied to cadastral surveying; however, as mentioned in Chapter 3, there are statutory requirements which must be considered before the technology can be legally used for this purpose. The main requirement pertains to the need for measurements to be legally traceable to national standards of measurement.

This chapter presents a brief review of the characteristics of GPS. Detailed treatment on the subject can be found in Seeber [1993], Leick [1995], Kleusberg and Teunissen [1996], Parkinson and Spilker (eds) [1996], Hofmann-Wellenhof *et al.* [1997] and Rizos [1997].

Cadastral surveys require accurate and precise measurements at the centimetre level (*vide* Section 3.3.3), which, in the context of GPS, can be satisfied only through the use of *relative positioning* techniques using the *carrier phase observable*. Hence, both concepts are discussed in this chapter. In order to appreciate the measurement uncertainties associated with the *relative positioning* techniques, an overview of the factors affecting the accuracy of GPS measurements is presented. Chapter 5 describes some of the current methods for verifying the GPS measuring system, i.e. for determining the measurement uncertainties in a GPS survey.

4.2 Modern measuring technology

Position-based measuring technology, such as GPS, is being introduced progressively into general surveying practice. This latest technology provides surveyors with accurate and reliable measurements, as well as, arguably, increased efficiency, productivity and versatility.

Technological growth will continue, particularly in satellite-based positioning technology. This has been confirmed recently by a government policy announcement by the President of the United States, affirming, *inter alia*, that there will be no direct user fees and that Selective Availability, i.e. intentional degrading of GPS signals, will be removed by the year 2006 [The

White House, 1996, p.2]. Hence, the cost of GPS equipment has been predicted to decrease significantly because of the removal of *an appreciable element of uncertainty* within the GPS industry which *will ultimately reduce risk, clarify prospects, and help chart a course for future investment in GPS applications* [GPS World Newsletter, 1996, p.6].

Further advancement in GPS is the planned deployment of the next generation of satellites which will have two additional signals accessible to civilian users [The White House, 1999]. Hatch [1996, p.58] claims that the addition of a third frequency would provide the following benefits to GPS positioning: *a new precision in measurements for orbital and satellite clock solutions, a new precision with which the ionospheric refraction can be measured, and a capability for high-precision kinematic navigation over much longer baselines than are currently possible.*

Position-based measuring technology and techniques will become more prevalent as they gain wider acceptance. This will happen when such equipment becomes more affordable and comparable with that of conventional terrestrial survey equipment. Apart from costs, other factors which will influence the use of position-based technology, such as GPS, in cadastral surveying include:

- the realisation of survey co-ordination aims, such as increased demand for cadastral surveys to be connected to the main survey control network;
- the continual demand for survey-accurate digital cadastral databases (DCDB), as users become more aware of the limitations of the existing graphical databases, due to their poor spatial accuracy [Grant *et al.*, 1992, p.211; and Priebbenow and Forrest, 1995, p.6];
- the progressive reduction of government's role in the provision, maintenance and upgrading of the infrastructure which supports survey co-ordination efforts, consequent on its phased transfer to the private sector (*vide* Section 2.3);
- the adoption of a geocentric datum by the year 2000 [Commonwealth of Australia, 1998, p.1];
- installation of more permanent GPS reference stations throughout regional centres, such as the concept of *GPSnet* in Victoria [Takac and Hale, 1996];
- development of long baseline real time kinematic GPS;
- integration of GPS and conventional terrestrial total stations [Hill, 1995; and Talbot and Nichols, 1995];
- the amendment of legislation to include the use of GPS for cadastral surveying; and
- the ability to establish legal traceability for GPS measurements.

Surveyors practising in jurisdictions which administer large mining, pastoral or marine leases are already using position-based technologies, such as GPS and photogrammetry (*vide*

Section 3.3.4.2). It is inevitable that position-based measuring technology and techniques will be used increasingly in the conduct of cadastral surveys.

4.3 Fundamental differences between GPS measurement technology and conventional terrestrial survey technologies

This thesis adopts the electronic distance measurement (EDM) instrument as a typical example of conventional terrestrial survey technology, because of its widespread, indeed general use in cadastral surveying.

Essentially, the EDM and GPS adopt the same measurement principle, that is, both measure the arrival time of signals in order to determine the range between the sensor and the reflector, in the case of the EDM, and the transmitter, in the case of GPS. However, there are many fundamental differences between the two measuring systems. One of the main differences is the *definition of scale*: for the EDM, scale is defined by the quartz crystal oscillator which is located within the instrument, while in GPS, scale is realised through the adoption of two constants, namely the speed of light in vacuum (c) and the earth's gravitational constant (GM). The speed of light is used to relate *phase measurements* to wavelengths, hence the range (*vide* Section 4.6). The gravitational constant is used to determine the principal parameters of satellite orbits.

GPS, which comprises the *control*, *space* and *user segments* (*vide* Section 4.4), differs from conventional survey equipment and techniques in that it does not measure angles and lengths between ground marks. Instead, it determines vectors in three dimensional coordinate space between ground marks in a geocentric reference system known as the World Geodetic System 1984 (WGS84) [Defense Mapping Agency, 1991].

Another major difference between the EDM and GPS is the GPS user's *inability* to control the quality of the navigation message and radio signals received at the sensor, which are elements essential for position determination. The user depends on the GPS space and control segments to provide the navigation message and signals at the appropriate operational tolerances. The integrity of the navigation message and signals is dependent on an autonomous external source, namely the United States. Section 4.8.1 provides a detailed description of the several anomalies, originating in the space and control segments, which can compromise the integrity of GPS.

The calibration of an EDM instrument is used to ascertain the measurement uncertainties associated with that instrument; however, such an operation is not applicable to GPS. An EDM instrument can be calibrated periodically because a well-maintained oscillator can be assumed to behave in a linear manner during interim periods. The same cannot be assumed for GPS because the precision and accuracy of GPS measurements depends on many variables, some of which are the:

- proper operation of the control, space and user segments;
- geometrical strength of the satellites configuration;
- length of the observation periods; and
- temporal, spatial and geographical nature of GPS baseline biases and errors.

So as to account for the aforementioned factors, *GPS measurements need to be verified during the actual survey.*

4.4 Overview of GPS

The complete Global Positioning System comprises three segments, namely the control, space and user segments, which are interdependent and must be treated as comprising an integral measuring system. The final results obtained in a GPS survey are dependent on the proper operation and treatment of the respective segments. The information flow and function of each segment is described in Figure 4.1.

GPS Segment	Input	Function	Product
Control	Pseudorandom RF signal Telemetry Time (UTC)	Calibrate time scale, predict ephemeris Manage space assets	Navigation message Commands
Space	Navigation message Commands	Provide atomic time scale Generate and transmit pseudorange signals Store and forward navigation messages	Pseudorandom RF signal Navigation message Telemetry
User	Pseudorandom RF signal Navigation message	Solve navigation equations Relative positioning	Position Velocity Time

Figure 4.1. System information flow compiled from Leick [1995, p.60] and Francisco [1996, p.447].

The control segment comprises a manned Master Control Station and four other automated globally distributed ground monitor stations. The main function of the control segment is to generate precise navigation messages [Russell and Schaibly, 1980, p.74]. The tasks of the control segment are to:

- command and control GPS satellites;
- determine *GPS Time* (*vide* Section 6.4.1);
- track and predict the satellite ephemerides and clock behaviour; and
- upload the navigation message to the satellites.

The navigation message contains information about the ephemerides of the satellites, clock behaviour, satellite health status, ionospheric correction terms and an almanac. An additional role of the control segment, and one not readily apparent, is the maintenance of the WGS84 reference system [Rizos, 1997, p.66]. The integrity-monitoring role of the control segment is discussed in Section 4.8.1.

The space segment comprises GPS satellites which provide the means for generating and transmitting radio signals. The satellites carry several atomic frequency standards, namely caesium and rubidium standards, upon which the accuracy of the system is dependent, since they generate the fundamental L-band frequency of 10.23 MHz. The broadcast signal comprises two carrier waves with frequencies in the microwave band; L1 (10.23x154=1575.42MHz) and L2 (10.23x120=1227.60MHz) [Anon., 1995b, p.10]. The carrier waves are modulated by two types of pseudorandom codes and a navigation message. The L1 carrier is modulated by the P (Precise) and C/A (Coarse Acquisition) codes, while the L2 carrier is modulated by the P code.

Most GPS textbooks, for example, Seeber [1993, p.229] and Hofmann-Wellenhof *et al.* [1997, p.22], describe the user segment as consisting of GPS receivers. In the context of surveying in Australia, Eckels [1987, p.15] and Rizos [1997, p.67] describe the user segment as comprising:

- hardware;
- observation procedures; and
- software, which includes processing methods for data reduction, network adjustments and transformations.

In the context of cadastral surveying (*vide* the requirements described in Chapter 3), the user segment includes:

- the surveyor, i.e. the person carrying out the measurement;
- survey equipment, including, *inter alia*, receivers, antennas, cables and tribrachs;
- survey observation techniques and procedures;
- data processing software and methods; and
- verification mechanisms (*vide* Chapter 5).

Essential components of the *procedures* are quality assurance requirements, which can be in the form of legislation, documentary standards or guidelines. The aforementioned elements, together with the control and space segments, constitute a measuring system which is required to attain results commensurate with the standards of accuracy stipulated in survey legislation (*vide* Section 3.3.3). In this regard, Eckels [1987, p.15] opines that the object of the user segment is *to achieve surveying accuracies from GPS by reducing the magnitude of the error sources that affect the system.*

4.5 GPS observables

There are two types of GPS observables: the *pseudorange* and the *carrier phase*. The basis of the pseudorange determination is the time interval taken to match the received codes (C/A and P) with their replicas generated within the receiver. This time interval scaled by the speed of light gives a measure of the *pseudorange*. The carrier phase observable is a measure of the difference between the phase of the received signal and the phase of the receiver oscillator at the epoch of measurement. The phase difference can be measured very precisely; however, the number of whole cycles between the satellite and the antenna is indeterminate. The number of whole cycles, albeit unknown, is an integer value termed *cycle ambiguity*.

In surveying, the carrier phase observable is used to achieve results at the centimetre level. The carrier waves, L1 and L2, have the shortest wavelengths of all the observables, being 19 cm and 24 cm respectively. As a *rule of thumb*, a high precision survey grade receiver should be able to resolve the phase difference to within 1%, which translates to approximately 2 mm for the L1 and L2 carriers. This value is very conservative because the performance of modern receivers exceeds the *rule of thumb* by approximately an order of magnitude (*vide* Section 4.8.10).

4.6 Measurement model

In this section, the mathematical models for GPS measurements are not derived from first principles since the task is covered adequately in Remondi [1984, pp.68-85], Goad [1985], King *et al.* [1985, pp.55-59], Grant [1990, pp.77-80] and Talbot [1991, pp.26-36]. The measurement model presented in this section represents a degraded model, i.e. it comprises all the factors which affect the accuracy of the measurement (*vide* Section 4.8). This section describes the basic processes for deriving meaningful quantities, such as *relative positions* and *vectors*, from GPS (Figure 4.2).

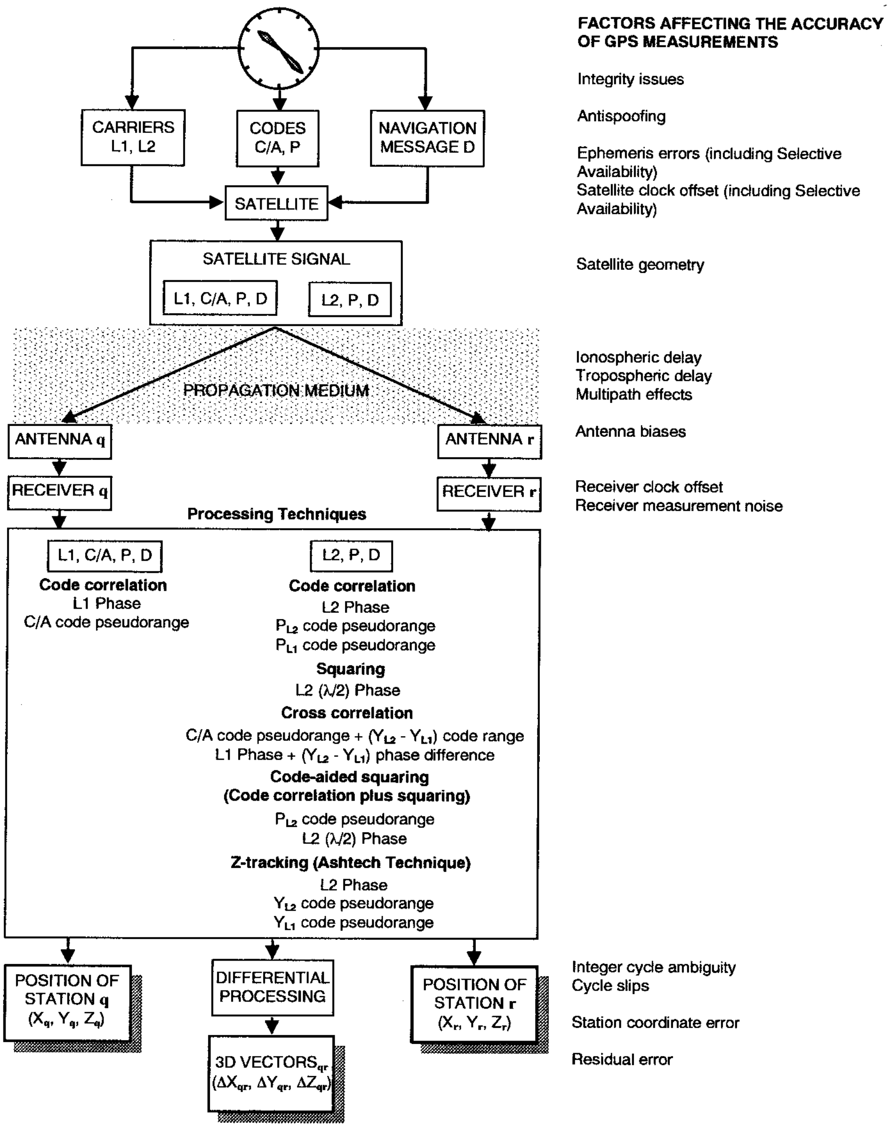


Figure 4.2. GPS measurement model compiled from Hofmann-Wellenhof *et al.* [1997]. For information regarding processing techniques, readers can refer to *ibid.* [1997, pp.83-87] and Leick [1995, pp.89-92].

The carrier phase observable comprises a fractional phase measurement and an accumulated cycle count based upon the integration of the Doppler frequency shift present on the carrier frequencies. The fractional phase measurement refers to the difference between the phase of the received satellite carrier and that generated by the internal receiver oscillator. Due to the fact that the measurement process cannot account for the whole number of carrier wavelengths between the antenna and the satellite, an accumulated cycle count based upon the Doppler frequency shift is measured. The measurements are made at equally spaced nominal receiver clock epochs.

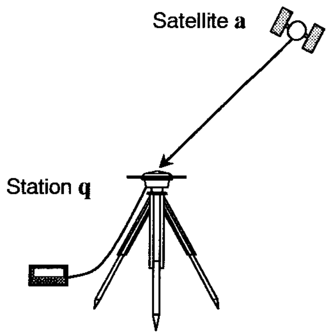


Figure 4.3. GPS positioning using the carrier phase observable.

One of the ways of expressing the carrier phase measurement model, in units of cycles, from receiver **q** to satellite **a** (Figure 4.3) is given as [Wells *et al.*, 1986, p.8.3]:

$$\phi_q^a = \frac{f}{c}\rho_q^a + f(dt^a - dT_q) + N_q^a + {}_{eph}d^a - {}_{ion}d_q^a + {}_{trop}d_q^a + mp_q^a + ant_q^a + \varepsilon_q^a \qquad (4.1)$$

Also, the carrier phase measurement model can be expressed in units of length as:

$$\Phi_q^a = \rho_q^a + c(dt^a - dT_q) + \lambda\left[N_q^a + {}_{eph}d^a - {}_{ion}d_q^a + {}_{trop}d_q^a + mp_q^a + ant_q^a + \varepsilon_q^a\right] \qquad (4.2)$$

where,

ρ_q^a	geometric range between satellite antenna **a** and antenna phase centre at **q**
f	nominal frequencies of the L1 and L2 carrier waves
c	speed of light in a vacuum defined as 2.99792458x10^8 m/s [Anon., 1995b, p.73]
dt^a	satellite clock offset from GPS Time (including the effects of Selective Availability)
dT_q	receiver clock offset from GPS Time
${}_{eph}d^a$	satellite ephemeris error (including the effects of Selective Availability)
λ	carrier wavelength $\left(= \frac{c}{f}\right)$
N_q^a	integer carrier phase ambiguity
${}_{ion}d_q^a$	ionospheric phase delay
${}_{trop}d_q^a$	tropospheric delay
mp_q^a	effects of multipath
ant_q^a	antenna bias, such as antenna phase centre offset and variation
ε_q^a	residual

The Cartesian coordinates of the satellite and station, being the sought-after quantities, are contained in the geometric range, ρ_q^a, expressed as:

$$\rho_q^a = \sqrt{(X_q - X^a)^2 + (Y_q - Y^a)^2 + (Z_q - Z^a)^2} \tag{4.3}$$

where,

X_q, Y_q, Z_q are the Cartesian coordinates of station $\mathbf{q}$, and

X^a, Y^a, Z^a are the Cartesian coordinates of satellite $\mathbf{a}$.

Both the satellite and station coordinates are expressed in terms of the WGS84 datum, which is earth-centred-earth-fixed. The unit of measurement for the geocentric Cartesian coordinates is the metre. Using these geocentric Cartesian coordinates, other quantities such as ellipsoidal coordinates (φ,λ,h) and plane coordinates (E,N,H) can be derived.

4.7 Relative positioning

In relative positioning, many of the factors affecting the accuracy of GPS solutions (*vide* Section 4.8) can be either eliminated or reduced by linear combination of simultaneous measurement equations in a process called *differencing* [Remondi, 1984, pp.86-89]. This approach is based on the premise that some of the factors are common, while others are correlated spatially. Differences may be formed *between receivers*, *between satellites*, *between epochs*, or combination of any of the aforementioned. The most frequently used baseline solutions are known as *single difference*, *double difference* and *triple difference*. The double difference solution is used in almost all processing algorithms to yield final relative positions for points of interest.

4.7.1 Single difference (between-receiver)

A *between-receiver single difference* can be formed by differencing carrier phase measurements from one satellite as measured simultaneously by two receivers (Figure 4.4).

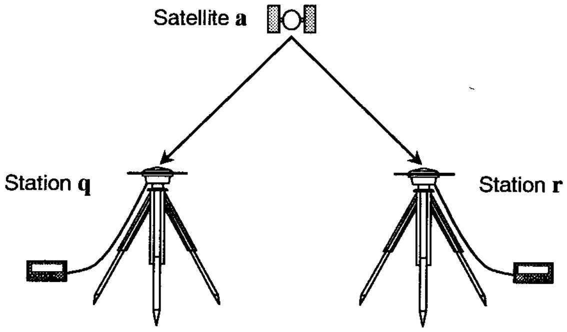


Figure 4.4. Single difference combination between receivers **q** and **r**.

The carrier phase measurement from receiver **q** to satellite **a** is given in equation (4.2). The carrier phase measurement from receiver **r** to satellite **a** is:

$$\Phi_r^a = \rho_r^a + c(dt^a - dT_r) + \lambda\left[N_r^a + {}_{eph}d^a - {}_{ion}d_r^a + {}_{trop}d_r^a + mp_r^a + ant_r^a + \varepsilon_r^a\right] \qquad (4.4)$$

Forming a single difference between receivers **q** and **r** to satellite **a** gives:

$$\Delta\Phi_{qr}^a = \Phi_r^a - \Phi_q^a$$

$$\Delta\Phi_{qr}^a = (\rho_r^a - \rho_q^a) + c(dT_q - dT_r) + \lambda\left[(N_r^a - N_q^a) + ({}_{ion}d_q^a - {}_{ion}d_r^a) + ({}_{trop}d_r^a - {}_{trop}d_q^a)\right.$$

$$\left. + (mp_r^a - mp_q^a) + (ant_r^a - ant_q^a) + (\varepsilon_r^a - \varepsilon_q^a)\right] \qquad (4.5)$$

The operator Δ denotes a between-receiver difference.

Since the two receivers are tracking the same satellite simultaneously, the result of the single difference solution is the elimination of satellite ephemeris errors (${}_{eph}d$) and satellite clock offset (dt).

Similarly, a between-satellite single difference can be formed by differencing carrier phase measurements from two satellites as measured simultaneously by one receiver.

4.7.2 Double difference (between-receiver and between-satellite)

A *double difference* can be formed by differencing two *between-receiver single differences* between two satellites (Figure 4.5). Double differencing is known also as between-receiver and between-satellite differencing.

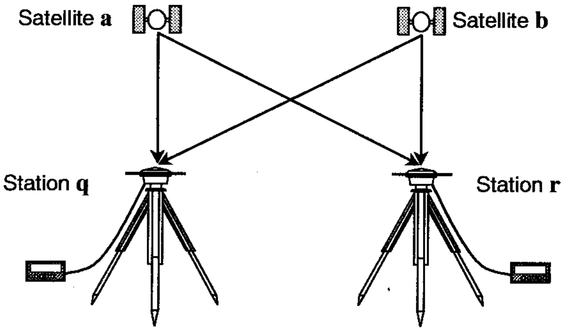


Figure 4.5. Double difference combination between receivers **q** and **r** and between satellites **a** and **b**.

The single difference solution between receivers **q** and **r** to satellite **a** is given in equation (4.5). The single difference solution between receivers **q** and **r** to satellite **b** is:

$$\Delta\Phi_{qr}^b = (\rho_r^b - \rho_q^b) + c(dT_q - dT_r) + \lambda\left[(N_r^b - N_q^b) + ({}_{ion}d_q^b - {}_{ion}d_r^b) + ({}_{trop}d_r^b - {}_{trop}d_q^b)\right.$$

$$+(mp_r^b - mp_q^b) + (ant_r^b - ant_q^b) + (\varepsilon_r^b - \varepsilon_q^b)\Big] \tag{4.6}$$

Double differencing between satellites **a** and **b** gives:

$$\nabla\Delta\Phi_{qr}^{ab} = \Delta\Phi_{qr}^{b} - \Delta\Phi_{qr}^{a}$$

$$\begin{aligned}\nabla\Delta\Phi_{qr}^{ab} = {} & (\rho_r^b - \rho_q^b - \rho_r^a + \rho_q^a) + \lambda\Big[(N_r^b - N_q^b - N_r^a + N_q^a) + ({}_{ion}d_q^b - {}_{ion}d_r^b - {}_{ion}d_q^a + {}_{ion}d_r^a) \\ & + ({}_{trop}d_r^b - {}_{trop}d_q^b - {}_{trop}d_r^a + {}_{trop}d_q^a) + (mp_r^b - mp_q^b - mp_r^a + mp_q^a) + (ant_r^b - ant_q^b - ant_r^a + ant_q^a) \\ & + (\varepsilon_r^b - \varepsilon_q^b - \varepsilon_r^a + \varepsilon_q^a)\Big]\end{aligned} \tag{4.7}$$

The operator ∇ denotes a between-satellite difference.

Equation (4.7) can be re-written as:

$$\nabla\Delta\Phi_{qr}^{ab} = \nabla\Delta\rho_{qr}^{ab} + \lambda\Big[\nabla\Delta N_{qr}^{ab} - \nabla\Delta_{ion}d_{qr}^{ab} + \nabla\Delta_{trop}d_{qr}^{ab} + \nabla\Delta mp_{qr}^{ab} + \nabla\Delta ant_{qr}^{ab} + \nabla\Delta\varepsilon_{qr}^{ab}\Big] \tag{4.8}$$

The following terms are eliminated or significantly reduced in a double difference solution: satellite clock offset (dt), receiver clock offset (dT) and satellite ephemeris errors (${}_{eph}d$). Terms such as integer carrier phase ambiguity (N), ionospheric phase delay (${}_{ion}d$), tropospheric delay (${}_{trop}d$), effects of multipath (mp), antenna related biases (ant) and residual (ε) remain in the solution. Most of these terms can be accounted for by using either mathematical models or empirical means. Some examples of empirical means (*vide* Section 4.8) are *zero baseline test* for the determination of measurement noise and meteorological observations for the determination of tropospheric delay. Section 4.8 describes the characteristics and effects of the aforementioned factors and the manner in which they should be considered and managed.

The term $\nabla\Delta\rho_{qr}^{ab}$ contains the Cartesian coordinates of stations **q** and **r** and satellites **a** and **b** (*vide* equation (4.3)). The Cartesian coordinates of satellites **a** and **b** can be determined using either the broadcast or precise ephemerides. Commonly, the coordinates of **q**, which are either known from a previous survey or estimated using the pseudorange point positioning, are held fixed during the processing phase. The sought-after quantities, being the Cartesian coordinates of **r**, are determined from the double difference solution by an iterative process explained in Remondi [1984]. It is important to note that the coordinates of station **r** *relative* to station **q** are the end product of the measurement process. These relative coordinates can be expressed also as differential three dimensional components (ΔX_{qr}, ΔY_{qr}, ΔZ_{qr}).

4.8 Factors affecting the accuracy of GPS measurements

The least initial deviation from the truth is multiplied later a thousandfold

Aristotle, On the Heavens, Bk 1, Ch. 5 [384-322 BC]

Figure 4.2 and equations (4.1) and (4.2) describe a measurement model incorporating several factors with the potential to degrade the accuracy of the model; some can be manifest even before the signal is transmitted from the satellite. As the signal travels to the antenna, it is subject to the effects of the atmosphere and localised site characteristics. Upon arrival, the signal, which is by now quite weak and noisy, is detected by the antenna and decoded by the receiver. Antennas and receivers, being manufactured items, are imperfect instruments. Generally, many of the factors which affect GPS measurements can be either eliminated or significantly reduced in relative positioning. Most of them are temporal, spatial and geographical in nature.

The following sections provide a review both of the nature of the factors which degrade the accuracy of the measurements, including estimates of the magnitude of resulting error, and of the methods for eliminating or reducing the consequential effects. An understanding of the characteristics of the factors (which are essentially risk factors) should lead to their appropriate management. Such an understanding is also necessary for the proper design of verification methods and/or risk management schemes.

4.8.1 Integrity anomalies in the GPS control and space segments

Integrity is a measure of the trust that can be placed in a system to provide the correct information. The correctness of information is dependent on the application, since each has specific accuracy requirements. In the context of navigation, the Federal Radionavigation Plan [1994, p.C-4] defines integrity as *the ability of a system to provide timely warnings to users when the system should not be used for navigation.* In the context of GPS surveying, an *integrity monitoring system* refers to those methods or techniques which can be used to monitor GPS so as to ensure that it is providing the correct information. Further, the monitoring system should be able to warn users when there is an integrity lapse. The essential elements of GPS to be monitored are those that affect GPS solutions directly, namely the navigation message and signals transmitted from the satellites. Both elements depend critically on the proper operation of the GPS control and space segments.

As mentioned in Section 4.3, a major difference between GPS measurement technology and conventional terrestrial survey technologies is the user's *inability* to control the quality of the signals and navigation message received. The user depends on the GPS Operational Control Segment (OCS) and the satellites to provide the navigation message and signals at the appropriate operational tolerances, which may or may not meet user requirements. The OCS includes the manned Master Control Station (MCS) facility located at Falcon Air Force Base, Colorado and four other automated globally distributed ground monitor stations. The MCS is responsible for monitoring and ensuring the integrity of GPS. Shank and Lavrakas [1993], Francisco [1996] and Crum and Smetek [1997] provide excellent descriptions of the MCS and its operations.

The mission of the MCS is *to maximize accuracy, reliability, integrity, and continuity to the worldwide user community. A significant part of this mission involves detection, prevention, and resolution of a host of satellite vehicle anomalies* [Crum and Smetek, 1997, p.133]. This mission is often difficult to fulfil. The literature cited provides valuable insights into some of the problems faced by the MCS in its endeavour to ensure the integrity of GPS. The MCS is not infallible; problems caused by hardware, software and human errors do occur and are often *invisible to normal performance monitoring statistics* [Shank and Lavrakas, 1993, p.469]. Usually, the effects of the problems are manifested in the form of unpredictable range errors beyond the operational tolerance.

In addition, according to Shank and Lavrakas [1993, p.466] and Francisco [1996, p.440], the current network of five monitor stations is inadequate to provide 24 hour coverage for all satellites. Figure 4.6 illustrates the track coverage provided by the monitor stations for satellites that are above 5° elevation angle at the antenna. The non-greyed areas represent signal monitoring gaps. The following example from Shank and Lavrakas [1993, p.466] illustrates one of the problems encountered at the MCS: *... PRN3/SVN11 had three anomalies within one week of each other resulting in ranging errors up to 2000-4700 meters for roughly 45 minutes before the analyst saw the problem due to lack of monitor station coverage.* The United States Department of Defense recognises that, currently, the coverage gaps *limit the OCS's ability to detect and mitigate anomalies* [Malys *et al.*, 1997, p.380]. However, there are plans afoot to increase the number of ground monitoring stations in order to improve the integrity of the Global Positioning System [*ibid.*, 1997].

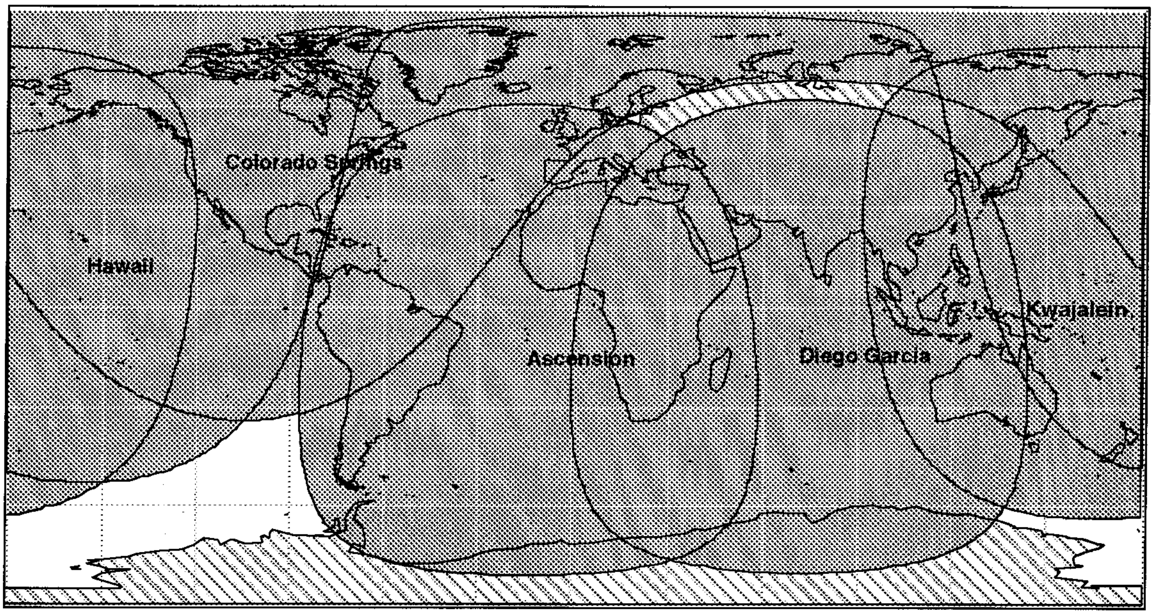


Figure 4.6. GPS monitor station coverage [Courtesy of Enge, P. 1998, March 10].

A degraded signal can be caused by either *integrity anomalies* or routine maintenance activities undertaken by the MCS. Usually, the former are *not* predictable, while the latter are announced to the users through the appropriate notices. An integrity anomaly includes *a degraded signal being transmitted without appropriate user notification through the navigation message and cases when the navigation message itself is at fault* [Shank and Lavrakas, 1993, p.466]. In most instances, users without the appropriate detection measures would be unaware of the occurrence of integrity anomalies because the satellite health message in the navigation data would indicate that the satellite was performing according to operational tolerances. As a possible consequence, the GPS solution accuracy could be seriously degraded. Examples of integrity anomalies occurring at the MCS and satellites include:

- *satellite clock or ephemeris range errors above an operational threshold not due to satellite maintenance,*
- *errors in the MCS-generated navigation upload, and*
- *errors in the MCS Kalman filter's estimation...*[*ibid.*, 1993, p.466].

There are two types of satellite anomalies, namely:

- Anomalies that are immediately apparent, such as a complete failure of a navigation payload component and the malfunction of the Navigation Data Unit (NDU), which is the main processor on board the satellite. In such situations, the L-band signal will be completely removed from use.
- Anomalies that are *not* immediately apparent, such as those caused by aging hardware components, temperature variations, clock jumps, *outgassing* of newly launched

satellites, *rare* satellite platform instabilities and seasonal variations in the satellite's orbit. Usually, these problems do not effect an immediate removal of the L-band signal from use because they are identified only after several occurrences. The main consequences of this type of anomaly are serious ranging and phase errors [Crum and Smetek, 1997, p.144].

For more details, and real examples regarding satellite anomalies, readers are referred to *ibid.* [1997]; explanation of the technical details associated with the causes of the anomalies is beyond the scope of this thesis.

Most of the problems occurring at the MCS are caused by hardware, software and human errors [Shank and Lavrakas, 1993, p.470]. Hardware problems include those associated with *communication lines*, *remote sites requiring maintenance*, and *MCS computers and consoles*. The unavailability of remote sites, namely ground antennas and monitor stations, due to maintenance, is of particular concern, because the MCS has no ability to monitor the integrity of the signal for any satellite that is not visible at other stations. In addition, the MCS loses the ability to validate the existence of any anomalies that may occur during this period. According to Francisco [1996, p.440], *regions of tracking coverage overlap (simultaneous L-band contact with the same SV by two monitor stations) are very important in establishing a robust GPS estimation process* (see Figure 4.6 for monitor station tracking coverage). *Observed residuals in pseudorange measurements must be allocated to probable errors in time and in SV position by the action of the Kalman filter estimator. Solutions for the states of an isolated satellite and of the monitor stations is quite fragile because of the extensive linear relationships that prevail in pseudorange-based measurement systems and to the effects of accumulated model uncertainty (process noise) when marginal measurement geometry exists to distinguish the error source. Common view strengthens any solution by enabling direct time transfer between MS sites.*

As alluded to in the preceding paragraph, many elements, including the errors, within GPS are critically dependent on each other, particularly the *MCS Kalman filter*, a suite of programs which is the central source of all GPS navigation data. Based on pseudorange measurements between satellites and monitor stations, the Kalman filter determines the orbital (position, velocity and acceleration due to solar radiation pressure) and clock (bias, drift and drift rate) state estimates and predictions that define the navigation data. Brown [1991a] provides an excellent treatise on the MCS Kalman filter and some of its modelling errors. *Mismodelling* occurs when the Kalman filter wrongly apportions error to the various states. *Mismodelling may be insidious because until a problem manifests itself through other symptoms, the operator will be unaware that something is wrong unless a rigorous check of all system displays is being performed each day. Each problem can, however, be traced* *back to some discrete starting point, such as a satellite eclipse, clock instability, a vehicle bus problem, or an MCS database change* [Crum and Smetek, 1997, p.140].

Problems associated with monitor station clocks are not uncommon [Shank and Lavrakas, 1993, p.466]. Typically, monitor station clock instabilities occur following primary to back-up frequency switch, which is a routinely performed activity. The problem causes the MCS Kalman filter to stray from GPS Time. As a result, ranging errors tend to grow steadily over a period of time. The problem is exacerbated because it is not easily detectable by normal performance measures (*vide* comments by Crum and Smetek [1997] in the previous paragraph).

Examples of human errors are not detailed in the literature cited; however, Shank and Lavrakas [1993, p.471] provide the following insight into the nature of human errors that occur within GPS: *the dynamics of the system under certain conditions can still cause incorrect human analyses with possible harmful effects to the User Segment and MCS operations*. The reference to the *dynamics of the system* is understood as the constant and vigorous interaction and interdependencies of the elements within GPS.

As previously mentioned, degradation of a signal can be caused by routine maintenance activities undertaken by the MCS, a study of which can provide an understanding of some of the causes of the integrity anomalies. As part of its stated mission, the MCS regularly maintains the satellite's navigation payload hardware, in particular the frequency standards and the associated components required to generate the signal at its nominal frequency. In addition, satellites are routinely manoeuvred in order to maintain their orbital positions. Since such maintenance activities cause inaccuracies in the navigation data and signal, the satellites concerned are usually declared to be *unhealthy*. A notice regarding any planned satellite's outage period, and reasons for the outage, is posted in the Notice Advisory to Navstar Users (NANU) which is available from the United States Coastguard (www.navcen.uscg.mil/gps/status/default.htm).

The Block II/IIA satellite vehicles carry two caesium and two rubidium frequency standards for redundancy purposes. The frequency standards regularly undergo two main types of maintenance: *ion pump operations* (IPO) and *C-field tuning*. Both operations, normally performed concurrently, are necessary to ensure a stable output frequency. The IPO involves the extraction of any impurities that accumulate in the caesium beam tube. C-field tuning is a process used to control the protective magnetic field, known as the C-field, which envelops the beam tube. Extreme variation in the temperature and beam current, and in the quartz crystal oscillator control voltage, can cause clock jumps, which, essentially, cause phase errors.

Satellites are maintained in their orbits using a process called *Delta-V*, controlled by the MCS, which involves igniting the satellites' thruster. Hence, it is important that the Delta-V process is performed when the designated satellite is visible at the monitor station. Bower and Dieter [1996] provide an excellent description of the aforementioned maintenance processes, whose main effects are degraded signal quality and inaccurate ephemerides, which can cause serious errors in GPS solutions.

This section has described some of the anomalies that have occurred in the control and space segments. These anomalies, some of which are rare and obscure, have been documented in the literature. The MCS is continually seeking to improve and develop techniques for monitoring the integrity of GPS and preventing some of the aforementioned problems. Some of these efforts are reported in the literature cited and in the *Proceedings of ION GPS*, in particular Malys *et al.* [1997]. However, the fact that anomalies have occurred and escaped detection by the control segment should be of concern to GPS users. Satellite and MCS anomalies, most likely, will continue to occur and their detection and prevention will continue to be difficult.

4.8.1.1 The effect of integrity anomalies on relative positioning

> *Although there may not always be a correlation between poor GPS navigation performance and poor GPS survey baseline results (as GPS integrity is generally very good), any periods of poor system performance as detected by the IM* (integrity monitoring) *network must be considered with suspicion.*
>
> Rizos [1997, p.171]

The previous section has described some of the anomalies that occur in the control and space segments. Most of the anomalies, such as those related to clocks and orbits, affect the accuracy of the pseudorange measurements. In point positioning, they degrade the accuracy of the derived coordinates. However, the question remains as to whether the anomalies would affect GPS baselines determined using the carrier phase observable in relative positioning.

One of the basic principles of relative positioning is *differencing* (*vide* Section 4.7) which enables the elimination or reduction of spatially correlated errors by forming linear combinations of the observation equations for two or more receivers simultaneously tracking the same set of satellites. Therefore, it is *highly unlikely* that the aforementioned anomalies would significantly affect GPS baselines. The anomalies, particularly those related to clocks, must be of a significant nature for the effects to be noticed, in which case either the receivers would not be able to track the corrupt signal or the observation would be rejected during the processing phase. As part of the internal quality control measures, most commercial baseline processors, given with adequate redundancy, can detect and exclude poor measurements during baseline processing.

The effect of ephemeris errors on relative positioning is discussed in Section 4.8.3. In relative positioning, ephemeris errors are effectively eliminated for short baselines (*vide* single difference equation (4.5)). However, equation (4.9) (*vide* Section 4.8.3) suggests that the impact of ephemeris errors is significant for long baselines and should be treated carefully.

The following example describes an anomaly which managed to elude all three GPS segments; associated with space vehicle PRN 19, it was reported in Cohen *et al.* [1996, p.430]. For some months, PRN 19 was transmitting an *abnormal* signal which affected receivers from different manufacturers in different ways, yet during this period, the OCS reported that PRN 19 was performing normally. According to Enge [1998], the abnormality could have resulted from signal multipath occurring at the satellite antenna; however, its cause remains unknown. Such a problem would only result from the use of different receiver architecture types, in which case, range errors of several metres would be experienced. Cohen *et al.* [1996, p.430] suggest that a potentially dire situation could result when ground monitor stations are equipped with receivers of the same type, whilst an aircraft receiver is of another type. In this case, integrity warnings would *not* be issued because the effect would not be detected at the ground monitor stations. One of the main conclusions to be drawn is that mixing of receivers with different architecture types is not advisable (*vide* Section 4.8.9). The PRN 19 problem can be found also in Daly *et al.* [1993, p.438] who reported errors of the order of 4 m in the differential solutions; however, they were uncertain as to whether the anomaly was a significant contributing factor.

The effect of the PRN 19 anomaly on carrier phase relative positioning is not reported in the literature cited. However, if the anomaly were related to signal multipath at the satellite antenna, as hypothesised by Enge [1998], then the findings from Young *et al.* [1985] may provide some insight. *ibid.* [1985, p.423] simulated the effect of signal multipath at the satellite antenna and found that the effect *cannot* be removed by differential techniques. The effect is expected to contribute different *error signatures* to receivers at separate locations. In addition, the effect may vary from satellite to satellite due to the different satellite antenna designs. *ibid.* [1985, p.424] found that the magnitude of the error *can be a several cm differential effect between the carrier and P-code, even over fairly short baselines.*

For more discussion of other types of rare anomalies associated with specific space vehicles, refer to Cobb *et al.* [1995] and Hansen *et al.* [1998]. Cobb *et al.* [1995, p.795] provide the following apt warning: *The fact that this glitch was unknown to the research community for so* *long begs an important question: Are there other spacecraft anomalies with similar impact which remain unknown today? If so, tomorrow's systems may not perform as well in the real world as today's analyses predict.*

Orbit errors and PRN 19 type anomalies emphasise the need for an independent monitoring system. In this thesis, the justification for implementing a GPS integrity monitoring system is argued for the purpose of surveying. However, the implementation of a GPS integrity monitoring system in Australia is inevitable for the benefit of the wider GPS user community. For some sections of this community, particularly those involved in land, aviation and marine navigation, safety issues are of paramount importance. For these users, integrity monitoring systems are necessary for the provision of timely warnings when GPS should not be used. In addition, many authorities, such as the Royal Australian Navy (RAN), use the coordinates determined using GPS to prove that they were actually at a particular location when a certain activity was undertaken. For example, the Royal Australian Navy often intercept boats undertaking illegal activities within the Australian maritime boundaries. Generally, the position of the interception point is determined using GPS. According to Mr Keith McPherson [1998], an expert witness in matters relating to satellite navigation systems, in cases involving activities close to the maritime boundaries, the court of law requires the RAN to prove that the logged position is actually where it purports to be. The proof is given in the following manner:

- The performance of GPS satellites during the period when the position was logged is demonstrated to be within operational tolerances. The information relating to satellite performance is obtained from permanent tracking stations located around Australia.
- The receiver and processing software used to determine the position are requisitioned and tested to ensure their proper functioning.

The above requirement by the court of law to prove the proper functioning of GPS satellites during a measurement process constitutes a case for implementing an integrity monitoring system in Australia.

The complete GPS technology comprises three segments, namely the control, space and user segments; these are interdependent and must be treated as an integrated measurement system. The final results obtained in a GPS survey are dependent on the proper operation and treatment of the respective segments. Although GPS was declared as having full operational capability (FOC) on April 27th 1995 [GPS World Newsletter, 1995], it still has inherent uncertainties. GPS was never intended to be used as a high precision surveying tool; the ingenuity of the geodesists and surveyors led to its applications at centimetre levels. As established in Section 4.8.1, under certain circumstances, the MCS cannot be relied upon to provide timely warnings to the users regarding integrity lapses occurring within the system. Anomalies in GPS will continue to occur and their detection and prevention will continue to be difficult. Many of the anomalies are quite rare and obscure, and their effects on the user segment are not well always understood. Further, other anomalies that have not been anticipated by the systems designers may yet occur. Therefore, implementing verification measures for the user segment only, whilst ignoring the control and space segments, is a highly risky proposition.

This thesis contends that, due to the uncertainties that exist within the control and space segments, an integrity monitoring system should be an important part of the overall verification scheme for establishing legal traceability of measurements. The monitoring system should form the first level in the hierarchy of a verification scheme because it verifies the performance of GPS signals and the navigation data prior to their reaching the user segment. Implementing an integrity monitoring system will ensure that the integrity of GPS can be *independently* verified in Australia should obviate the need for dependence on an unreliable external source. In addition, an Australian integrity monitoring system would provide additional redundancy into the Global Positioning System. Some of the current integrity monitoring systems, particularly those implemented for aviation navigation, are described in Section 5.5. Some of the elements from these systems are used in Chapter 6 for the formulation of an integrity monitoring system for Australia.

4.8.2 Antispoofing and Selective Availability

For security reasons, the United States Department of Defense has denied civilian users full use of GPS by implementing *Antispoofing* and *Selective Availability*. Antispoofing, a mechanism intended to defeat deception jamming, is implemented by encrypting the P code. The encrypted P code is known as the Y code and can be accessed only by authorised users [Spilker Jr., 1996, p.76]. As shown in Figure 4.2, there are several techniques which can be used to exploit the encrypted P code. Selective Availability is the intentional degradation of the accuracy of the Standard Positioning Service (SPS), which is based on the C/A code. The accuracy of the horizontal coordinates of a point determined under Selective Availability is expected to be within 100 m at least 95% of the time [Anon., 1994, p.A-37]. Selective Availability can be implemented by [Georgiadou and Doucet, 1990, p.54; and Van Graas and Braasch, 1996, p.602]:

- corrupting the orbital parameters of the satellite, also known as the ε-process; and
- manipulating or dithering the satellite clock output frequency, also known as the δ-process.

The former prevents an accurate determination of the satellite's position, while the latter degrades both the pseudorange and carrier phase observables. The implementation of the first option is a moot point. The effect was not evident in a test conducted by Zumberge and Bertiger [1996, pp.590-593] to ascertain the accuracy of the broadcast orbits in comparison with precise orbits.

Selective Availability is not a significant factor in relative positioning, especially for short baselines, i.e. 10-20 km [Talbot, 1990; Rocken and Meertens, 1991; and Hofmann-Wellenhof *et al.*, 1997, pp.142-143]. Presently, the operating range of most real time kinematic survey systems is limited to 10 km (see for example Trimble Navigation Limited [1994] and Leica [1996b]) mainly due to the decorrelation of errors over longer baselines. The Selective Availability policy may not be a consideration in the future, since its eventual removal is planned (*vide* Section 4.2).

4.8.3 Ephemeris errors

Satellite ephemeris error is the discrepancy between the actual position of a satellite and its position determined using the broadcast ephemeris [Seeber, 1993, p.297; and Rizos, 1997, p. 252]. Under the Selective Availability policy, orbital parameters are deliberately manipulated; however, ephemeris errors can also be caused by inaccurate modelling of the satellite's position and velocity, due to errors in the tracking data, tracking station coordinates, force models, and the algorithm used for orbit computation [Colombo, 1986, p.65]. *Integrity anomalies* occurring in the control and space segments constitute further sources of ephemeris errors (*vide* Section 4.8.1).

The effects of ephemeris errors on baselines have been investigated by various authors using different approaches, such as geometrical methods [Beutler *et al.*, 1988], simulation [Zielinski, 1989] and comparative means [Remondi and Hofmann-Wellenhof, 1989]. Both advantages and disadvantages are associated with each method; however, an analysis is only as good as the assumptions made and situations adopted for the analysis. Generally, the aforementioned authors agree that the analysis of ephemeris errors is complicated due to the following reasons:

- ephemeris errors are unique to individual satellites; and
- the accuracy of baseline solutions is dependent on a number of other factors, such as satellite geometry, number of available satellites, observation time and the survey technique.

The effect of ephemeris errors on a baseline follows a *rule of thumb* given in Vanícek *et al.* [1985, p.56] as:

$$\frac{\mathrm{dB}}{\mathrm{B}} = \frac{\mathrm{dr}}{\rho} \qquad (4.9)$$

where B is the baseline length, dB its associated error, ρ is the range to the satellite and dr is the satellite position error. *ibid.* [1985, p.56] derived equation (4.9) using vector geometry and suggest that the relationship gives a pessimistic estimation for the baseline error; Zielinski [1989, p.123] agrees. According to some authors [Wells *et al.*, 1986, p.9.3; Remondi and Hofmann-Wellenhof, 1989, p.15; and Hofmann-Wellenhof *et al.*, 1997, p.68], in the presence of Selective Availability, orbit errors associated with the broadcast ephemeris can range from less than 5 m up to 100 m. Assuming that ρ is approximately 20200 km and dr is 20 m for the broadcast ephemeris, then using equation (4.9), the scale error in the baseline is 1 ppm.

In relative positioning, ephemeris errors can be significantly reduced (*vide* single difference equation (4.5)); however, equation (4.9) suggests that the impact of ephemeris errors, like Selective Availability, is significant on long baselines and should be treated carefully. In order to reduce the effects of ephemeris errors, the following operational strategies [Rizos, 1997, p. 256] can be considered:

- use post-computed precise ephemerides, which can be obtained from various sources, one of which is the International GPS Service (IGS), through the internet site: (igscb.jpl.nasa.gov). This site claims that the accuracy of the IGS precise ephemerides is better than 0.2 metres and states that the service is not yet available for real time applications);
- adjust the orbits as additional parameters (an option which is not available in most commercial GPS software);
- increase the observation time in order to average the effects; and
- shorten the baseline lengths according to the relationship shown in equation (4.9).

4.8.4 Clock errors

Satellite and receiver clocks are not perfect instruments. However, their accuracy and stability is adequate for certain applications. For point positioning, the clocks fulfil their roles well within specifications. For applications, such as surveying, the clocks' behaviour and limitations must be understood and treated accordingly.

The performance of a clock, in terms of frequency, is determined by its *accuracy* and *stability*. *Accuracy* is the degree of conformity with a definition, such as the definition of the SI *second*, while *stability* is a measure of the change in a clock's rate as averaged over one interval to the next [Allan *et al.*, 1974, pp.153-154]. Frequency stability can be characterised by the *Allan variance,* $\sigma_y^2(\tau)$, where τ is the sampling time interval and y is the fractional frequency fluctuations. The theoretical development of the Allan variance is presented in Allan [1966]. A good review of the various types of frequency standards and their associated performance is presented in Lewis [1991].

The on-orbit performances of the rubidium and caesium clocks in Block I/II satellites have been evaluated over many years, see for example Van Melle [1990], McCaskill *et al.* [1990], McCaskill *et al.* [1993] and McCaskill *et al.* [1996]. Generally, the frequency stability of the clocks is in the order of 10^{-13} (τ = 1 day), which is better than the specified value of 2 x 10^{-13} [McCaskill *et al.*, 1990, p.134]. The long term stability of the clocks is in the order of 10^{-14} (τ = 100 day). Atomic frequency standards are known to have excellent long term frequency stability. The frequency stability of the clocks in the Block IIF satellites, which have been planned to replace the Block IIA and IIR satellites, is expected to be of the order of 10^{-14} (τ = 1 day). Based on the on-orbit performance of the current clocks, this figure is considered to be a conservative estimate [Ghassemi and Fisher, 1997, p.410].

Most receiver clocks of geodetic quality, for example those from Leica, use the oven-controlled crystal oscillator (OCXO), or its variations, which have frequency stabilities of less than 10^{-11} (τ = 1 s) and 10^{-7} ($\tau \approx$ 1 year) [Piezo Technology Inc., 1998]. Some manufacturers, for example Trimble Navigation Ltd, use temperature-compensated crystal oscillators (TCXO) with frequency stability of less than 10^{-9} (τ = 1 s) and 10^{-6} ($\tau \approx$ 1 year) [RAKON Ltd, 1997, p.22]. Quartz crystal oscillators have good short term frequency stability. It should be noted that for high precision applications, such as time transfer, manufacturers use oscillators with commensurate frequency stability.

Satellite clocks are allowed to drift off the reference time system, i.e. GPS Time (*vide* Section 6.4.1), but they are carefully monitored on a continuous basis by the OCS, as well as the United States Naval Observatory (USNO), and are reset occasionally so that they are within 1 millisecond of GPS Time [Wells *et al.*, 1986, p.9.2]. A clock's behaviour, expressed as offset, drift and drift-rate, is known accurately and is included in the navigation message in the form of clock corrections, which are coefficients of a second order polynomial defined in the Interface Control Document [Anon., 1995b, p.72]. These clock corrections are used to relate satellite clock time to GPS Time.

Most code tracking receivers have the ability to update or reset their clocks to GPS Time by solving for the clock offset using the pseudorange observables. A clock's ability to remain on GPS Time is dependent on the stability of its oscillator. Commonly, manufacturers adopt techniques which rely on the short term stability of the crystal oscillators. Receiver manufacturers control the receiver clock time by either adjusting or *steering* it to accord with GPS Time. Some receiver clocks are allowed to drift in a controlled manner to within 1 millisecond of GPS Time (Figure 4.7). *Clock steering* can be achieved either by applying the clock offset to every epoch of measurement (Figure 4.8) or by using a feedback process to control the oscillator's frequency. Due to the different techniques used by the various manufacturers for obtaining GPS Time, users often are advised not to mix measurements from different receivers so as to avoid time synchronisation problems.

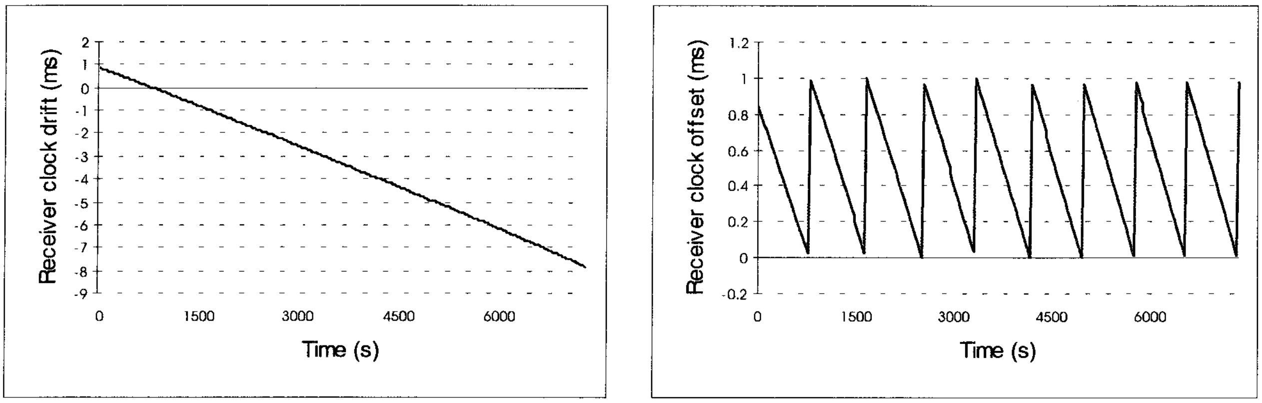


Figure 4.7. The left graph illustrates a clock drift, while the right graph shows clock offset with periodic reset (within 1 millisecond) in a Trimble 4000SSE receiver.

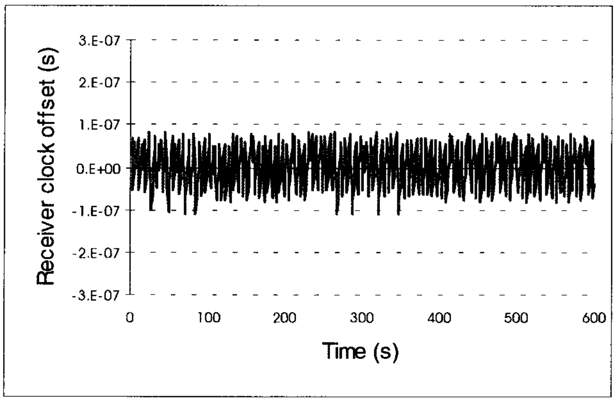


Figure 4.8. Clock steering in a Leica SR9500 receiver.

A clock error, simply, is the deviation of the clock's performance from a specified value. Some of the sources for satellite clock errors, such as clock jumps, most of which are manifested as phase errors, have been discussed in Section 4.8.1. The magnitude of the errors are unknown; however, it is significant enough to cause cycle slips [Cobb *et al.*, 1995; and Hansen *et al.*, 1998]. As mentioned in Section 4.8.1, satellite clock errors can be detected by an integrity monitoring system. Selective Availability (*vide* Section 4.8.2), which dithers the satellite clock's fundamental frequency, is a deliberate source of clock error. Apart from phase errors, another manifestation of clock errors, as explained in Rizos and Grant

[1990, pp.79-81], is in the form of *time-tag* errors, which are essentially time synchronisation problems between receivers and satellites.

Clock errors can be eliminated through observation differences: single differencing (between-receiver *vide* equation (4.5)) eliminates satellite clock errors, while double differencing (*vide* equation (4.8)) eliminates both satellite and receiver clock errors. This approach is valid only when the observations are made *simultaneously*. The concept of simultaneous observations holds only within the limits of synchronisation between the various orbital (ephemeris), satellite and receiver time scales. The subject of simultaneity is treated comprehensively in Rizos and Grant [1990]. The assumption of simultaneous observations mainly depends on the performances both of the satellite's atomic frequency standards and the receiver's quartz crystal oscillators. On the issues of synchronisation, *ibid.* [1990, p.98] recommend the following:

- The observations at all receivers of the same type should be taken within 30 milliseconds of each other in order to ensure that satellite clock errors are eliminated in the between-receiver differencing.
- Receiver clocks should be synchronised with each other at the microsecond level to ensure that all observation time-tags are consistent with each other.
- All receiver time scales should be synchronised to a standard time scale, such as GPS Time, to within a few milliseconds in order to maintain baseline errors of less than 1 ppm.

The aforementioned recommendations are very modest in view of the highly stable nature of the satellite and receiver clocks. And it should be noted that very conservative frequency stability values were used to arrive at these conclusions. For example, it was assumed that the frequency stability of the satellite clocks is of the order of 10^{-10} rather than 10^{-13}.

Based on the foregoing discussions, satellite and receiver clock errors can be effectively eliminated through observation differencing, particularly in the double differenced solution.

4.8.5 Satellite geometry

Satellite geometry, which varies temporally and spatially, refers to the number of visible satellites and their distribution; it is quantified by the *dilution of precision* (DOP) [Wells *et al.*, 1986, p.4.22]. Before GPS was declared as having full operational capability (FOC), DOP indicators were used generally as a survey planning tool; they may be used to identify temporal weakness in the geometric strength for rapid static and kinematic surveys [Leick, 1995, p.255]. In these surveys, DOP indicators can be used to estimate the length of occupation time [Merminod *et al.*, 1990]. In built-up areas, where satellite visibility may be limited, they can be used for scheduling optimum observation periods.

Satellite geometry is an important factor in real time kinematic surveys, particularly for resolving the integer cycle ambiguity (*vide* Section 4.8.13). Firstly, the redundant satellites (i.e. those in excess of the minimum required for a solution) tracked at any instant can increase the efficiency and reliability of ambiguity resolution. Secondly, under favourable satellite geometry conditions, the time required to resolve ambiguities can be reduced [Hofmann-Wellenhof *et al.*, 1997, p.215]. A good satellite geometry does not, however, always necessarily lead to efficient and reliable ambiguity resolution, because signals from low elevation satellites could possibly be corrupted with multipath and atmospheric effects.

4.8.6 Ionospheric delay

The ionosphere is that layer of atmosphere that lies between 50 km and 1000 km above the earth's surface. It comprises free electrons and ions resulting from ionisation by solar ultraviolet radiations. The ionosphere is a dispersive medium for electromagnetic waves, i.e. the refractive index is a function of the operating frequency. Ionospheric effects are highly variable both temporally and spatially. For example, daytime effects differ from those affecting observations taken at night because of the difference in solar activity. Further, the effects are different for short and long baselines, due to variations in propagation paths.

The main effects of the ionosphere on GPS signals are: group delay of the pseudorange measurements and carrier phase advance [Hofmann-Wellenhof *et al.*, 1997, pp.99-101]. The phase advance can be described as a negative delay. Ionospheric delay introduces a scale error which shortens baselines [Georgiadou and Kleusberg, 1988b, p.4; and Beutler *et al.*, 1989 p.29]. Beutler *et al.* [1988, p.28] derive an approximation for the ionospheric L1 phase delay scale factor as:

$$\frac{\mathrm{dB}}{\mathrm{B}} = -0.7 \times 10^{-17} \times \mathrm{E} \qquad (4.10)$$

where B is the baseline length, dB its associated error, and E is the total electron content (TEC). The TEC is expressed as the number of free electrons per square metre. Typically, for mid-latitude sites, the approximate daytime and night-time vertical TEC values are of the order of 10^{18} m^{-2} and 10^{17} m^{-2} respectively [Langley, 1996b, p.128]. The corresponding scale errors in baselines determined using the L1 phase are 7 ppm and 0.7 ppm. A relationship between ionospheric delay and satellite elevation is described in Georgiadou and Kleusberg [1988b, p.4].

Coco *et al.* [1990] report an investigation which reveals a correlation between ionospheric delay and baseline lengths. The data used in the investigation were observed during near solar maximum conditions. Twenty three baselines between 7 km to 2300 km were measured in three separate campaigns. *ibid.* [1990, p.339] demonstrate that the daytime and night-time ionospheric errors of a single difference solution are 0.53 ppm and 0.16 ppm respectively.

Several techniques may be employed so as to reduce the ionospheric effect. Dual frequency receivers can take advantage of the dispersive nature of the ionosphere by making simultaneous L1 and L2 phase observations. A linear combination of the L1 and L2 observation equations (*vide* equation (4.2)) may be formed to produce a new observable called *ionospheric free*, or L3. The derivation of the observable can be found in several publications including Hofmann-Wellenhof *et al.* [1997, pp.95-96 & 106-108]. The main disadvantage with this observable is the increase in measurement noise comprising mainly multipath and residual biases [Bock *et al.*, 1986, p.286]. In linear combinations of phase observables the amplification of measurement noise follows the Law of Propagation of Variances [Beutler *et al.*, 1989, p.32; Wübbena, 1989, pp.455-458; and Takac *et al.*, 1998, pp.42-43]. The noise level of a double difference solution using the L3 observable compared to that of the L1 observable is increased by a factor of 3.3 [Kleusberg, 1986, p.257; and Takac *et al.*, 1998, p.43]. Hence, single frequency observations, either L1 or L2, are preferred in the determination of short baselines [King *et al.*, 1985, p.85; Hatch and Larson, 1985, p.289; and Bock *et al.*, 1986, p.286]. The ionospheric effect for nearby stations is highly correlated and, therefore, can be reduced significantly by differencing techniques. However, the L3 observable should be used for the determination of long baselines, due to the decorrelation of the ionosphere's effect which, in turn, causes an increase in the ionospheric bias-to-noise ratio.

Seeber [1993, p.304] points out that another disadvantage associated with the L3 observable is the fact that it is a first order approximation only and shows that the magnitude of the ignored second order terms is 26 mm for vertical ionospheric effect. An improved model to account for the higher order terms is proposed in Brunner and Gu [1991]. By using simulated data, *ibid.* [1991] managed to obtain residual range errors, associated with the proposed model, of less than 2 mm. According to Rizos [1997, p.263], the effect of higher order terms should be considered only for very high accuracy applications involving long baselines.

For a single frequency receiver, the ionospheric model [Anon., 1995b, pp.98, 106a & 107-108b] transmitted as part of the broadcast navigation message can be used for reducing the ionosphere's effect. *ibid.* [1995b, p.106a] states that the broadcast model can compensate for at least 50% of the ionospheric delay. Coco *et al.* [1990, p.391] suggest that the broadcast model tends to overestimate the ionospheric delay. From their investigation, described in the preceding paragraphs, they found that the model can account for 73% of the ionospheric delay [*ibid.*, 1990, p.395]. They also show that significant improvements can be gained by correcting the measured delay using the broadcast model prior to forming the single difference solution. Georgiadou and Kleusberg [1988b] describe a model for correcting single frequency carrier phase observations based on estimated vertical ionospheric delays derived from the observations of one dual frequency receiver in the vicinity of the site.

Apart from the aforementioned techniques, the conduct of surveys during periods of low solar activity, for example at night, also reduces the ionospheric effect.

4.8.7 Tropospheric delay

The troposphere is that layer of atmosphere which extends from the earth's surface to a height of about 50 km. Strictly, the troposphere, tropopause and stratosphere form the *neutral* atmosphere. However, since most of the mass of the neutral atmosphere is contained within the troposphere, the whole neutral atmosphere is referred to loosely as the troposphere, which comprises neutral atoms and is a non-dispersive medium for radio frequencies below 30 GHz [Brunner and Welsch, 1993, p.42]. Hence, tropospheric refraction, unlike ionospheric refraction, cannot be estimated by dual frequency observations.

The tropospheric effect is both temporal and spatial in nature; it causes a delay in the propagation of GPS signals, which introduces a scale error tending to *lengthen* baselines [Beutler *et al.*, 1988, p.26]. According to Brunner and Welsch [1993], the delay varies according to the zenith angle of the propagation path and the height of a station. It is also dependent on the atmospheric humidity, pressure, temperature and water vapour content. Modelling the near-surface atmospheric structure is commonly used for estimating the propagation delay [Seeber, 1993, p.307].

Tropospheric delay can be expressed as a product of the zenith delay and a function which maps the increase in delay with decreasing elevation angle [Brunner and Welsch, 1993, p.46]. Derivations of the tropospheric delay can be found in Seeber [1993, pp.45-46] and Hofmann-Wellenhof *et al.* [1997, pp.109-110]. Generally, the zenith delay is separated into dry and wet components; consequently, it can be determined from meteorological observations. However, Brunner and Welsch [1993, p.48] warn that meteorological observations often produce results which are poor when compared with those from the default model values. Several authors, including Beutler *et al.* [1989, pp.28-29] and Janes *et al.* [1991, p.160], have cautioned against the use of meteorological observations, particularly in small networks with height differences of less than 100 m, because of local micro-climate conditions and the difficulty in obtaining truly representative meteorological values. Beutler *et* *al.* [1988, p.22] demonstrate that minor variations in meteorological data adopted can have a significant impact in the estimation of the zenith delay. Generally, *standard atmosphere* data are used instead of meteorological observations; the standard atmosphere is created by defining reference pressure, temperature, and humidity at sea level. Meteorological data for a site are then estimated based on its height [Brunner and Welsch, 1993, p.48]. It should be noted that the commercial processing software Trimble GPSurvey Version 2.20 does allow the use of meteorological observations for tropospheric modelling [Trimble Navigation Limited, 1996a, pp.6-32]. Based on the foregoing discussions, this option may have detrimental effects, particularly if the user is relatively inexperienced.

Many tropospheric models and mapping functions have been developed for estimating the tropospheric delay, some of which are described in Hofmann-Wellenhof *et al.* [1997, pp.110-118]. Janes *et al.* [1991] and Mendes and Langley [1994] provide extensive evaluation of the accuracy of most of the available models and mapping functions. *ibid.* [1994, p.87] conclude that virtually all the tested mapping functions provide sub-centimetre accuracy for elevation angles above 15°.

Based on the assumptions that similar meteorological conditions are experienced at both ends of a baseline and the satellites are uniformly distributed, Beutler *et al.* [1988, p.26] derive an approximation for the scale factor of the tropospheric delay as:

$$\frac{dB}{B} = \frac{d_t^z}{r_s} \sec(z_{max}) \tag{4.11}$$

where B is the baseline length, dB its associated error, d_t^z is the zenith delay, r_s is the geocentric radius of the observing station and z_{max} is the maximum zenith angle. According to *ibid.* [1988, p.26] and Janes *et al.* [1991, p.158], assuming that the atmosphere is laterally homogeneous and that an appropriate tropospheric model is used, equation (4.11) could yield a residual scale error of the order of 0.1 ppm at a maximum zenith angle of 70°. Brunner and Welsch [1993, p.51] state that tropospheric delay principally affects the accuracy of height differences. According to an approximation derived in Beutler *et al.* [1988, p.23], relative height errors, as a result of relative troposphere errors, can be amplified by a factor of about 3.

In relative positioning, over short baselines, receivers can be assumed to be simultaneously tracking signals travelling along the same paths through the atmosphere, and thus the tropospheric delay can be reduced significantly by the differencing process. Generally, this assumption holds true for signals tracked at elevation angles above 15° and stations with relative height differences of less than 100 m.

4.8.8 Multipath effects

Multipath is the phenomenon whereby a signal arrives at the antenna via many indirect paths as a result of reflection and diffraction; it causes a carrier phase error of less than a quarter of a wavelength [Georgiadou and Kleusberg, 1988a, p.173], while the pseudorange error is limited to one chip length of the pseudorandom codes, i.e. 293 m for the C/A code and 29.3 m for the P code [Lachapelle *et al.*, 1989, p.344]. Since the effects of multipath are site dependent and not correlated between antenna locations, the effects on carrier phase measurements in relative positioning cannot be eliminated or reduced through differencing techniques. However, multipath has several characteristics which can be used to distinguish the direct from the reflected signals. The ensuing paragraphs describe some of the features of multipath and the techniques available for reducing its effects.

Multipath signals are periodic in nature. Evans [1986] and Georgiadou and Kleusberg [1988a] demonstrate that, for the same site and repeated geometry between the satellite, reflector and antenna, the effects of multipath are highly repeatable after one sidereal day. Based on this, multipath effects for a particular site can be mapped in order to infer multipath parameters. The understanding of this characteristic is particularly useful for determining multipath effects at permanent reference stations.

A direct GPS signal is right hand circular polarised (RHCP), while its reflected image is left hand circular polarised (LHCP). Antennas designed for right hand circular polarised signals are not as responsive to left hand circular polarised signals. Further, multipath signals arrive after the direct signals and, generally, are weaker than the direct signals, due to signal power loss resulting from the reflection [Townsend and Fenton, 1994, p.144]. The understanding of these characteristics has led to the development of many multipath mitigation techniques, most of which fall into four categories: antenna design, use of signal processing schemes, data combination and operational procedures.

Two types of antennas commonly used in surveying to counter the effects of multipath are antennas with ground planes and choke ring antennas. A ground plane is used to shield the antenna from signals arriving from below the antenna. However, multipath signals can still arrive at the antenna due to reflection from upright objects, as well as a result of diffraction at the edge of the ground plane. Ground planes, due to their size, are useful for static surveys but are quite impractical for kinematic surveys. Choke ring antennas have concentric circular troughs, at a spacing of one quarter wavelength deep, which act as barriers to signals arriving from near horizontal directions; they are generally quite large, heavy and costly. Other suggested antenna designs include the use of radio frequency absorbent material for ground planes [Bletzacker, 1985], wideband antennas [*ibid.*, 1985] and antennas with low gain pattern for near horizontal signals [Leick, 1995, p.312].

Several signal processing schemes are available for reducing the effects of multipath, including narrow correlator [Van Dierendonck *et al.*, 1992], multipath estimating delay lock loop (MEDLL) [Van Nee, 1992], and multipath estimating technique (MET) [Townsend and Fenton, 1994]. Major proprietary multipath mitigation techniques include Everest™ [Trimble Navigation Limited, 1996b], Edge and Strobe Correlator™ [Garin *et al.*, 1996] and Leica's Multipath Technique [Hatch *et al.*, 1997]; most of these take advantage of the characteristics of the cross-correlation function. Generally, the schemes are implemented in receivers to reduce multipath effects on the pseudorange measurement. Reduction of multipath effects on the pseudorange can increase the reliability of ambiguity resolution (*vide* Section 4.8.13).

Multipath effects can be inferred through data combination; for short baselines, they may be estimated by analysing the difference between L1 and L2 phase measurements [Georgiadou and Kleusberg, 1988a]. The combination of code and phase observables can give an indication of the multipath effects on the pseudorange [Evans, 1986; Evans and Carr, 1989; and Langley, 1996a, p.160]. Axelrad *et al.* [1994] estimate the spectral parameters (i.e. frequency, amplitude and phase offset) of multipath in the carrier signal to noise ratio (SNR) to construct a profile of the multipath effects in the carrier phase. The profile is then used to remove multipath effects from the actual phase measurements. A refinement of this technique is presented in Comp and Axelrad [1996].

Operational strategies, such as site selection, long observation times and avoidance of low elevation satellites, can be employed to reduce the multipath effects. Sites with highly reflective features should be avoided. Due to the periodic nature of multipath signals, long observation times, appropriate for static surveying, can average the effects of multipath. However, long observation times may not be possible in kinematic surveys. Further, the antenna's elevation mask can be set higher in order to avoid low elevation signals.

As described in the foregoing paragraphs, the effects of multipath can be reduced using several options; many of these are in fact incorporated in the hardware, i.e. the antennas and receivers. Further, operational strategies, which are the best means for multipath reduction, should be considered. In the context of surveying, the most appropriate means for reducing multipath effects is a combination of careful selection of hardware and the use of informed operational strategies.

4.8.9 Antenna biases

Baseline vectors are determined between antenna phase centres. The phase centre is the apparent electrical centre, which is usually not coincident with the physical or geometric centre of the antenna. Phase centres vary according to the incidence angle, i.e. azimuth and elevation, of the incoming signal. Further, the L1 and L2 phase centres are not coincident. The effects of phase centre variations are more pronounced on long baselines, i.e. more than 100 km [Wu *et al.*, 1993, p.95-96], since the antennas then observe satellites at different elevation angles (Figure 4.9). As a result, residual range errors can occur since the errors do not cancel in a double difference solution (*vide* equation (4.8)). For high precision applications and surveys which require the use of different antenna types, the location of the antenna phase centre and its pattern of variation must be determined accurately. Schupler and Clark [1991, p.33] illustrate several situations relating to the consequences of ignoring the effects of phase centre offset on a baseline.

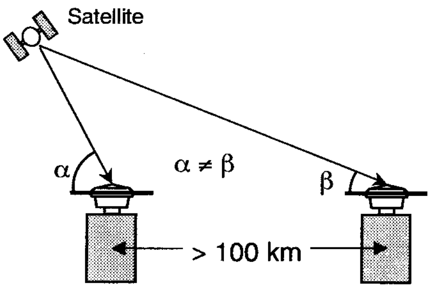


Figure 4.9. Observed elevation angles on long baselines.

Several authors (including Langley [1996a, p.144], Rocken *et al.* [1995, p.7-1] and Wübbena *et al.* [1997, p.250]) agree that the magnitude of phase centre variations for geodetic quality antennas is typically at the *sub-centimetre* level. Using known short baselines, Wiget *et al.* [1990, p.845] found that the phase centre offsets for certain microstrip patch antennas were less than 1 cm. This finding appears to be consistent with the laboratory results presented in Schupler *et al.* [1994]. However, most importantly, Schupler and Clark [1991, p.36], Schupler *et al.* [1994, p.283] and Rothacher *et al.* [1995, p.336], using laboratory and field experiments, agree that the phase variations in antennas of the same make and model are generally *insignificant* for geodetic measurements. Schupler *et al.* [1994, p.283] found that the microstrip patch antennas, in particular, have very consistent phase patterns, one consequence of precise, automated manufacturing techniques.

In order to reduce the effects of antenna biases, GPS equipment manufacturers advise users to orientate antennas of the same type in the same direction, such as magnetic north, on the assumption that antenna biases are similar in magnitude and direction (*vide* findings by

Schupler *et al.* [1994, p.283] in the previous paragraph). If this assumption is true, and the recommendation is followed, the effects of the bias on short baselines can be reduced in a double difference solution. However, for longer baselines, in which the observed elevation angles (Figure 4.9) and direction of magnetic north may not be the same, the effects should be considered and treated carefully. Generally, mixing of different antenna types in a survey is discouraged; however, if it is unavoidable, the phase centre pattern, particularly the vertical component, must be determined and included in the processing software. Tests for determining the location and pattern of phase centre are discussed in Section 5.6.2. Further discussion on the character of phase centre offsets and variations for different antenna models can be found in the literature cited as well as through the internet, e.g. the *Geosciences Research Division* of the U.S *National Geodetic Survey* (NGS) (www.grdl.noaa.gov/GRD/GPS/Projects/ANTCAL) and the *University NAVSTAR Consortium* (UNAVCO) (www.unavco.ucar.edu/science_tech/technology/publications). Manufacturers can provide nominal values for antenna phase centre offsets upon request.

The foregoing paragraphs have described the effects of antenna biases in general high precision work having an accuracy requirement of better than 1 ppm. In the context of cadastral surveying, where accuracy requirements worse than 50 ppm apply (*vide* Section 3.3.3), the effects of antenna biases can be reduced by following the manufacturer's advice regarding orientating antennas of the same type in the same direction. This procedure should be incorporated into survey practice.

4.8.10 Measurement noise

The precision of GPS observables is partially dependent on the ability of the receiver hardware to track the signal. GPS receivers, being manufactured items, are not perfect devices and will always have some inherent tracking limitations. These limitations, known collectively as receiver measurement noise, are major constituents of the random measurement error term (ε) in the carrier phase observation equation (4.2). The main contributors to the measurement noise are: *receiver noise*, *antenna noise* and *code and carrier tracking loop jitter* [Martin, 1980; and Langley, 1997]. Detailed discussions on the subject of receiver measurement noise can be found in Ward [1996] and Van Dierendonck [1996].

Measurement noise, which cannot be eliminated or reduced in a double difference solution, is random in nature and is independent of baseline length. An indicator of the amount of noise in a signal is the *signal-to-noise ratio*. As previously mentioned, in linear combinations of phase observables, for example ionospheric free (*vide* Section 4.8.6), the amplification of measurement noise follows the Law of Propagation of Variances. From equation (4.7), the residual error, largely due to measurement noise, is expressed as $(\varepsilon_r^b - \varepsilon_q^b - \varepsilon_r^a + \varepsilon_q^a)$. It can be shown, using the Law of Propagation of Variances, that the combined noise for a L1 phase double difference solution is:

$$\sigma_{\nabla\Delta_{L1}} = \sqrt{\sigma_{L1}^2 + \sigma_{L1}^2 + \sigma_{L1}^2 + \sigma_{L1}^2} = 2\sqrt{\sigma_{L1}^2} \qquad (4.11)$$

where σ_{L1}^2 is the variance for a receiver measurement noise. As an example, Leica [1996a, p.3] specifies that the new SR9500 receivers have a precision (σ_{L1}) of 0.2 mm (rms) for undifferenced L1 and L2 phase measurements. From equation (4.11), the combined noise for a L1 phase double difference solution using the SR9500 receivers is determined as $\sigma_{\nabla\Delta_{L1}} = 0.4$ mm. Most modern receiver technology can measure phase difference with precisions of better than 1 mm [Rocken *et al.*, 1995]. For practical purposes, errors of less than 1 mm bear no significant effect on the overall accuracy of the solution. However, cadastral surveyors are required to maintain survey equipment so as to ensure that it performs at a tolerable level (*vide* Section 3.3.4.2). The prudent surveyor should conduct and maintain records of routine tests for evaluating receiver tracking performance. Tests for determining the magnitude of the effects of measurement noise are discussed in Section 5.6.1.

4.8.11 Cycle slips

A cycle slip is a jump in the instantaneous accumulated phase by a whole number of cycles [Hofmann-Wellenhof *et al.*, 1997, p.206]. The accumulated phase is the sum of the fractional phase and the number of whole cycles of phase between initial acquisition and end of observation. Hofmann-Wellenhof *et al.* [1997, pp.206-207] list the possible causes of cycle slips as:

- obstructions to the satellite signal due to trees, buildings, bridges and mountains;
- low signal-noise-ratio (SNR) due to ionospheric conditions, multipath, high receiver dynamics or low satellite elevation; and
- failure in the receiver software which leads to incorrect signal processing.

Phase errors resulting from satellite clock anomalies (*vide* Section 4.8.1) may also cause cycle slips; a recent such event is reported in Hansen *et al.* [1998].

Most modern receivers have inbuilt algorithms capable of detecting almost all cycle slips [Seeber, 1993, p.272]. Following detection, the slips are tagged in the data set. Talbot [1991, pp.63-64] suggests that the *integrated Doppler counter* and SNR provided in receivers can be used as indicators of cycle slips. Several detection and repair methods may be employed during the data editing phase; a good review thereof can be found in Lichtenegger and Hofmann-Wellenhof [1990]. According to *ibid.* [1990, p.59], the methods vary according to the manner in which the available measurements (L1, L2 and codes) and *a priori* information (satellite and station coordinates) are combined. The observation mode, i.e. static or kinematic, is also a consideration.

4.8.12 Reference station coordinate accuracy

As mentioned in Section 4.7.2, the coordinates of one particular station are adopted as the reference during the processing of static and kinematic surveys. Subsequent station coordinates are estimated based on these reference coordinates. Generally, reference coordinates can be derived from the following sources:

- coordinates derived from a previous survey. These coordinates are usually based on a local plane coordinate system or national grid system, such as the Australian Map Grid (AMG) [National Mapping Council of Australia, 1972] and would require transformation to the WGS84 datum;
- coordinates determined using differential GPS with an accuracy of less than 5 m on the WGS84 datum;
- coordinates which are scaled from maps. According to r.18 of the *Survey Co-ordination (Surveys) Regulations* 1992 (Victoria), the accuracy of coordinates scaled from a 1:25000 topographic map should be better than 20 m on the AMG (the 1:25000 map series, usually, has complete State coverage); and
- coordinates determined using pseudorange point positioning with an accuracy of within 100 m on the WGS84 datum.

Remondi [1984, pp.225-228], using empirical tests, shows that errors in the reference coordinates propagate into baseline vectors as scale errors. *ibid.* [1984, p.226] states that, in general, an error of 1 m in the horizontal components relates to a scale error of approximately 0.1 ppm, whilst an error of 1 m in the height component relates to a scale error of less than 0.03 ppm. Using geometrical methods, Beutler *et al.* [1988, pp.37] report similar results. Talbot [1990] found that the effects of Selective Availability were propagated into baseline solutions through the degraded reference station coordinates. *ibid.* [1990], using simulation techniques, concur with the findings in Remondi [1984, pp.225-228]. Eckels [1987, pp.102-103] and Rizos [1997, p.259] liken the effects of errors in reference coordinates to those of ephemeris errors (*vide* equation (4.9)) and quote a scale error of 0.05 ppm for an error of 1 m in the reference coordinates.

Table 4.1 shows that reference coordinates derived from pseudorange point positioning can cause a baseline scale error which exceeds the manufacturer's specification for a real time survey system with an operating limit of 10 km. For real time kinematic survey systems, manufacturers often recommend that the accuracy of reference station coordinates must be within 10 m on the WGS84 datum (see for example Trimble Navigation Limited [1995, p.1-19]). Table 4.1 indicates that, for static survey, a 1:25000 map may not be an appropriate source for reference coordinates.

Source	Accuracy (m)	Scale error (ppm)	mm / 10 km	Real time kinematic[1]	Static (Dual frequency)[2]
				10 mm + 2 ppm	5 mm + 1 ppm
				(30 mm for 10 km)	(15 mm for 10 km)
Previous survey	< 0.1	0.01	0.1	✓	✓
Differential GPS	< 5	0.1	5	✓	✓
1:25000 Map	< 20	1	20	✓	✗
Point positioning	< 100	10	100	✗	✗

Note: [1] Trimble Navigation Limited [1994] and [2] Trimble Navigation Limited [1992]

Table 4.1. Relationship between the reference coordinate accuracy and scale error for a 10 km baseline.

The accuracy requirements for cadastral surveying are worse than 50 ppm, which means that a position error of 100 m can be tolerated. This might indicate that pseudorange point positioning would suffice. However, in view of all the accuracy degrading factors described in the previous sections, the effects of inaccurate reference coordinates should be avoided by the adoption of more accurate values. Further, manufacturers' accuracy specifications for the respective GPS survey systems should be considered, because scale errors introduced as a result of low accuracy reference coordinates may not satisfy the specifications (Table 4.1). Good estimates of reference coordinates can increase the reliability and efficiency of ambiguity resolution, particularly in real time kinematic surveys where short observation sessions are the norm. In his particular test, Talbot [1990, p.139] found that a 90 min observation session was inadequate to achieve baseline accuracy of 1 ppm using reference station coordinates which are accurate at the 10 m level.

4.8.13 Integer cycle ambiguity

As described in Section 4.6, the number of whole cycles between the satellite and the antenna is indeterminate on initial signal acquisition. This unknown number of whole cycles is an integer known as the *cycle ambiguity*, which has to be resolved in order to gain the full accuracy potential of carrier phase observations. An incorrect estimation of the integer ambiguity introduces a bias in the baseline.

Over the last 15 years, and for different applications, many ambiguity resolution techniques have been developed; a review and comparison is provided in Han and Rizos [1997]. Detailed discussions on the operational and performance aspects of the techniques can be found in Hofmann-Wellenhof *et al.* [1997, pp.214-249]. Generally, techniques differ according to the various adopted constraints, such as satellite geometry, short baseline and initial estimates of integer values [Han and Rizos, 1997, p.54].

The aim of all ambiguity resolution techniques is to determine the integer ambiguity correctly, reliably and efficiently. For kinematic applications, resolution time is also an important consideration. In principle, the ambiguity could be resolved with one epoch of data. Efficient and reliable resolution of integer ambiguity depends on the following factors:

- favourable satellite geometry;
- good estimate of the initial position;
- data with minimal biases, particularly from multipath and atmospheric effects; and
- an adequate amount of data.

Surveyors rely on the ambiguity resolution techniques employed in the processing software to provide the required solution. However, based on the foregoing discussion, the following operational techniques can be used to ensure that optimal results are obtained, particularly in real time kinematic applications:

- use dual frequency receivers;
- avoid high multipath environment by careful site selection;
- increase observation time when suspect conditions, such as high multipath environment, poor satellite geometry and increased solar activity, are encountered;
- force the system to reinitialise between occupations;
- reoccupy stations at a later time to ensure decorrelation of observing conditions, such as change in satellite geometry, satellites and environmental conditions; and
- when possible, verify solutions against independent results from previous surveys.

4.9 Summary

This chapter has discussed:

- the measurement models for deriving GPS relative positions or baseline vectors; and
- the factors which degrade the accuracy of the models.

The understanding of which is important for developing any scheme which would facilitate the traceability of GPS measurements.

Most of the accuracy degrading factors are either eliminated or significantly reduced in relative positioning through the use of differencing techniques. However, this is possible only when certain equipment, processing and operational strategies, which incorporate essential precautions, have been either adopted or applied. Table 4.2 provides a summary of the techniques that can be used to improve the accuracy of GPS measurements. Rizos [1997, p.277] presents a similar table which outlines the various options that can be used to manage GPS measurement biases and errors.

Accuracy degrading factors	Elimination or reduction techniques		
	Processing	Equipment	Operational strategies
Integrity anomalies	Not applicable	Not applicable	Integrity Monitoring System
Selective Availability	Differencing	Not applicable	Not applicable
Ephemeris (Orbit)	Differencing Precise ephemerides	Not applicable	Ensure baseline lengths are short Increase observation time to allow effects to be averaged
Satellite clock	Differencing	Not applicable	Integrity Monitoring System
Satellite geometry	Not applicable	Not applicable	Careful planning
Ionospheric delay	Differencing Ionospheric free observable	Dual frequency receivers	Avoid low elevation satellites Ensure baseline lengths are short Observe during low ionospheric activity
Tropospheric delay	Differencing Tropospheric delay models Meteorological observations (highly inadvisable)	Not applicable	Avoid low elevation satellites Ensure baseline lengths are short Avoid extreme height differences
Multipath effects	Not applicable	Antenna with ground plane Choke ring antenna Receiver with multipath mitigation techniques	Avoid low elevation satellites Increase observation time to allow effects to be averaged Careful site selection
Antenna biases	Incorporate manufacturers' or scientifically determined parameters	Antenna selection	Identical antennas orientated in the same direction Ensure baseline lengths are short (< 100 km)
Receiver clock	Differencing	Not applicable	Not applicable
Measurement noise	Not applicable	Appropriate selection	Not applicable
Cycle slips	Detection and repair	Not applicable	Careful site selection
Reference coordinates	Not applicable	Not applicable	Use coordinates with accuracy of better than 100 m
Integer cycle ambiguity	Ambiguity resolution techniques in processing software	All the above	All the above Adopt independent verification strategies

Table 4.2. Accuracy degrading factors and their elimination or reduction techniques.

Following a review of the literature, magnitudes of residual effects of ionospheric and tropospheric delays, antenna biases and measurement noise have been inferred. *Rules of thumb*, which are pessimistic accuracy indicators, for ephemeris errors and reference coordinate accuracy have been discussed. A combined effect of the factors has not been proposed due to their complex behaviour as a group. An indication of the expected accuracy from a GPS survey system can be obtained from a cross-section of the manufacturers' specifications (Table 4.3). Often, these specifications are independently corroborated in tests conducted by the survey and academic communities.

Observation technique	Accuracy
Static (Single frequency)	1cm ± 2ppm of baseline length (<20km)
Static (Dual frequency)	5mm ± 1ppm of baseline length
Fast-Static (Single/Dual frequency)	1cm ± 1ppm of baseline length
Kinematic (Single/Dual frequency)	1cm ± 1ppm of baseline length
Real Time Kinematic (Single/Dual frequency)	1cm ± 2ppm of baseline length

Table 4.3. GPS baseline accuracies compiled from Trimble Navigation Limited [1992; 1994], Leica [1996b] and Allen Osborne Associates [1998].

This chapter has highlighted, *inter alia*, that GPS extends beyond the user segment. As discussed in Section 4.8.1, the space and control segments are not infallible. Integrity lapses in these segments will continue to occur and their detection and prevention will continue to be difficult. Many of the anomalies are quite rare and obscure, and their effects on the user segment are not always well understood. Further, other anomalies that have not been anticipated by the systems designers may yet occur. Therefore, implementing verification measures for the user segment only, whilst ignoring the control and space segments, is a highly risky proposition. Hence, this thesis contends that an integrity monitoring system should be an important part of the overall verification scheme for establishing legal traceability of measurements. The monitoring system should be the first level in the hierarchy of a verification scheme because it verifies the performance of GPS signals and the navigation message prior to their reaching the user segment. Implementing an integrity monitoring system will ensure that the integrity of GPS can be *independently* verified in Australia and should obviate the need for dependence on an unreliable external source.

This chapter has discussed the inappropriateness of *calibrating GPS* in the traditional sense, i.e. periodic calibration on approved test sites. The main reasons are:

- In contrast to the operation of conventional survey instruments, the Global Positioning System is not controlled by the user.
- Most of the accuracy degrading factors vary temporally, spatially and geographically, and are dependent on the length of observation sessions and baseline lengths.

This realisation forms the basis for the departure from the current perception of calibration. GPS measurements must be verified and, hence, made traceable to their standards of measurements *during* a survey and not pre- or post-survey. This approach would lead to the realisation of the objective of legal traceability as defined in Section 2.2.3. The verification schemes need not detect and identify individual errors; however, they must be able to indicate whether a GPS survey has complied with the required accuracy specifications for achieving traceability under the current legislation. Such a scheme, which incorporates most of the elements discussed in this chapter, is developed and presented in Chapter 6.

5. METHODS FOR VERIFYING THE GPS MEASUREMENT SYSTEM

5.1 Introduction

In current Australian measurement and cadastral survey systems, a physical measurement attains legal force consequent on clear demonstration that the measurement has been compared with a national standard of measurement. The *National Measurement Act 1960* (Cwlth) provides the legislative framework for establishing legal traceability of measurements (*vide* Chapter 2); States and Territories may enact legislation with regard to the verification of means of measurements (*vide* Chapter 3). The requirements must be consistent with s.10 of the National Measurement Act, which prescribes the means for attaining legally traceable measurements. The survey legislation stipulates that surveyors *must* use calibrated and well maintained survey instruments, and adopt sound verification methods, when undertaking a measurement process; it also specifies necessary measurement practices and appropriate accuracy requirements. Through this *holistic* approach, the quality of measurements can be assured, and legal traceability of measurements can be achieved.

One of the requirements for achieving legal traceability, as stipulated in s.10 of the National Measurement Act, is the availability of methods or means for relating measurements to the appropriate standards of measurement (*vide* Section 2.2.3). This chapter provides a review of some of the available methods, applicable to surveying, for testing and verifying the GPS measurement technology; a comparative analysis of their characteristics is also provided. None of the methods reviewed verifies GPS as a whole, namely the control, space and user segments (*vide* Section 4.4); most are designed to test either individual segments or a combination thereof. Currently, none of the methods is being used as a means for achieving legal traceability of GPS measurements, although most are either being used, or recommended to be used, for quality control purposes. Most are based on accepted survey concepts.

The review and comparative analysis provide an insight into those approaches with the potential to be appropriate for developing a scheme for achieving legally traceable GPS measurements in Australia. Much of the discussion in this chapter has been published in Boey and Hill [1995], Boey [1997] and Boey *et al.* [1997].

5.2 Review criteria

The main questions adopted for the review are:

- Which GPS segment, i.e. control, space or user, is verified?
- Which part of the user segment (*vide* Section 4.4), i.e. user, equipment, procedures and processing, is tested?
- What GPS measurement, i.e. length or relative position, is being verified in order to establish traceability?
- What are the operational issues and the basic infrastructure associated with each method?

The first, second and third criteria are the requirements described in Chapters 2, 3 and 4. Verification methods proposed for achieving legal traceability of measurement must satisfy these three requirements. The fourth criterion addresses pragmatic issues such as resource management, which includes personnel and equipment, and *ease of use*, i.e. complexity of a method. The ensuing treatment of these issues, which are important for the successful implementation of any verification method and which are not discussed elsewhere in the literature, are general in nature, and are based on past and existing practice and experience. Since the relevant literature does not address significant issues pertaining to implementation and maintenance costs for the respective methods, the additional costs of each method are indicated where possible. These added costs are derived using simple and basic assumptions (Appendix); these shown in Table 5.2 in Section 5.10 are used to order the verification methods in a hierarchy, and are not intended to constitute definitive implementation costs.

5.3 Surveyors' competency

Discussions pertaining to test or verification methods often neglect to note one very significant element of the measuring system: the human factor. Chapter 3 has discussed the cadastral survey system and its requirements for ensuring that surveyors are competent to perform cadastral surveys. Cadastral surveyors are required to possess certain qualifications which reflect their competency in the areas of surveying, cadastral law and measurement technology, such requirements being necessary to preserve the integrity of the cadastre. By law, cadastral surveyors owe a duty of care to their clients and the general public, who may rely and/or act upon the information or advice provided. The current *indicators* or *measures* of a surveyor's competency are:

- Licensing or registration of cadastral surveyors.
- Continuing Professional Development (CPD).

- Accreditation of GPS surveyors or companies.
- Acquired GPS knowledge.
- Field audits or inspection and survey plan examination.

The last is one of the best indicators of a surveyor's knowledge and skills, since checks and verification are achieved by independent means.

The overall model for verifying GPS measurements must include some means for the assessment of a surveyor's competency, particularly in the area of measurement science. Surveyors are required to demonstrate that they have a basic understanding of, and are sufficiently proficient in, the application of the technology, in which professional knowledge and practical skills are important for its proper application and operation, and the attainment of appropriate high quality results.

Current indicators apply directly to the surveyor responsible for the survey, i.e. the surveyor who attests to the correctness of the results and whose name is uniquely and forever associated with the survey. The requirements for the indicators, to which costs are correlated, vary between jurisdictions; where the indicators are mandatory, the requirements may not necessarily be as onerous as for those jurisdictions in which the indicators are voluntary.

5.4 Best practice

Best practice for cadastral surveying is embodied in survey legislation and prescribed in guidelines and specifications, for example the *Survey Practice Handbook – Victoria*, *Standards and practices for control surveys (SP1)* and *Best Practice guidelines use of the Global Positioning System (GPS) for surveying applications*. These have been introduced so as to ensure that surveyors are able to achieve the required standards of accuracy stipulated in the legislation. So far, the guidelines and specifications have been technology dependent (*vide* Section 3.3). However, certain guidelines, such as the use of properly maintained survey equipment (for example survey tapes, tripods and tribrachs), correct set-up and measurement of instrument heights, obtaining redundant and independent measurements, proper recording of field data, and performing network closures are generally applicable in accepted professional survey practice. Since most of the requirements, particularly those stipulated in legislation, are mandatory, neither the surveyor nor the Institutions respectively are required to comply with or develop new documentary specifications. Further, additional costs should not be incurred.

5.5 Integrity monitoring systems

> *The GPS system is maintained by the US Department of Defense and variations in the GPS signal are not always notified in advance. By continuously receiving and examining GPS data from a number of sites, it is possible to detect any deliberate or accidental changes in the GPS signal. Failure to account for these changes may cause considerable error in calculated positions.*
>
> [Commonwealth of Australia, 1995b].

Section 4.8.1 has described some of the anomalies, occurring in the control and space segments, which cause degraded navigation message and signals. Section 4.8.1.1 established that the anomalies are unlikely to affect GPS baseline solutions determined using relative positioning, because spatially correlated errors are either eliminated or significantly reduced through differencing. However, residual ephemeris errors do persist even after differencing, particularly for long baselines. In addition, rare and obscure anomalies occurring in the control and space segments, such as those of the PRN 19 type, have on occasion eluded all three GPS segments and, potentially, could have caused dire consequences in the case of aviation navigation. Hence, an Australian integrity monitoring system is required to monitor the control and space segments, as well as to meet the need for some degree of independence. Due to the uncertainties that exist within the control and space segments, such a system should be implemented as part of a verification scheme for establishing the legal traceability of GPS measurements. This section describes current integrity monitoring systems, particularly those implemented for aviation navigation, with the objective of providing an insight into potential measures that may be applicable for the development of an integrity monitoring system for Australia (*vide* Chapter 6).

An integrity monitoring system must be able to monitor GPS so as to ensure that it is supplying the correct information. In the event of anomalies and malfunctions, which degrade the accuracy of the GPS solutions, but are not indicated as such in the navigation message, the monitoring system must be capable of warning the users that such event(s) are occurring.

Most of the existing integrity monitoring systems have been developed for the purposes of precision aviation approach navigation. The civil aviation authorities recognised that GPS does not have the capability to notify users of signal malfunctions in a timely manner. According to Braff *et al.* [1996, p.336], *For some types of signal malfunctions, it can take on the order of an hour for notification; whereas, the integrity monitoring response times required for flight operations are in the order of seconds.* Therefore, additional means for providing timely warnings regarding the integrity of GPS are necessary.

The capability of integrity monitoring systems is dependent on the application; some are designed only for fault detection, while others, such as those used in the Wide Area Augmentation System (WAAS) [Enge and Van Dierendonck, 1996], have both detection and correction capabilities. Generally, integrity monitoring systems can be classified as being either *internal* or *external* [Brown, 1990, p.45]. Those in the former group attempt to provide integrity by using the information available inside the receiver, such as redundant measurements or receiver clock information, for example Receiver Autonomous Integrity Monitoring (RAIM). Those in the latter group use a network of permanent ground monitoring stations with precisely known locations to verify GPS signals, either in real time or post event. The information relating to the quality or health of the signals is broadcast to users using various communication links. A third approach is the integration of GPS with other sensors, such as inertial navigation systems (INS), Loran-C and GLONASS. Readers are referred to Parkinson and Spilker (eds) [1996] for detailed treatment on the subject of integrated systems. All the aforementioned methods may often be combined, to provide a near fail-safe combination, particularly in precision aviation approach navigation.

The Receiver Autonomous Integrity Monitoring (RAIM) method uses an over-determined solution to perform self-consistency verification of the measurements; it requires at least five pseudorange measurements to five satellites with good geometry to allow the detection of position errors. The most popular RAIM detection scheme is the *snapshot* approach. Five RAIM methods [Brown, 1996, pp.145-152] are associated with the snapshot detection scheme, namely:

- *the range comparison method*;
- *the least square residuals method*;
- *the parity method*;
- *maximum separation of solutions*; and
- *constant-detection-rate/variable-protection-level method.*

The underlying principle for the above methods involves forming linear combinations of the observation equations to determine a solution, which is then used as a basis for comparison or prediction for other solutions obtained from a combination of equations formed using redundant measurements. Generally, the solutions are compared and residuals are determined. Small residuals would indicate that the measurements are quite consistent, while large residuals would indicate the presence of errant satellites. *ibid.* [1996] provides a detailed account of the aforementioned detection schemes. The concept of RAIM or its equivalent is not available in commercial survey grade receivers or baseline processors. Most commercial baseline processors, given adequate redundant measurements, can detect and exclude poor measurements, but not suspect satellites.

The concept of using a network of precisely known permanent ground monitoring stations to verify the integrity of GPS can be described by reviewing the WAAS. Braff *et al.* [1996, p.353-354] give an account of the evolution of the Wide Area Differential GPS to WAAS. The WAAS, according to Enge and Van Dierendonck [1996, p.117], *is a safety-critical system consisting of a signal-in-space and a ground network to support enroute through precision approach air navigation. It is designed to augment GPS so that it can be used as the primary navigation sensor. The WAAS augments GPS with the following three services: a ranging function, which improves availability and reliability; differential GPS corrections, which improves accuracy; and integrity monitoring, which improves safety.* Of the three services described, the one that is of relevance to this thesis is *integrity monitoring.* Figure 5.1 illustrates the general concept of WAAS, whose basic configuration comprises the following elements:

- a network of ground monitoring stations;
- central processing facilities;
- communication links and broadcast system;
- GPS and geostationary satellites; and
- the user.

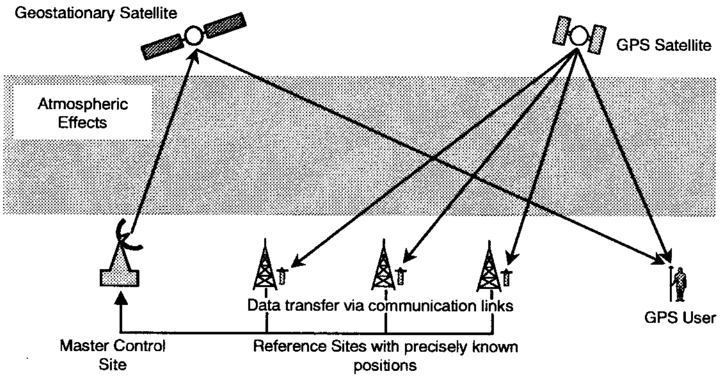


Figure 5.1. The concept of Wide Area Augmentation System [adapted from Enge and Van Dierendonck, 1996, p.118].

WAAS comprises a network of ground monitor stations with precisely known locations. Each station is equipped with high precision clocks and GPS receivers capable of tracking all satellites within the field of view. The ground monitor stations are divided into two segments: Reference Sites and Master Sites. The Reference Sites are responsible for collecting pseudorange measurements from all GPS satellites in view and signals from the geostationary satellites. The data is sent via any convenient communication link, such as telephone, radio or satellite, to the Master Sites for processing to determine the integrity, differential corrections, residual errors, and ionospheric delay information for each satellite. This information is broadcast as a WAAS message to users via geostationary satellites.

In the WAAS, the integrity function is *used to warn the user not to use GPS for navigation, or it could warn the user not to use a specific GPS satellite* [Enge and Van Dierendonck, 1996, p.128]. Such warnings are issued when the *GPS satellites are behaving incorrectly* [*ibid.*, 1996, p.118] and when the ground network cannot determine the differential corrections with confidence, due to various factors, such as degraded satellite ephemeris or poor signals. The warnings are applicable only to those satellites within the coverage area. Typically, the integrity of GPS is appraised based on the residuals determined by comparing the estimated pseudoranges to the measured pseudoranges. Residuals lying within the specified tolerance would indicate that the satellites are healthy, while large or rapidly varying residuals would indicate otherwise.

In summary, the preceding paragraphs have described some of the techniques that are available for monitoring the integrity of GPS, particularly the space and control segments. Most of these methods have been developed primarily for aviation navigation purposes. However, some elements of the methods could be used for the formulation of an Australian integrity monitoring system. Adopting these elements, Section 6.6 develops a model of an integrity monitoring system as part of a scheme for establishing legally traceable GPS measurements which would require a once-only establishment cost. Data archiving and dissemination would incur an additional cost, which is however expected to be minimal, because software for automating the process may be purchased commercially.

5.6 Hardware and Software Tests

As mentioned in Section 3.3.4.2, surveyors must use calibrated and routinely maintained equipment. This section reviews some of the methods available for testing three elements within the GPS user segment, namely the receiver, antenna and processing software. These methods play an integral role in the whole verification scheme and provide a means for evaluating the performance of equipment and processing software. Hardware tests are those conducted for a particular model and make of receiver and antenna, while software tests are those conducted for a particular type and version of GPS processing software. The tests can be divided into two categories: tests that can be conducted by the user, and tests that are performed by government, academic or private agencies.

5.6.1 Receiver tests

The nature of receiver measurement noise has been described Section 4.8.10. Recently, the U.S *Institute of Navigation* [1997] published a set of recommendations for testing receivers. Since, the tests are designed for evaluating the performance of receivers used for navigation purposes, they are not directly relevant to this thesis.

Measurement noise, due to its random nature, can only be modelled stochastically; however, a surveyor can determine its magnitude and ensure that it is of a tolerable level. Several authors [Boey and Hill, 1995, p.108; Boey *et al.*, 1996b; Langley, 1996a, p.156; Reilly, 1996, p.22; Hofmann-Wellenhof *et al.*, 1997, p.164; ICSM, 1997c, p.4; and Rizos, 1997, p.172] have suggested that a *zero baseline test* can be used for determining receiver measurement noise. The test involves connecting two or more receivers to the same antenna (Figure 5.2), an antenna splitter being used to supply the same antenna signal to the receivers. The baseline vector computed from such a test should be free of common errors, such as satellite and propagation related errors, which are eliminated in the double differenced solutions. The baseline vector components should be zero; therefore, any residual could be attributed mainly to measurement noise and any residual biases in the receiver tracking scheme. Wells *et al.* [1994] and Boey *et al.* [1996b] describe zero baseline solutions for the C/A code pseudorange and the L1 and L2 carrier phase of the Ashtech Z-12 and Leica SR9500 receivers respectively. Rocken *et al.* [1995, p.1-2], presenting extensive zero baseline test results for several commercially available receivers, found that the measurement precision for both L1 and L2 carriers is *sub-millimetre.*

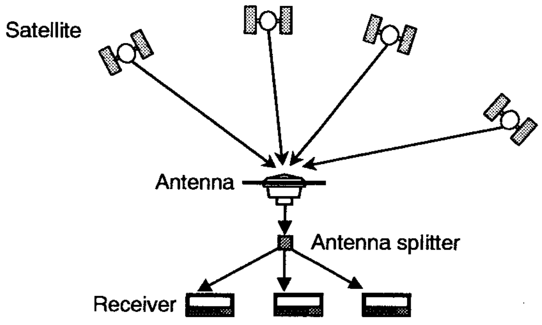


Figure 5.2. Zero baseline test.

Essentially, the test results provide an indication of the measurement noise performance in a double differenced solution for a vector between two receivers. The test *does not* indicate in any manner the noise performance of a receiver. So as to isolate and identify the noise performance for a receiver in a zero baseline test, receivers could be tested using a series of combinations. Gourevitch [1996] describes a technique that can be used for determining the noise performance of a receiver.

The zero baseline test is relatively simple to perform and does not require special software, ground truth or controlled environment. The only extra piece of equipment required is an antenna splitter, the cost of which is minimal compared to the costs of the set of equipment. The time required by the surveyor to conduct the test results in an additional cost. The test enables receiver performance to be monitored over time, thus, establishing a performance history for the receivers. Regular verification of receiver tracking performance should be part of an instrument's routine use.

5.6.2 Antenna tests

The characteristics of antenna biases have been described in Section 4.8.9. The phase centre pattern and its location can be determined using several procedures, often categorised as *laboratory* and *field* tests. Laboratory tests are carried out in an anechoic chamber (a room free of internal reflections, i.e. multipath (*vide* Section 4.8.8)). Field tests are based on short baseline estimation techniques. Laboratory tests produce *absolute* phase patterns, while field tests provide *relative* variations. Sims [1985], Schupler and Clark [1991], Schupler *et al.* [1994] and Schupler *et al.* [1995] discuss experiments conducted in anechoic chambers. Examples of field tests can be found in Wiget *et al.* [1990, p.845], Rothacher *et al.* [1995], Wübbena *et al.* [1997] and Mader [1998].

Most of the field tests, for example Rothacher *et al.* [1995], Rocken *et al.* [1995] and Mader [1998], are performed on very stable pillars. The baseline vectors between the pillars are known precisely and are typically less than 20 m, so as to avoid atmospheric errors. The field tests are sometimes known as *antenna rotation tests*, because one of the antennas, known as the reference, is held fixed, while the others are rotated incrementally. Usually, the test takes a whole day to perform.

One of the main problems associated with field tests is the influence of multipath (*vide* Section 4.8.8). Many authors, including Evans [1986] and Georgiadou and Kleusberg [1988a], have shown that the effects of multipath, for the same site and repeated GPS satellite geometry, are highly repeatable after one mean sidereal day. This characteristic of multipath is often included in some of the field tests. In order to reduce the effects of multipath, an antenna field test, as proposed by Wübbena *et al.* [1997], requires at least two days to perform; typically, a short baselines to minimise atmospheric effects. The first day serves as a reference during which two antennas would remain fixed. During the second day one of the antennas would be rotated and tilted in order to experience different azimuths and elevations, while the other receiver, acting as the reference, would remain fixed. Baseline solutions from both days are then differenced to reduce multipath effects. The remaining errors in the solutions are considered to be due to antenna phase variation and other random measurement errors, such as measurement noise (*vide* Section 4.8.10).

Another method used to describe the characteristics of antenna phase centre is *modelling*. Geiger [1988] modelled the error functions for a variety of antenna types. The functions can be incorporated in the observation equations together with other modelled errors, such as the tropospheric mapping functions.

The foregoing paragraphs have presented several methods for determining the characteristics of antenna phase centres. Generally, most authors, including Seeber [1993, p.311], Rothacher *et al.* [1995, p.333] and Rocken *et al.* [1995, p.7-3], agree that results obtained from laboratory tests are inconsistent with those from field tests. Among some of the main reasons for the inconsistency and unreliability are:

- the characteristics of antenna phase centres differ within and between the various antenna types;
- the effects of multipath in the field tests have not been fully characterised and therefore cannot be properly considered in the tests [Wübbena *et al.*, 1997, p.254; and Schupler *et al.*, 1994, p.294];
- there are uncertainties in the tropospheric mapping functions (*vide* Section 4.8.7) which mainly affect the vertical component of the phase centre variations. This is evidenced by the symmetric nature of the phase patterns in the azimuth (as evidenced in the *wireframes* or *sombrero plots* presented in Schupler *et al.* [1994] and Rocken *et al.* [1995] respectively). Hence, Schupler *et al.* [1994, p.292] suggest that some antenna phase centres could be modelled simply as functions of zenith or elevation angle. This was later confirmed in Schupler *et al.* [1995]. In order to precisely estimate the vertical component of the phase patterns, better estimates of tropospheric mapping functions (which are themselves, in the main, approximations [Mendes and Langley, 1994]) would be required.

However, as mentioned in Section 4.8.9, many authors who have performed extensive laboratory and field experiments agree that the magnitude of phase centre variations for geodetic quality antennas is at the *sub-centimetre* level. Also, the effects of phase variations in antennas of the same make and model are *insignificant* for geodetic measurements.

5.6.3 Software tests

GPS processing software for surveying comprises two fundamental components, namely a baseline processor and network computations for adjustments and datum transformation. Typically, receiver manufacturer-supplied processing software, which is compatible only with the particular type of receiver, differs from manufacturer to manufacturer. Alternatives to manufacturer-supplied software, receiver-independent and third-party processing software are, however, commercially available. The need to validate GPS processing software is highlighted by a test conducted by Sluiter *et al.* [1994], which involved collecting GPS data with four types of commercial geodetic grade receivers on two known baselines; a short baseline of 10 km and a long baseline of 100 km. The data was processed using manufacturer-supplied software, as well as converted to the standard Receiver INdependent EXchange (RINEX) format [Gurtner and Mader, 1990] and processed using receiver-independent software. Solutions, determined using manufacturer-supplied software, for both long and short baselines are of comparable accuracy. However, solutions determined using the receiver-independent software, albeit of comparable accuracy, differ from those determined using manufacturer-supplied software, particularly for long baselines. The comparable accuracy shown within the respective set of solutions suggests that the data collected is of similar quality. Following the analysis of the test results, Sluiter *et al.* [1994, p.340] state that: *When comparing results, it soon became apparent that not only the amount and quality of the data recorded by each receiver cause differences in the results, but to a very large extent, also the software to compute baselines. ibid.* [1994] did not comment on the implications of the test; however, the following could be surmised:

- GPS data collected using commercial receivers should be processed with the manufacturer-supplied software; and
- both receiver-independent and manufacturer-supplied software should be used with caution.

GPS processing software contains many idiosyncrasies due to the abundance and variety of available processing philosophies (*vide* Section 4.8.13). There is no documented method for testing processing software; however, the most commonly known means is through the use of sample or test data. Typically, the test data would comprise data collected for a network of known points, such as that established by the U.S Federal Geodetic Control Subcommittee (FGCS) set-up (*vide* Section 5.8). Data from previous surveys, which have known uncertainties, can also be used as test data. The zero baseline test (*vide* Section 5.6.1) could provide a very limited means for testing the baseline processor. However, the method cannot be used to test the network computation features and baselines between two antennas.

Test data should be provided in receiver-independent format and be able, at least, to provide the following indicators:

- the success of cycle slip repair;
- the quality of the different observables, such as L1, L2 and ionospheric free solutions;
- the accuracy of the atmospheric models; and
- the quality of the final solution following network computations.

The expected outcomes of the test should be supplied with the data, so that users may determine whether the software is providing the required solutions. In Australia, an approved set of test data could be supplied by those authorities or agencies responsible for the proper conduct of surveying and the verification of GPS measurements. The additional cost to the surveyor is associated with the time required to conduct the test as well as the lost opportunity to perform income generating work.

5.6.4 General evaluation and certification tests

Several organisations and institutions around the world conduct independent *hardware* and *software* tests. Usually, the tests, such as those by University NAVSTAR Consortium (UNAVCO), U.S *National Geodetic Survey* (NGS) and *Australian Surveying and Land Information Group* (AUSLIG) are performed for scientific purposes and, therefore, are performed to the highest standards, while others, such as those by the FGCS, may be performed to evaluate the performance of GPS surveying systems. Generally, these organisations have the resources and infrastructure for conducting extensive and rigorous investigative tests, as a result of which the equipment or software may be given an approval certification. Most of the tests are performed in laboratories and sites which, typically, are beyond the means of the average user. Apart from lack of means and expertise, issues of independence and credibility are also pertinent considerations. The international and national institutions could be recognised or accredited as *reference sites* by the responsible Australian authority for having the capability for performing high quality investigative tests. Certification or seals of approval and test results published by these institutions could be recognised as adequate proof that a particular hardware, software or operational procedure has the ability to comply with Australian standards. This approach would obviate the need, on the part of the surveyor, to prove the performance capability of the hardware and software.

An example of a government initiative is the Commercial Receiver Test Program (CRTP) [GPS World Newsletter, 1994] implemented in the United States. In 1994, the NAVSTAR GPS Joint Program Office and several U.S Department of Defense (DoD) laboratories developed the CRTP as a user-pays service, which included rigorous testing and evaluation of commercial GPS receivers and systems. The program was intended for receiver manufacturers and was received enthusiastically by the manufacturers, since it provided an opportunity for independent reviews, particularly for those companies with limited testing and evaluation facilities. The opportunity for technology transfer may also be realised through the program; another benefit being the award of a *seal of certification* following satisfactory compliance with the operational performance standards specified by the receiver manufacturer. The *seal* was intended to be used by the manufacturers for promotional and commercial purposes. Although the fate of the program is unknown since the article by *ibid.* [1994], its concepts and intentions are worth considering for any future implementation of a similar initiative in Australia.

5.6.5 Summary

This section has described some of the methods available to the user for testing and evaluating receivers, antennas and processing software. Some of the methods, such as the zero baseline test and test data for validating software, are simple and can be performed by the user. The costs associated with the tests are minimal. An antenna splitter for the zero baseline test may be hired, and test data may be obtained through the internet. Regular testing is recommended as part of a maintenance program since it provides for a historical performance record for the equipment and software.

Evaluation and certification tests provided by government, private and academic institutions have been described. In general, the tests performed by these institutions are extensive and rigorous in nature; users would probably be required to pay for such services.

5.7 EDM Calibration Baselines

Alexander [1992; 1995] and Reilly [1996] have proposed that existing EDM calibration baselines could be used for verifying *GPS derived lengths*. This suggestion is not novel since early tests for evaluating GPS receiver performance were conducted using lengths of baselines determined from EDM instruments as a basis of comparison [Brunner *et al.*, 1986]. According to Alexander [1995], GPS derived lengths can be traced to the national standard of length by comparing them with the known lengths determined for the EDM calibration baselines. This verification process, which, essentially, is an adaptation of the EDM calibration procedures, is outlined in Alexander [1995]. Neither *ibid.* [1995] nor Reilly [1996] provided a rationale for their propositions.

Some of the arguments that could be presented to support the use of EDM calibration baselines for verifying GPS derived lengths are:

- during verification, the option does provide a very limited means for achieving traceability of lengths;
- during verification, the option does provide limited verification for the control and space segments, because achieving a tolerable agreement between measured and known quantities, which have been independently determined, implies that the measurement technology has performed normally and the measurement process has been conducted correctly;
- the calibration infrastructure exists, but would require modification to include baselines longer than 1.5 km (as discussed later, this is not a viable option); and
- the verification procedures would be simple and relatively straightforward, due to the surveyor's familiarity with the current EDM calibration process.

This section presents an overview of the current EDM calibration scheme and *refutes* the proposition that EDM calibration baselines could be used to achieve legally traceable GPS derived lengths.

Currently, in Australia, EDM calibration baselines are used for comparing electronic distance measurements as determined by EDM instruments with the national standards of measurement, namely frequency and length (see Figure 2.9 for the traceability chart). Further discussions on the calibration of EDM instruments and the traceability of electronic distance measurements can be found in Rüeger [1980; 1985; and 1991]. A calibration facility comprises a number of stable concrete pillars set out in a linear array. For certification purposes, the inter-pillar distances are measured and monitored regularly, using instruments of higher order of precision than those of the instruments being calibrated. Most of the existing EDM calibration baselines have been physically and geometrically designed for short range (less than 1500m) EDM instruments. According to *ibid.* [1991, p.209], long range calibration baselines will not be established due to the advent of GPS. The present survey legislation requires EDM instruments to be calibrated at regular intervals (*vide* Section 3.3.4.2). *ibid.* [1990, pp.186-221] provides a comprehensive treatise on the subject of baseline design and the calibration process.

Alexander [1995, p.1] proposes that the minimum uncertainty associated with the verification of GPS derived lengths using the certified EDM calibration baselines should be ± (4.0 mm + 20 ppm) at the 95% confidence interval, but *ibid.* [1995] does not provide a derivation of this value. Currently, calibration baselines are certified with an uncertainty of ± (1.5 mm + 20 ppm) at the 95% confidence interval [*ibid.*, 1995, p.1]. According to Rizos [1997, p.96], independent empirical tests, using the static GPS technique to determine a range of baseline lengths, have shown that the uncertainty of test results is approximately ± (3 mm + 1 ppm) at the 67% confidence interval. Manufacturers of GPS equipment, typically, quote an accuracy specification of ± (5 mm + 1 ppm) at the 67% confidence interval for results obtained in static surveys (*vide* Section 4.9). To determine the feasibility of the proposal by Alexander [1995], the accuracies of a range of baseline lengths have been calculated using the aforementioned specifications (Table 5.1). The value proposed by *ibid.* [1995] may be considered as too stringent, particularly for lengths shorter than 500 m (shaded columns in Table 5.1). This failure is expected, since relative tolerances have been shown to be too restrictive for short lines (*vide* Section 3.3.4.4). The uncertainty values shown in Table 5.1 are determined at the 95% confidence interval by assuming a normal distribution for the errors.

Lengths (m)	Proposed	Empirical tests	Manufacturer
	± (4 mm + 20 ppm)	± (3 mm + 1 ppm)	± (5 mm + 1 ppm)
1	4	6	10
10	4	6	10
100	6	6	10
200	8	6	10
300	10	6	10
400	12	7	11
500	14	7	11
1000	24	8	12
5000	104	16	20

Table 5.1. The uncertainties of a range of lengths determined using GPS static surveys.

Section 4.3 has described the fundamental differences between EDM and GPS. Several shortcomings are associated with the use of EDM calibration baselines for verifying GPS derived lengths. Most of these are attributed to the temporal, spatial and geographical nature of the GPS baseline errors (*vide* Section 4.8). The precision of a GPS baseline is highly dependent on the length of the observation period, baseline lengths and the geometrical strength of the satellite configuration during the observation sessions. Most importantly, unlike EDM instruments, two of the major components of GPS, namely the space and control segments, are beyond the control of the user. The combination of all these factors implies that it is almost impossible to replicate the conditions of the verification process during actual surveys. In addition, the requirement to calibrate at regular intervals presumes that during the intervening period, the measurement system will operate in a reliable and consistent manner. In the case of GPS, such a presumption is untenable, due to the nature of GPS errors and the system's dependencies on observation periods and satellite configuration (refer to Section 4.8.1 for discussions on GPS integrity lapses). For the above reasons, the NSC may not be able to approve the proposed verification method, unless the measurement uncertainties determined during verification can be proven to be representative of those obtained during actual survey conditions.

The proposed verification process described by Alexander [1995] is an adaptation of the EDM calibration procedures. The operational and data processing procedures are not necessarily the same as those that would be typically employed in GPS surveys, such as static, rapid static and kinematic techniques. Both the precision and accuracy of GPS solutions are dependent on the procedures employed, as well as on the processing software adopted for the survey. The paper by Sluiter *et al.* [1994] has highlighted the need to test the processing software (*vide* Section 5.6.3). That investigation also demonstrated that on short baselines, such as those of EDM calibration baselines, most processing software would yield similar results; however, differences in the results were realised for long baselines. This indicates that verifying GPS derived lengths using EDM calibration baselines could confirm that, under certain conditions and depending on the type of procedures used, the technology is able to determine lengths traceable to the national standard. However, this becomes less valid if the technology is to be used for purposes beyond the bounds of the proposed verification process, as a significant degree of extrapolation of the capabilities of GPS would be required.

The final argument against the use of EDM calibration baselines concerns the one dimensional nature of the approach. A GPS baseline vector has two components: magnitude and direction; verifying one of the components, namely length, does not ensure the accuracy of the vector. The direction of a vector is an important consideration, particularly in network computations [Morgan *et al.*, 1986, p.4]. The final solutions generally of interest to surveyors are those determined from network computations. From a practical perspective, it is most unlikely that GPS will be used for determining length only. Verification methods should be developed and aimed at ensuring the overall accuracy of the vector.

In summary, the EDM calibration baseline option *does not* provide a long term and rigorous solution, for the following reasons:

- it cannot fully account for the temporal, spatial and geographical nature of GPS baseline errors;
- it provides very limited verification scope, due to the improbability of replicating actual survey conditions;
- its proposed operational and data processing procedures are different from those typically employed in GPS surveys;
- it is one dimensional in nature, since it does not attempt to verify the direction component of the baseline vector; and
- it does not verify the GPS control and space segments during an actual survey.

Since the infrastructure currently exists, establishment cost would be minimal; however, the costs for carrying out the verification would be necessary.

Stewart *et al.* [1998] present a variation of the EDM calibration baseline concept by incorporating EDM calibration baselines into a first order control network. The authors contend that since the EDM calibration baselines currently provide the means for traceability to the national standard of length, such should also be possible for GPS derived lengths, upon verification by means of the network of baselines [*ibid.*, 1998, p.438]. Essentially, this approach is similar to the *test network* concept which is discussed in Section 5.8.

5.8 Test Network

The concept of using a network of baselines especially established for testing the performance of GPS surveying systems is based on the U.S Federal Geodetic Control Subcommittee or FGCS (formerly known as the Federal Geodetic Control Committee or FGCC). The FGCS established a reliable framework of first-order geodetic control stations, which provides manufacturers of GPS surveying systems with an opportunity to test and verify their performance. A GPS surveying system comprises the instrumentation, hardware, software, and procedures. The baselines in the network vary in length from less than 1 km to longer than 100 km (Figure 5.3). The network was initially surveyed using high precision conventional terrestrial survey methods and has since been re-surveyed many times using high accuracy GPS methods. The results of all the surveys are collated and used to form the basis of comparison for the analysis and evaluation of test results. Hothem [1990] reports that, generally, an agreement of ±(10 mm + 1 ppm) can be expected.

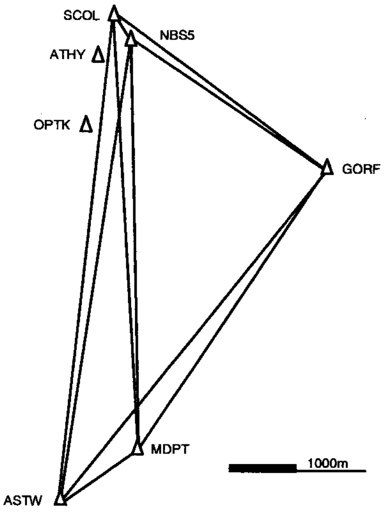


Figure 5.3. A typical FGCS test network [from Talbot, 1992, p.3].

All aspects of the test, including data collection and computation of results, are performed by the manufacturer's staff. Normally, the entire test is completed in approximately four to five days; it involves no small logistical effort, due to the separation of the stations and the rigour of the test requirements. One of the objectives of the exercise is to conduct the test in an environment that would represent *actual working conditions*. At the end of each day, GPS observations are processed using broadcast ephemerides. The results are evaluated in terms of Cartesian coordinate differences (dX, dY, dZ), baseline lengths, ellipsoidal height differences, and azimuth. The basis for the evaluation includes: repeatability of baseline measurements, loop closures, minimally constrained 3-D least squares adjustments and agreement with terrestrial and past GPS results. Upon confirmation by the FGCS that the test results are satisfactory, manufacturers are issued with a compliance report and can then use the fact that their products have been successfully *FGCS TESTED* as a promotional tool. Ayers and Yau [1995] and Talbot [1992] describe, from a manufacturer's perspective, the conduct of the test and the analysis of the test results. Information relating to the network set-up, test procedures and evaluation of results can be found in FGCC [1986; and 1988] and Rizos [1997, pp.173-174].

The FGCS approach, albeit with some minor adaptations, also has been suggested by a number of countries. In Australia, the ICSM has published two sets of GPS practice guidelines [ICSM 1994; 1997c] for control surveys and surveying applications respectively. The former places emphasis on the *GPS system*, which comprises the *satellite segment, receiver hardware, field procedures* and *software* [*ibid.* 1994, p.B-6.5], while the latter focuses on GPS *equipment* [*ibid.* 1997c, p.4]. The procedures recommended by the ICSM are intended to test the GPS system as well as the field practices that would be employed on a project. According to the ICSM, validation should be performed on a *small test network* comprising EDM calibration baselines and *high order* geodetic control stations. The test network should be a *polygon with station spacing not less than 50 m and preferably not more than 10 km* [*ibid.* 1994, p.B-6.6]. GPS baseline vectors, in terms of Cartesian coordinates (dX, dY, dZ), should be included in a network adjustment using the method of least squares. The final solution is compared against the known values of the control points in the network. The ICSM does not appear to specify any agreement tolerances; however, the manufacturer's specification has been recommended as a *measure of precision* [*ibid.*, 1994, p.B-6.6].

The New South Wales Surveyor General's Directions No. 9 [1997] incorporate a set of procedures for using GPS to undertake cadastral surveys. The procedures include the use of *an approved State GPS test network* for validating measurement techniques, GPS hardware and software, and processing methodologies. In situations when validation on the test network is impracticable, the Directions recommend the use of *a local network of State survey control marks*. The difference between the derived and given coordinates should be less than 25 mm + 5 ppm for horizontal coordinates and 60 mm + 12 ppm for height [*ibid.*, 1997, p.9-2].

The Land Information of New Zealand or LINZ (formerly known as the Department of Survey and Land Information or DOSLI) states that, in the event that there is a need *to prove receiver hardware, field procedures, and processing, a system test may be required* [DOSLI, 1996, p.7]. The test includes the measurement of a *test network* comprising at least four geodetic control stations. The size of the test network and the conduct of the test should be commensurate with the requirements of the application. In Greece, Katsambalos and Savvaidis [1996, p.91] recommend the use of *calibration networks* for the purposes of providing quality control for EDM devices and GPS receivers.

The Geodetic Survey of Canada, in cooperation with the Provinces, has established several networks, known as *GPS validation networks* or *basenets*, for assessing the qualifications of potential contractors or service providers to perform GPS surveys to a specific accuracy level [Craymer *et al.*, 1990; and Craymer *et al.*, 1993]. The networks comprise forced centring pillars and baseline lengths that range from less than 1 km to 100 km. Where possible, EDM calibration baselines are incorporated in the networks. The coordinates of the points in the networks are initially established by the Geodetic Survey Division (GSD) using first order standards and specifications; these coordinates then form the basis of comparison. The evaluation of test results is based on the internal precision of GPS baselines, coordinate differences, statistical compatibility and similarity transformation between the solutions from the contractor and GSD [*ibid.*, 1990, pp.255-257]. The required accuracy of the validation results varies from 1 cm + 2 ppm to 1 cm + 50 ppm depending on the location of the network [*ibid.*, 1993, p.3]. Following the satisfactory completion of the assessment, the contractors are deemed to be qualified to perform certain types of GPS survey. According to *ibid.* [1990, p.251], the *most significant change in our specifications is a greater emphasis on contractor qualification rather than the strict specification of procedures.* For those GPS service providers who have a keen commercial interest in government GPS survey contracts, the onus is on them to be *qualified* or *accredited contractors.*

Recently, the Public Sector GPS Users Committee or PSGUC [1997] in British Columbia, Canada, published a set of standards and specifications for resource surveys using GPS. The required accuracies for resource surveys range from 1m to 10 m. The publication is a result of a recognition by the PSGUC of the need for a set of uniform standards and specifications for both government agencies, being contract administrators, and GPS contractors. According to *ibid.* [1997, Section A], *lack of a published specification will result in an uncontrolled degradation of the spatial databases which are used for planning and* *management of ... resources*. By publishing the standards and specifications, *ibid.* [1997, Section C4] aim to achieve the following goals:

- *To establish realistic, reasonable levels of accuracy by task assignment, and to classify the surveys to be performed by end specifications aimed at achieving target accuracies.*
- *To provide capability for integration of requirements across government agencies and to standardize those requirements where common standards are applicable.*
- *To qualify GPS systems (i.e. equipment, processing methods, and personnel) by a GPS Contractor System Validation survey to establish the accuracies achievable under various conditions.*

The third goal is the same as that adopted by Craymer *et al.* [1990]. The PSGUC [1997, Section D4] recommend that education, training and validation surveys be used as part of quality assurance for GPS resource surveys. In addition, *Validation Test Ranges* should be established to *replicate most, if not all, the typical GPS surveying tasks/features that are currently encountered by contractors.*

The foregoing descriptions of current adoption and implementation of the test network concept have highlighted two different levels of emphasis. Some jurisdictions concentrated on the ability of GPS instrumentation and techniques to comply with the required accuracy standards, while others were concerned with the qualification of surveyors or contractors. The differing institutional motives for requiring validation account for this difference of emphasis. In the context of establishing legal traceability, test networks could be used partially to achieve that aim, provided that the surveyor who conducted the test is the person who will be subsequently undertaking GPS surveys. That surveyor is ultimately responsible for ensuring the correctness of information shown on a survey plan. Test networks provide an avenue for assessing the surveyor's GPS knowledge and practical skills.

The use of validation test networks for qualifying or accrediting GPS surveyors have the following advantages:

- they constitute an educational tool, and according to Rüeger [1991, p.208], *Experience has shown that surveyors will support the scheme...once they accept that checking one's instrument is an important aspect of quality assurance in professional practice*; and
- survey results can be standardised, both in terms of accuracy and lodgement format.

In principle, the goals espoused by Craymer *et al.* [1990] and the PSGUC [1997] are very similar to those of survey coordination, as well as the current scheme of licensing or registration of cadastral surveyors in Australia (*vide* Section 3.3). The disadvantage of such an approach is that only those interested in pursuing government contracts would probably be willing to subject their GPS survey equipment and surveying techniques for assessment.

However, the Canadian approach could be used for accrediting surveyors or survey companies for performing GPS surveys in Australia.

To some extent, the approach is similar to that of EDM calibration; tests are performed at specially established facilities and conducted at regular intervals or when a need arises. The arguments against these specific elements of the test, particularly those related to the nature of GPS errors, have been outlined in Section 5.7. The factors affecting the accuracy of measurements encountered during test conditions are highly unlikely to be repeated during an actual survey. Other arguments against the adoption of the test network approach include the following:

- The costs of establishing and maintaining such networks may be quite high. The physical infrastructure, in terms of pillars and other survey equipment, will need to be established (such costs may be lessened in areas where sound geodetic control or permanent GPS reference stations are available). The network of survey pillars and marks must be maintained and resurveyed at regular intervals; and
- The test may be logistically cumbersome, in that it requires the use of personnel and equipment, which would otherwise be available for productive commercial purposes.

Support for the option is anticipated to be weak, for the latter reason. In addition, the matter of enforcement of the legal requirements for the GPS measurements to be verified using a test network must be addressed. The following comment from Rüeger [1991, p.208] provides insight into one possible outcome: *Based on the past and present experience with the legal requirements for the calibration of surveyor's tapes and bands, it is predictable that the Surveyors-General as verifying authorities are unlikely to enforce legal requirements for EDM instrument calibration.* This prediction could be equally applicable to the GPS case, because Surveyors-General or other responsible agencies have very limited resources, further depleted by the current trend of governments to reduce the responsibilities of survey departments through outsourcing. A solution might be found in promoting the importance of verification as part of quality assurance, through awareness campaigns and tertiary education curricula.

In summary, the test network approach could partially provide a means for achieving traceable GPS measurements. The option provides an ability to *control* the test according to the type of GPS equipment, operational procedures and processing software; test results could be independently analysed and verified by the appropriate authorities. Most importantly, the approach provides an avenue for the assessment of the surveyor's GPS knowledge and practical skills. Hence, several institutions have used test networks to qualify and accredit GPS surveyors. However, like the EDM Calibration Baselines option (*vide* Section 5.7), the strongest argument against the proposition is the issue of *repeatability*, since it is highly improbable that test conditions can be replicated during actual surveys. In addition, in view of the laborious nature of the test, and for economic reasons, the option may not attract the strong support of the professional surveying community.

5.9 Survey connection to geodetic network

The use of the national geodetic network for verifying cadastral surveys performed with GPS has been suggested by LINZ, whose set of published guidelines recommend that cadastral surveys performed using GPS should be connected to at least three geodetic control points in order to verify the reliability of the *origin marks* [DOSLI, 1994, p.6]. However, the guidelines are general in nature and do not detail either for the verification process or the evaluation of results. Like the ICSM, LINZ has published two sets of practice guidelines (*vide* Section 5.8). There appears to be some inconsistencies in the recommended guidelines relating to the requirements for GPS tests and the verification methods. The ambivalence appears to be related to a perceived need to distinguish between the types of survey applications, namely geodetic and plane surveying. Apart from the scale of operation, GPS is used in a similar manner for both types of surveys. Tests and verification procedures should be rationalised and based on the same principles. An important point to note is that geodetic network provides the reference frame for other work. Consequently, the network has to be established with greater rigour and redundancy in order to achieve uniformly higher, and more consistent, accuracy.

Literature relating to the recommendation and adoption of a national geodetic network for testing and verification purposes is limited. The reason for the lack of discussion could be due to the perception that test networks (*vide* Section 5.8) are usually established as part of the geodetic network and are therefore regarded as generically synonymous. However, Australian geodetic networks *cannot* be considered as test networks until such time that idiosyncrasies and heterogeneity existing within and between the networks are removed. The quality of the coordinate set of the control stations in the network is significantly influenced by a combination of factors, such as the instrumentation employed, survey methodology and the degree of rigour of the error and adjustment models. One of the main reasons given by Collier and Leahy [1992] for the readjustment of the Melbourne survey control network is the problem of incompatibility of GPS measurements with the survey control network. *ibid.* [1992, p.287] state that, *it is a common problem to have to distort measured GPS data to obtain agreement with existing survey control.* Recently, the Department of Natural Resources [1998, p.25] reports that the high precision GPS network in Queensland has been distorted to fit the existing primary AGD84 stations. As a result, coordinate precision is now stated at the decimetre level. Such uncertainties within Australian geodetic networks emphasise the need for a GPS integrity monitoring system.

Australia is to adopt a geocentric datum (*vide* Section 6.5.1); one perceived benefit should be the generation of a homogeneous coordinate set, which provides greater confidence and reliability in the geodetic network, so enabling the geodetic network to be used for verifying GPS measurements. The most pragmatic level of the geodetic network that could be considered for verification purposes is that level occupied by the GPS permanent reference stations (*vide* Section 6.5.1). At this level, the spacing between reference stations is approximately 50 km. In a study of base station densification, Takac [1997a, p.6] demonstrated that reference stations with a 50 km separation in growth areas can provide survey accurate results with occupation times of approximately 10 min. The existing high precision GPS networks would seem to be useable; however, the spacing of the control stations, approximately 100 km, may be considered to be insufficiently dense. The network's coverage would have to be denser to encourage its use for verification purposes, but such densification is, however, unlikely, due to government policy regarding the reduction of the emplacement and coordination of ground marks [Department of Land Information, 1998, p.24].

In this option, cadastral surveys performed using GPS are connected, using recommended guidelines, preferably to more than three appropriate GPS permanent reference stations or geodetic control stations, as available in the vicinity of the survey area. Following the completion of the survey, the results are analysed and compared with the known values of the reference stations or geodetic control stations. If the tolerances are met, the survey can be certified as correct. Stewart *et al.* [1998] describe a statistical method for comparing network solutions from a survey with known values. The advantages of using the geodetic network as part of a verification process are:

- the results of *each* survey are verified during the survey, rather than at regular intervals, (hence, temporal and geographical aspects of GPS errors are accounted for during each survey);
- ideally, all three GPS segments would be verified, therefore obviating the need for implementing an integrity monitoring system;
- the approach obviates the need to make special verification excursions, because verification is performed during the conduct of a survey;
- the objectives of survey coordination are achieved because surveys can be rationalised based on a common spatial referencing system; and
- the option is technology-independent, i.e. any measurement technology, including EDM devices, can use the network for verification purposes.

The disadvantages of the option are:

- surveyors have to exercise professional discretion regarding the manner in which the connections are made. This can be partly overcome by the development and recommendation of *best practice* guidelines such as those published by the ICSM [1994; and 1997c]. The recommendations should include network design and observation strategies, which can ensure the accuracy and reliability of the survey; and
- many jurisdictions, particularly those with *Survey Coordination Acts*, require cadastral surveys to be connected to the geodetic network, where practicable. In these jurisdictions, there would be no additional cost incurred on the surveyors. There is a possibility for cost savings to governments and, ultimately, industry itself because GPS surveys, following connection to the network, could be used to assist in the maintenance or monitoring of the geodetic network. However, in jurisdictions where there is no requirement for surveys to be connected to the geodetic network, surveyors would have to make an extra effort to connect their surveys to it and would therefore incur additional costs. The possibility of using GPS permanent base stations in the same manner as control points may lessen some of the maintenance costs.

In summary, subject to the requirement for greater density of marks and overall homogeneity of coordinate set, the geodetic network is the most desirable and feasible option for providing a means for verifying cadastral surveys performed using GPS. Most importantly, GPS measurements are compared and traced directly, i.e. during a survey, to the Australian Fiducial Network (AFN), which has been determined as a *recognized-value standard of measurement* pursuant to s.8A of the National Measurement Act (*vide* Section 6.5).

5.10 Summary

This chapter has reviewed some of the existing methods for testing and verifying the elements of the Global Positioning System. The attributes of each method are described in relation to their relevance to surveying and the achievement of legally traceable GPS measurements. A summary of the discussions in this section is presented in Table 5.2. The Verification Methods in the first column of Table 5.2 are arranged according to cost (derivation of the annual costs and the basic assumptions used for the derivation are provided in Appendix). The legal requirements are obtained from Chapter 2 and Chapter 3. Essentially, elements which contribute to the accuracy of the final result must comply with the requirements stipulated in survey and measurement legislation.

The *ease of use* for each method was also evaluated. The test network option, albeit a thorough approach, is considered to be the most laborious, logistically demanding and resource intensive. Like the test network, the EDM calibration option requires special excursions for verification purposes. The other options are considered to be relatively easier to implement. The geodetic network option appears to be the most practical, because verification is performed during the actual survey.

The geodetic network option has inherent verification mechanisms. Connecting a GPS survey to at least three known points, which have been independently determined, enables the survey to be verified in terms of scale and orientation. The space and control segments are verified. However, inadequacies in the geodetic network coverage and coordinate homogeneity would require the implementation of integrity monitoring system in Australia. An integrity monitoring system will be necessary if methods other than the geodetic network option are preferred. Further, other options would require the verification process to be designed in such a manner that actual survey conditions are replicated, which is improbable in practice. Table 5.2 can be used as a decision-making matrix for designing appropriate verification methods.

Most of the methods reviewed in this chapter, particularly those in current use, have been developed for quality control purposes; however, some elements of the methods, as shown in Table 5.2, can be adopted for formulating a model for achieving legally traceable GPS measurement. This task is presented in Chapter 6.

LEGISLATION	LEGAL REQUIREMENTS				
	Control and Space segments (definition of the *metre* and *second*)		User segment		
	Ephemeris[1]	Clocks[1]	Hardware, software and operational procedures	Accuracy of specific measurements	Surveyor's GPS knowledge and practical skills[2]
Surveyors Act / Survey Act	✓	✓	✓	✓	✓
National Measurement Act	✓	✓	✓	✓	×

✓ applicable × **not** applicable

VERIFICATION METHODS	VERIFIED COMPONENTS OF THE MEASUREMENT SYSTEM					VERIFICATION REQUIREMENTS	ANNUAL COSTS IN ADDITION TO EXISTING REQUIREMENTS[6]
	Control and Space segments (definition of the *metre* and *second*)		User segment				
	Ephemeris[1]	Clocks[1]	Hardware, software and operational procedures	Accuracy of specific measurements	Surveyors GPS knowledge and practical skills[2]		
Best Practice for cadastral surveying[3]	×	×	×	✓	Partial	For each survey (mandatory requirement)	None
Indicators of Surveyors skills and experience[4]	×	×	×	×	Variable[7]	Many are mandatory requirements	Depends on jurisdictional requirements
Hardware and Software Tests[5]	×	×	✓	×	×	Global recognition	Minimal institutional costs
Integrity Monitoring System	✓	✓	×	×	×	Continuously at 1 or 2 monitor sites in Australia	Minimal institutional costs
Test Data for Software	×	×	Partial	×	Partial	Once for every version	Cost for a surveyor ≈$80
Zero Baseline Tests	×	×	Partial	×	×	Annually	Cost for a surveyor ≈$190
Survey Connection to Geodetic Network	✓	✓	✓	✓	✓	For each survey	Depends on jurisdictional requirements, may not be any additional costs to surveyors and potential institutional cost savings
EDM Calibration Baselines	×	×	Partial	×	Partial	Annually	Institutional (for one baseline): Establishment costs ≈$1,120 Maintenance costs ≈$1,120 Surveyor's costs ≈$1,120
GPS Test Network (for testing GPS Survey System)	×	×	✓	×	✓[8]	Annually	Institutional (for one network): Establishment costs ≈$2660 Maintenance costs ≈$2240 Surveyor's costs ≈$2240

✓ **able** to verify × **unable** to verify

[1] These elements must be able to provide the required legal accuracy specifications during an actual survey.

[2] The Surveyor is the person responsible for ensuring measurements are legally traceable.

[3] Includes using properly maintained survey equipment, correct set-up and measurement of instrument heights, obtaining redundant and independent measurements, proper recording of field data, and performing closures.

[4] Includes current Licensing or Registration scheme, Continuing Professional Development (CPD), Accreditation of GPS surveyors or companies, acquired GPS experience, Field Audits or Inspections, and Survey Plan Examination.

[5] Includes tests performed by international and national institutions which are recognised by the responsible Australian authority to have the capability for performing high quality investigative tests. *Certification* or *Seals of Approval* from these institutions could be recognised as adequate proof that a particular model and make of hardware (for example receiver and antenna) has complied with the accuracy specifications. The same applies to a particular type and version of GPS processing software.

[6] The costs shown are not and should not be used as definitive implementation costs. The assumptions made in the costs derivation are described in Appendix.

[7] Variable because a method could be used as a strong or weak indicator depending on the way the indicators are measured and applied in the different jurisdictions.

[8] The method provides an indication of the knowledge and skill of the person who conducts the test and does not apply to any other person who subsequently uses the hardware and software.

Table 5.2. Summary of Legal Requirements and Verification Methods.

6. ESTABLISHING THE LEGAL TRACEABILITY OF GPS MEASUREMENTS

6.1 Introduction

In the current Australian measurement system, the *National Measurement Act 1960* (Cwlth) provides the basis for achieving the legal traceability of measurements. According to s.10 of the Act, the four principal requirements for establishing the legal traceability of measurement in Australia (*vide* Section 2.2.3) are:

- A measurement must be of a physical (measurable) quantity.
- Australian legal units of measurement for the sought-after measurement must be prescribed.
- Appropriate Australian standards of measurement must be available.
- The methods or means for relating measurements to the appropriate standards of measurement must be available.

This chapter presents a discussion on the development of two models for establishing the legal traceability of GPS measurements for the purposes of cadastral surveying. However, only one is tenable within the provisions of the National Measurement Act and is, therefore, recommended for implementation.

Electronic distance measurement (EDM) provides an example of an existing measurement for which legal traceability can be achieved. The implementation of the four principal requirements for achieving the legal traceability of EDM is illustrated in Table 6.1.

Requirement	Electronic distance measurement (EDM)
Physical quantity	Length
Unit of measurement	The metre which is the length of the path travelled by light in a vacuum during a time interval of 1/299 792 458 of a second (r.5 of the National Measurement Regulations).
Primary Standard (the practical realisation of the unit)	Helium-Neon laser stabilised with a cell of iodine [CSIRO, 1996].
Means of relating a measurement at the working level to the Primary Standard	Calibration of EDM instrument on certified baseline [Rüeger, 1985].

Table 6.1. The legal traceability of EDM.

Firstly, this chapter identifies within GPS the physical measurements, and their associated units of measurement, that are meaningful and practical in the context of cadastral surveying. Secondly, models for achieving the legal traceability of GPS measurements are developed and described. This chapter is a result of the consolidation and application of the concepts presented in Chapters 2 to 5 inclusive.

6.2 Physical measurements in GPS

The aim of this thesis is to develop a model for establishing legally traceable GPS measurements for cadastral surveying in Australia. Therefore, GPS measurements, defined within the context of this thesis (*vide* Chapter 2, Chapter 3 and Chapter 4), that are meaningful and practical for cadastral surveying must be identified. This task can be achieved by examining the current measurements used for describing title boundaries in plans of survey, plans of subdivision, certificates of title and crown grants. Chapter 3, in particular Table 3.3, has identified three types of measurements used in current survey legislation, namely lengths, angles and positions. Commonly, a length and an angle are used together, as a vector, to define a title boundary.

Time is the basis of all GPS measurements. In the context of cadastral surveying, time, as a measurement for describing the dimension of a title boundary, is meaningless and apparently irrelevant. However, time can play an important role in describing the temporal or historical aspect of cadastral information, which includes survey measurements. From the discussions on the factors which affect the accuracy of GPS measurements (*vide* Section 4.3 and Section 4.8), temporal aspects, such as time and date of measurement, are important considerations for proving the accuracy of GPS measurements at a particular epoch. The temporal aspect of traceability has been discussed briefly in Section 2.2.2.

As mentioned in Chapter 4, only GPS relative positioning techniques, using the carrier phase observable, can meet the accuracy requirements of cadastral surveying, which are at centimetre levels (*vide* Table 3.3). Section 4.6 and Section 4.7 have identified the outcomes of a GPS measurement process as either baseline vectors or a set of coordinates which have been determined with respect to another fixed set of coordinates. Coordinates so determined are known as *relative positions*, often expressed as geocentric Cartesian coordinates (X, Y, Z) on the WGS84 datum. In order to be meaningful and practical for cadastral surveying, these coordinates must be transformed onto a local plane coordinate system or national grid system, such as the AMG, in which the title boundaries are defined. Three dimensional baseline components (ΔX, ΔY, ΔZ) can be also expressed in terms of slope distance, azimuth and zenith distance.

From the foregoing discussions, the following measurements from GPS are considered as meaningful and practical for cadastral surveying: *time*, *relative positions or coordinates*, and *baseline vectors*. Time and length are defined as physical or measurable quantities in the National Measurement Act (*vide* Section 2.4). Plane angles, being geometric quantities, are not required to be traceable to a standard of measurement (*vide* Section 3.3.4.2). Relative positions or coordinates, however, are yet to be defined as physical or measurable quantities in the National Measurement Act. The ensuing sections describe these measurements and their associated units and standards of measurement in greater detail.

6.3 Basic assumptions

This thesis proposes two models for achieving the legal traceability of GPS measurements. The fundamental difference between the two models concerns the domain of measurement. Simply, the elements of a measurement are: an input, a set of processes or operations, and an outcome (*vide* Section 2.4.2). In this thesis, these elements are categorised into two domains, namely the *operation domain*, comprising the input and operations, and the *result domain*, comprising the outcome (Figure 6.1). A similar model for GPS is presented in Figure 4.1 (*vide* Section 4.4).

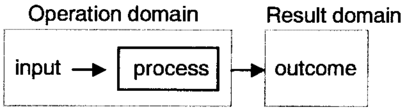


Figure 6.1. A simple measurement model as defined in Section 2.4.2.

The first model treats *time* as the most basic measurable quantity in GPS. In this regard, the set of operations is relative positioning and the outcome is any quantity which is a derivative of time, such as time, velocity and positions. The underlying assumption in this model is that the accuracy of the outcome is completely dependent on the integrity of the operation domain. In other words, by controlling the operational means, the outcome can be ensured to meet the necessary accuracy requirements. The basis of this assumption is analogous to the concept of *quality control* (*vide* Section 2.3.2) and the existing measurement process in surveying, i.e. the combination of surveyor's competency, calibrated equipment and appropriate survey methods (*vide* Chapter 3), which is assumed to be adequate for providing the desired outcome.

The second model concentrates on the outcome or result of measurement, i.e. the *result domain*. In relative positioning, the results are expressed as either baseline vectors or relative positions. **The results, rather than the operational means, are verified**. (A third model could be presented as a hybrid of the elements from the first and second model; however, this option is not considered in this thesis).

6.4 Measurement of time

This section describes a means for achieving the legal traceability of GPS measurements by adopting time as the basis of GPS measurements. This model concerns the *operation domain* of the measuring system.

6.4.1 The international and national traceability of time

In GPS, time is used to generate the signals and for time-tagging purposes. In this regard, the two forms of time used in GPS are *time interval* and *time scale*. The SI unit for both expressions of time is the *second* (*vide* Section 2.4.3). A time interval is a measurement of duration between two events, while a time scale is any system which allows the unambiguous ordering of events. An example of time interval is the definition of the *second*, which is a unit of duration. There are several examples of time scales used in geodesy and surveying; however, for the purposes of this thesis, the time scales of immediate concern are the International Atomic Time (*Temps atomique international*, TAI), Coordinated Universal Time (Universal Time Coordinated, UTC) and GPS Time (GPST). A study of time and time scales in relation to GPS can be found in Rizos and Grant [1990].

Conceptually, TAI, UTC and GPST are atomic time scales based on the frequency corresponding to a certain resonance of the caesium atom (refer to the definition of the *atomic second* in Section 2.4.3). The realisation of the SI unit of time, the *second*, is carried out using a small number of the most accurate laboratory primary caesium standards. In 1996, caesium standards from the Physikalisch-Technische Bundesanstalt (PTB), Germany; National Institute of Standards and Technology (NIST), USA; and *Observatoire de Paris* (OP), France, were used to provide the *second* [Time Section of the BIPM, 1998, p.2].

TAI is a *paper clock* computed based on a weighted average of clock readings from the comparisons of about 230 commercial caesium standards kept by 65 laboratories around the world. GPS is the principal tool for national and international comparisons of atomic clocks. A description of the principles of GPS time transfer can be found in Lewandowski and Thomas [1991]. TAI is a very stable and uniform time scale; its medium-term stability, expressed in terms of the Allan standard deviation, $\sigma_y(\tau = 40\text{days})$, is estimated to be 1.3 x 10^{-15} [Time Section of the BIPM, 1998, p.2].

Due to the irregularities in the earth's rotation, TAI cannot be used as a practical time scale for civil use. As a compromise, UTC was introduced as the basis of legal civil time. UTC and TAI differ by an integer number of seconds, known as *leap seconds*, so that UTC does not deviate from Universal Time (UT1), which represents the actual orientation of the earth in space, by more than 0.91 s. Leap seconds are determined by the International Earth Rotation Service (IERS), while the generation of TAI and UTC is the responsibility of BIPM. Both IERS and BIPM work very closely together. Currently, TAI - UTC = 32 s with the 1 January 1999 leap second. The origin of TAI is defined as UT1 - TAI ≈ 0 on 1 January 1958.

TAI and UTC are disseminated as time differences with respect to the independent local time scales, TA(k) and UTC(k). The BIPM publishes the differences in a mid-monthly bulletin called *Circular T*, which is available via the BIPM internet site (www.bipm.fr). The traceability of time across the world is direct and can be easily demonstrated through national links to UTC via the BIPM (Figure 6.2). The abbreviations for the names of the contributing laboratories in Figure 6.2 are given in BIPM [1996, pp.20-21]. Some of the nodes in Figure 6.2 refer to countries instead of the contributing laboratories, for example AUS. A full description of the manner in which the *second* and UTC are calculated and disseminated can be found in Guinot [1994/1995], BIPM [1996] and the Time Section of the BIPM [1997].

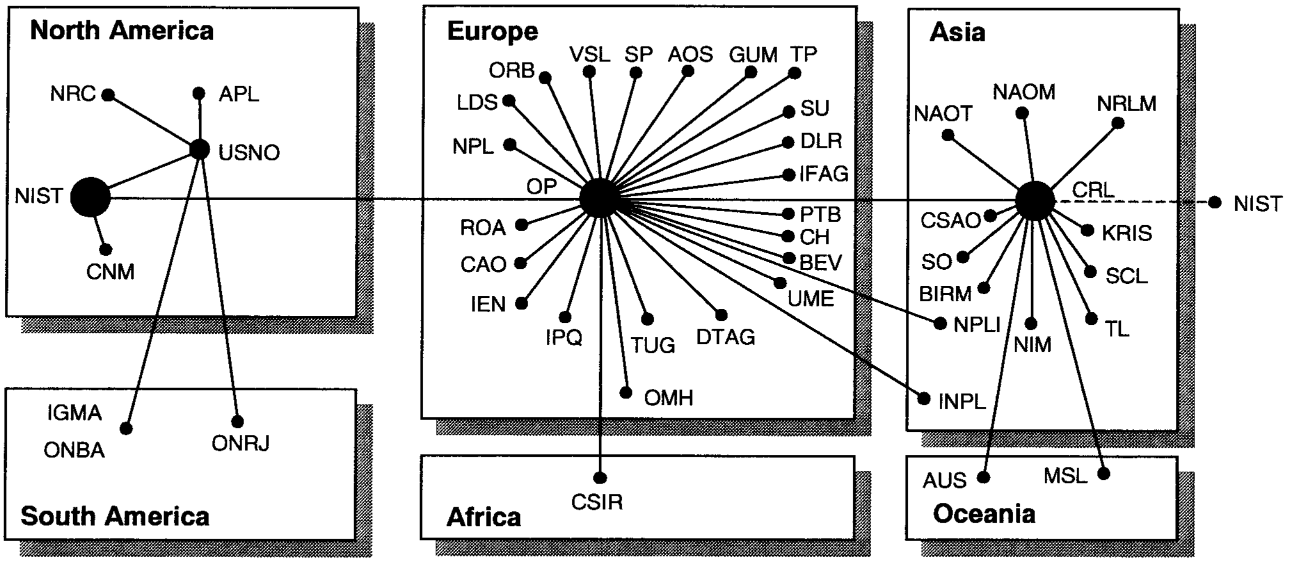


Figure 6.2. Organization of the international GPS time links that provide data for the calculation of TAI [from Time Section of the BIPM, 1997, p.2].

Recently, in Australia, UTC(AUS) was formally recognised as the national standard of civil time [CSIRO, 1998]. The maintenance of UTC(AUS) is the responsibility of CSIRO. Like TAI, TA(AUS), and thus UTC(AUS), are generated from an ensemble of atomic clocks scattered around the country, some of which contribute to the generation of TAI. The physical realisation of UTC(AUS), i.e. the primary standard for civil time, is obtained using a caesium clock and a micro-phase-stepper [BIPM, 1996, p.22]. Figure 6.3 illustrates the manner in which TA(AUS) and UTC(AUS) are generated and disseminated. Currently, in Australia, the unit of time, being the *second*, and the civil time scale, being UTC(AUS), are defined in r.21

of the National Measurement Regulations and s.8AA of the National Measurement Act respectively.

All the laboratories shown in Figure 6.2 and Figure 6.3 are linked via GPS [BIPM, 1996, pp.22-27]. A full listing of all the laboratories contributing to TAI and the number and type of atomic clocks in those laboratories is provided in *ibid.* [1996, pp.22-27].

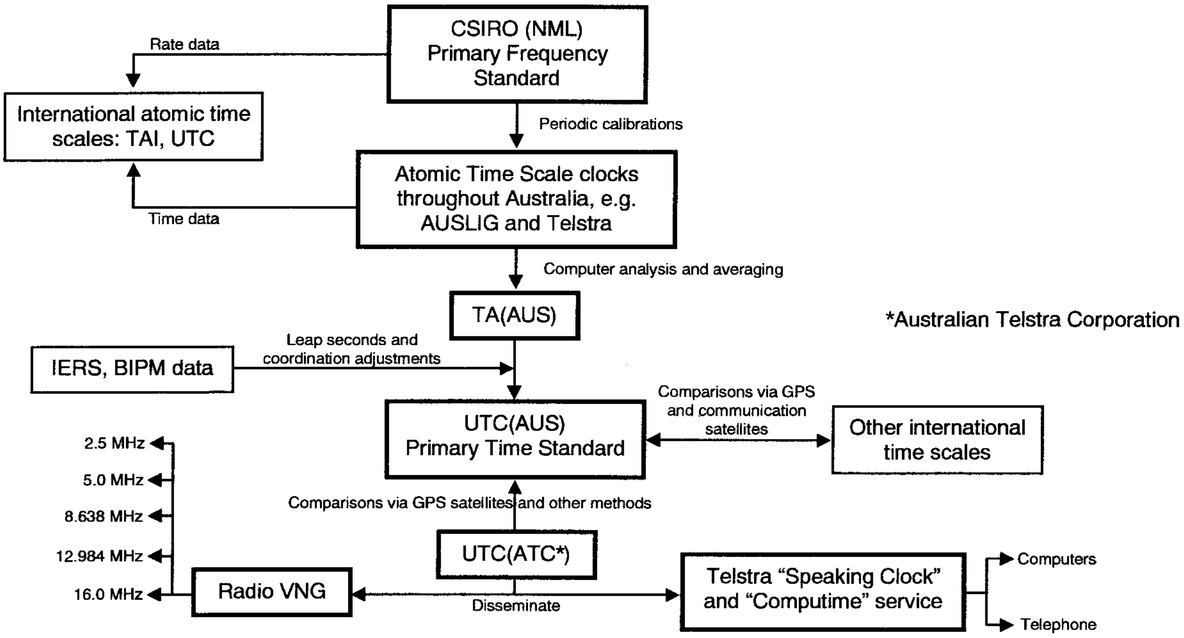


Figure 6.3. Australian national time system [from NSC, 1995, p.9].

GPST, like TAI, is a composite or *paper clock* comprising all operational monitor station and satellite frequency standards. The theory of the GPS composite clock is presented in Brown [1991b]. The GPS epoch is 0000 UT (midnight) on 6 January 1980, i.e. GPST was synchronised with UTC(USNO, MC) determined by the Master Clock (MC) held at the United States Naval Observatory (USNO), which was then 19 s behind TAI. Hence, there is a constant offset of 19 s between TAI and GPST (TAI - GPST = 19 s). Currently, GPST - UTC = 13 s with the 1 January 1999 leap second. The exact relationship between UTC and GPST is UTC - GPST = -13 s + CO, where CO is a quantity of the order of a few hundreds of ns, varying with time [BIPM, 1996, p.75]. Essentially, CO comprises ionospheric delays and ephemeris errors. The BIPM calculates CO on a daily basis and the evaluation is available via the BIPM internet site under the filename utcgpsXY.ar, where XY denotes the year. Using data from these files, Figure 6.4 shows the magnitude of CO for the period between 1 January 1994 and 31 December 1997; the average value during this four year period is 40 ns.

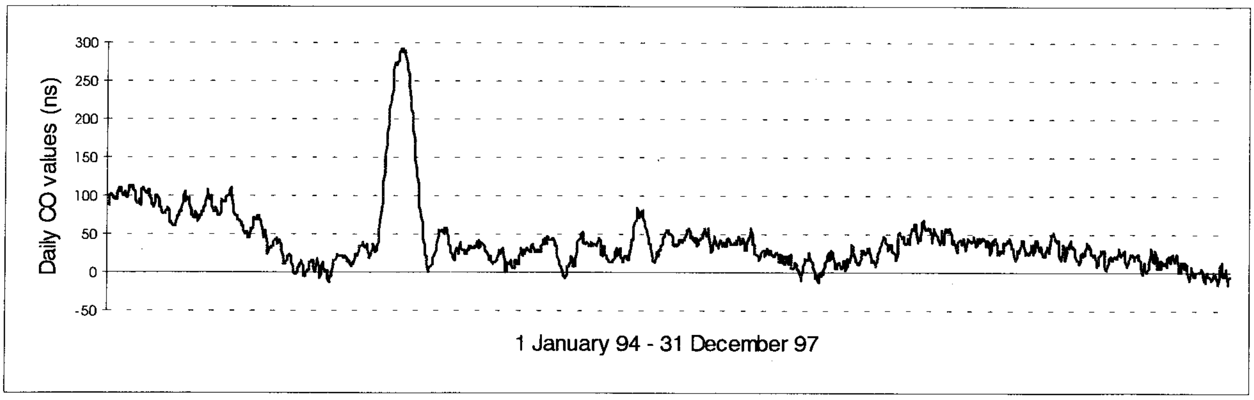


Figure 6.4. Daily CO values between 1 January 1994 and 31 December 1997.

The OCS is required to control GPST to be within 1 μs of UTC(USNO) (modulo 1 s) [Anon., 1995b, p.32]. The USNO internet site (tycho.usno.navy.mil) regularly provides graphs of UTC(USNO) – GPST, which show the steering performance to be typically within 20 ns.

Circular T publications for the period from 27 March 1996 to 27 December 1998 indicate that UTC - UTC(USNO, MC), on average, is well within 10 ns (Figure 6.5); Allan [1998, p.29] agrees. In comparison, for the period from 27 March 1996 to 27 March 1998, UTC - UTC(AUS), on average, is approximately 100 ns (Figure 6.5). The period from 1 April 1998 to 30 December 1998 has not been considered, due to the apparent excessive drift of UTC(AUS). Eventually, the Master Clock, located in Canberra, for UTC(AUS) was replaced on 2 December 1998, as noted in *Circular T 132* (14 January 1999).

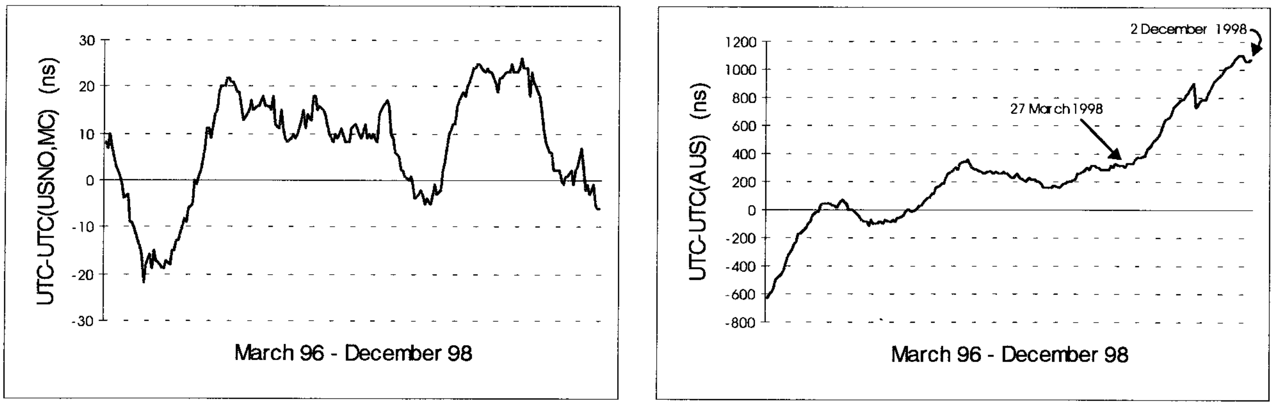


Figure 6.5. Left and right graphs show UTC - UTC(USNO) and UTC - UTC(AUS) for the period from 27 March 1996 to 27 December 1998 respectively.

The difference in the accuracies of UTC(AUS) and UTC(USNO) depends on several factors, some of which are:

- the number and quality of clocks used in the determination of UTC(k). UTC(AUS) is determined based on approximately 20 atomic clocks [Commonwealth of Australia, 1997], while UTC(USNO) is based on 47 atomic clocks, as at 4 December 1998 [USNO, 1997];

- the *time scale algorithm* used in the calculation of UTC(k) and UTC. A time scale algorithm calculates the time offset of each clock from ensemble time, which is the time scale, at a given epoch. A description of two different types of time scale algorithm used world-wide can be found in Tavella and Thomas [1991]; and
- the weighting scheme at the local and international levels. Weights of the contributing clocks can be inspected via the BIPM internet site under the filename wXY.ZT, where XY and ZT denote the year and month respectively. Generally, the clocks that contribute to UTC(AUS) are weighted lower than those of UTC(USNO) due to, *inter alia*, the above factors. An outline of a weighting procedure used by the BIPM for calculating TAI can be found in Quinn [1991, pp.900-901].

In 1993, the Consultative Committee for the Definition of the Second (*Comité Consultatif pour la Définition de la Seconde,* CCDS) expressed the wish to maintain UTC – UTC(k) within 0.1 μs; the recommended tolerance is 1 μs [Guinot, 1994/1995, p.435]. Note that, in 1997, CCDS was renamed as the Consultative Committee for Time and Frequency (*Comité Consultatif du Temps et des Fréquences*, CCTF). UTC - UTC(USNO, MC), UTC - GPST and UTC - UTC(AUS) all lie within the desired CCDS desired tolerances.

The preceding paragraphs have described the relationships between the various time scales, namely TAI, UTC, UTC(k) and GPST. The world uniformity of time is assured by the common use of UTC. As mentioned in Section 2.4.4, the realisations of the *second* and UTC have been improved recently, due to the advancements in the technology of atomic frequency standards and GPS time transfer techniques. Essentially, as a result of the established relationships, traceability within (nationally), and between (internationally) the respective time scales can be easily demonstrated (Figure 6.6). **The basis for traceability is the frequent international comparisons of the various time scales, the results of which are easily accessed and interpreted.**

6.4.2 Traceability of GPS measurements based on time

In principle, GPS measurements, which are derivatives of time, are traceable to UTC(USNO), which is a primary standard of time, as well as to UTC. However, according to s.10 of the National Measurement Act, the legal traceability of measurements in Australia can be demonstrated only through an established relationship with an Australian standard of measurement (*vide* Section 2.2.3). Further, there is no provision in the Act for the recognition of international standards of measurement. For these reasons, traceability of measurements to either UTC(USNO) or UTC has no legal basis. Reversal of this situation would require amendment of the National Measurement Act to include a reference to international standards of measurement.

The conceptual and operational elements in any national measurement system are implemented to serve the country's specific needs (*vide* Chapter 2). However, some countries cannot afford, and are not technologically capable of maintaining, primary standards of measurement. As a result, the recognition of standards of measurement, and thus measurements, from another country is not a trivial undertaking. For such a recognition to occur in Australia, the standards of measurement and reliability of the link between standards of measurement and the relevant calibration and testing services of foreign countries must be demonstrated to be equivalent to those in Australia. For this reason, one occasioned mainly by the demands of international trade, the BIPM has proposed the concept of *international equivalence of national measurement standards* for ensuring international traceability of measurements (*vide* Section 2.6). This concept aims to provide for a more systematic and transparent approach in undertaking international comparisons through the adoption of BIPM guidelines for key comparisons. Australia is a party to a draft mutual recognition agreement on national measurement standards and certificates issued by national metrology institutes. The final agreement is expected to be signed by the directors of national metrology institutes in October 1999 [BIPM, 1998b]. The recognition of international equivalence of national measurement standards could provide a means for achieving international traceability of measurements; however, as explained in the preceding paragraph, such measurements have no legal basis in Australia.

In the context of the foregoing discussions, the stumbling block for achieving the legal traceability of GPS measurements appears to be the current National Measurement Act. However, there is a great likelihood that this Act will be amended, consequent on international pressures, to extend the legal traceability of measurements to international standards of measurement. **Upon such an eventuality, the appropriate and practical means for establishing the legal traceability of GPS measurements would be to adopt *time* as the fundamental physical quantity**. The SI unit of time is the *second* and its standards of measurement are atomic frequency standards, such as caesium clocks and hydrogen masers, which are used also to realise UTC and UTC(k).

As mentioned in Section 2.4.4, by implicitly adopting an exact value for the speed of light, the *metre* can be realised by any source of electromagnetic radiation whose frequency is known or can be measured. One of the three CIPM recommended methods for realising the *metre* is *by means of the length l of the path travelled in vacuum by a plane electromagnetic wave in a time t; this length is obtained from the measured time t, using the relation $l = c \cdot t$ and the* *value of the speed of light in vacuum* c *= 299 792 458 m/s*. This method of realising the *metre* is the most direct and is implemented in many space based positioning techniques, including GPS. Figure 6.6 shows the manner in which GPS measurements are traceable to UTC. In Figure 6.6, the transfer of units to the *working level* GPS measurements is direct. The satellite atomic clocks, used to define GPST, are used to generate timed signals for GPS measurements. In other words, GPS measurements are determined directly from a standard of measurement. This approach obviates the need to establish a relationship with a standard through the conventional hierarchical comparison method (*vide* Section 2.4.4).

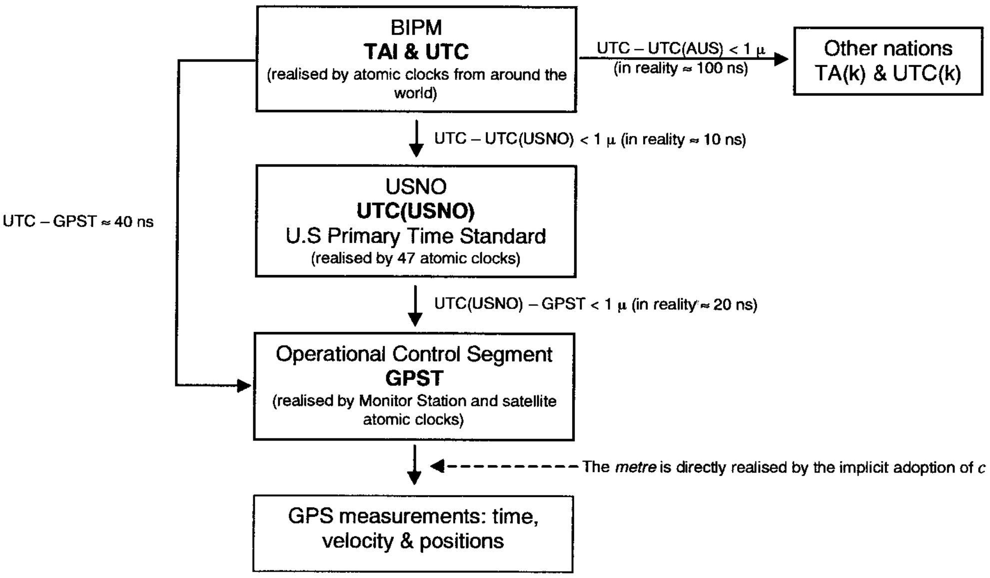


Figure 6.6. Traceability of GPS measurements to international standard of time.

In order to ensure the accurate measurement of time in GPS, the performance of the satellite and receiver clocks must be acceptable. In the normal course of operation, the satellite and receiver clocks perform to very high standards (refer to Section 4.8.4 for discussions on clock performances). Normal clock errors can be effectively eliminated by observation differencing, particularly in the double differenced solution. Satellite positions, broadcast as satellite ephemerides, of acceptable tolerances are required for the determination of accurate receiver coordinates. The nature and effects of ephemeris errors have been discussed in Section 4.8.3, which also established that the errors are effectively eliminated by observation differencing. The term *effectively* is used as a qualification, since some residual errors, as a result of differencing, will be present; however, their magnitude is insignificant, in view of the relatively low accuracy requirements of cadastral surveying, which are unlikely to be better than 50 ppm (*vide* Section 3.3.3).

The preceding paragraph has described a normal operation scenario; however, GPS does suffer from occasional integrity lapses (*vide* Section 4.8.1). As regards relative positioning, the effects of the anomalies, particularly those associated with satellite clocks and ephemerides, are insignificant (*vide* Section 4.8.1.1). This statement is only true so long as it is based on reported incidents. Since no measuring system is perfect, anomalies in GPS will continue to occur and their detection and prevention will continue to be difficult. Many of the anomalies are quite rare and obscure, and their effects on the user segment are not always well understood. Further, other anomalies, particularly those that have not been anticipated by the systems designers, may yet occur. For these reasons, this thesis proposes that an integrity monitoring system should be an important part of the overall scheme for establishing the legal traceability of GPS measurements; such a system should be used to monitor and verify the performance of GPS signals and the navigation data prior to their reaching the user segment. Implementing an integrity monitoring system will ensure that the integrity of GPS can be *independently* verified in Australia and should obviate the need for dependence on an unreliable external source. Section 6.6 describes a proposed integrity monitoring system for Australia. Unlike the approach associated with the calibration of EDM, the integrity monitoring system can indicate the operational status of the GPS measuring system *during* the conduct of a survey.

Apart from ensuring that the control and space segments are operating appropriately, the user segment, as defined in Section 4.4, must be controlled so as to provide results commensurate with the standards of accuracy stipulated in survey legislation. This objective, as shown in Table 5.2 (*vide* Section 5.10), can be achieved by ensuring that the surveyor is sufficiently competent, and by adopting best practice guidelines for cadastral surveying with GPS, such as those published by ICSM [1997c]. These guidelines should incorporate the processing, equipment and operational strategies shown in Table 4.2 (*vide* Section 4.9) in order to control the factors which degrade the accuracy of GPS measurements. In addition, the guidelines should outline independent verification methods, such as re-occupation and connecting to previously surveyed marks.

In summary, this section has described an option for establishing the legal traceability of GPS measurements by adopting time as the fundamental physical quantity. The basic assumption made in this section is that within GPS, through the correct determination of time (be it time interval or time scale, both of which are related) all other time-based quantities can be determined to meet the accuracy requirements of cadastral surveying. For this assumption to be valid, an integrity monitoring system is required to monitor and verify the operation of the control and space segments. Furthermore, the user segment must be controlled by ensuring that the surveyor is sufficiently competent and follows best practice guidelines for cadastral surveying with GPS, which incorporate the processing, equipment and operational strategies for managing the factors which degrade the accuracy of GPS measurements. In this model, GPS measurements are traceable to the satellite atomic frequency standards and eventually to UTC. More importantly, the traceability of measurements is achieved *during* a survey.

6.5 Relative positions

This section describes a means for achieving the legal traceability of GPS relative positions. **The model concerns the *result domain* of the measuring system and is proposed within the ambit of the four principal requirements of s.10 of the National Measurement Act** (*vide* Section 2.2.3).

As previously mentioned, relative positions are coordinates determined with respect to another fixed set of coordinates. In the case of GPS, these coordinates are based on the World Geodetic System 1984 (WGS84), a geocentric Cartesian coordinate system, defined in Defense Mapping Agency [1991]. In order to be meaningful and practical for cadastral surveying, the coordinates must be transformed onto a local plane coordinate system or national grid system, such as the AMG, in which the title boundaries are defined. The relationships between different datums are contained in well-defined transformation formulae. Since title boundaries can be represented as either coordinates or two dimensional vectors, i.e. lengths and angles, GPS derived measurements, such as coordinates and vectors, can be used to describe title boundaries.

One of the four principal requirements for establishing the legal traceability of measurement in Australia is that **a measurement must be of a physical quantity** (*vide* Section 2.2.3). Positions or coordinates are not defined as physical or measurable quantities in the National Measurement Act. However, this does not suggest that positions are not physical quantities. The Act stipulates units of measurement for vectors, such as velocity, acceleration and force, which indicates that some vectors, according to the Act, can be considered as physical quantities. Commonly, only the magnitude or scalar component of a vector is specified, while the direction is implied, for example velocity, acceleration and force. For this reason, some vectors might have been mistakenly perceived as scalar quantities. Section 2.4 has discussed the characteristics of a physical quantity. Essentially, relative positions are three dimensional vectors, which can be expressed also in terms of slope distance, azimuth and zenith distance. **Lengths and angles are defined as physical quantities in the National Measurement Act. Therefore, a position vector, which comprises length and direction, could be considered also as a physical quantity.** In the context of this thesis, a position can be numerically described only by reference or relative to a coordinate system, such as WGS84. In such a case, the units of measurement can be either angular and/or linear, depending on the manner of representation. In a Cartesian coordinate system, the SI *metre* can be used, while in a geographic or geodetic coordinate system, angular units are used. The conversion between the various coordinate systems is given in well-defined formulae. The magnitude of a vector is expressed in linear units, while its direction is given in angular units.

Ciddor [1997, p.2], in his report to the NSC, argued that the position of a point, which is a *vector displacement* of that point from the origin of a specified coordinate system, is a physical quantity. Based on this report, and the opinions of experts from national and international scientific organisations, the Australian Government Solicitor's letter dated 1 September 1997 agrees that **position can be considered as a physical quantity** and advises that the coordinates of the geodetic stations which constitute the Australian Fiducial Network (AFN) (*vide* Section 6.5.1) should be determined, by the NSC, as *recognized-value standards of measurement of position* in pursuance of s.8A(1) of the National Measurement Act. The determination was formalised on 22 April 1998 in the *Commonwealth of Australia Gazette* [1998]. Recognized-value standards of measurement, according to s.8A(1) of the Act, are either prescribed magnitudes of physical quantities or prescribed values obtained by the use of appropriate formulae, for example the velocity of electromagnetic waves in a vacuum, acceleration due to gravity and density of water. Some determinations of recognized-value standards of measurement can be found at the NSC internet site (www.nsc.gov.au)

The value of a quantity can be determined by comparison with a standard of measurement (*vide* Section 2.4). According to s.8A(1) of the Act, the value of a physical quantity can be determined as a standard of measurement, hence the term *recognized-value standards of measurement*. Therefore, pursuant to the provisions of the Act, the value of a quantity can be ascertained by comparison with a value recognised as the standard of measurement. **The values of the positions of the AFN geodetic stations, specified in angular units, have been determined as the standards of measurement of position** [*ibid.*, 1998]. **The values of positions of any subsequent survey marks can be ascertained by comparison with the values of the positions of the AFN geodetic stations**. This approach is the basis for establishing the legal traceability of GPS derived positions.

6.5.1 The hierarchy of the national geodetic networks

The present national geodesy plan is the progressive adoption of a geocentric datum, in the form of the Geocentric Datum of Australia (GDA) to be completed by the year 2000. The resolution to adopt a geocentric datum was driven essentially by the advent of space based positioning technologies, such as GPS, which provide three dimensional coordinates in a geocentric reference frame, and their popular use for scientific research cooperation at international and national levels. Featherstone [1994, p.7] and Collier *et al.* [1996, p.7-10] describe some of the reasons for Australia's decision to move to a geocentric datum, and the anticipated benefits of such a change.

The practical realisation of the GDA is the Australian Fiducial Network (AFN) and the Australian National Network (ANN). These networks comprise very stable geodetic sites distributed across the Australian continent. Manning and Harvey [1992; 1994], Steed [1996a; 1996b] and Morgan *et al.* [1996] describe the stages involved in the establishment of each network. The networks were linked to the International Terrestrial Reference Frame 1992 (ITRF92) during the International GPS Service for Geodynamics (IGS) campaign in 1992. The ITRF92 coordinates for the AFN and ANN were determined in a regional adjustment by constraining the coordinates of several IGS *core stations* [*ibid.*, 1996, p.110]. Later, the coordinates were converted to an epoch of 1994.0 by applying the appropriate velocity estimates [*ibid.*, 1996, p.119]. This set of coordinates is thus known as the GDA94 coordinates.

The estimated precisions of the coordinates in the AFN and ANN coordinates are 2-4 parts per billion (ppb) and 10 ppb respectively [Commonwealth of Australia, 1995a, p.5]. The difference in the estimated precisions is due to the duration of the observation periods: the AFN data were collected over several weeks and, intermittently, over a number of years, while the ANN data were collected over a few days only. Another reason is the fact that, in general, the ANN stations are not permanent monuments, but ground marks [*ibid.*, 1995a, p.5]. Morgan *et al.* [1996, p.iv] estimate that the horizontal precision of the coordinates in the AFN and ANN is less than 3 cm, while the vertical precision is less than 5 cm, both at the 95% confidence level in the ITRF92. The two forms of precision estimates for the coordinates convey the same information in different manners. The ppb value, when evaluated for a distance from the geocentre, should yield a value of less than 3 cm for any coordinate in the AFN (2-4 ppb) and 7.5 cm for any coordinate in the ANN (10 ppb).

Together, the AFN and ANN form the highest order of geodetic networks in the nation; Morgan *et al.* [1996] have therefore classified the AFN and ANN as a *zero order network*, which provides a framework within which lower order geodetic networks are constructed, such as those at the State and Territory levels. Recently, the State and Territory geodetic networks, consisting of GPS networks (refer to Dickson and Zahra [1992] for a description of the Victorian and New South Wales *high precision GPS networks*) and conventional observations, were combined in a national re-adjustment in which the GDA94 coordinates of both the AFN and ANN were constrained [ICSM, 1997b]. The results of this adjustment will be used by the jurisdictional authorities to constrain supplementary networks. The standard error ellipses for the coordinates, at the 67% confidence level, range from less than 1 cm to more than 50 cm [ICSM, 1997a]. The majority, i.e. more than 50%, of the error ellipses are less than 5 cm.

Another level of the national geodetic hierarchy could be that occupied by the networks of GPS permanent reference stations, which have been established by the various jurisdictions to support navigation and positioning applications. For example, Takac and Hale [1996] describe Victoria's efforts in providing GPS permanent reference stations for applications at centimetre positioning accuracies. In Victoria's case, Takac [1997b, p.6] recommended that the coordinates of the reference stations should be determined within the framework of the AFN and ANN.

In order to provide a practical means for cadastral surveys to be connected to a higher order geodetic network, an additional network, termed a *tertiary network*, has to be introduced. Several issues must be considered regarding the spacing between the stations which constitute the tertiary network, some of which are:

- The legal requirements for cadastral surveys to be connected to the AMG; see, for example, *Surveyors (Cadastral Surveys) Regulations 1995* (Vic.) and *Survey Co-ordination (Surveys) Regulations 1992* (Vic.). Such requirements are necessary only when coordinated marks are within *practicable* reach. According to the Surveyor-General of Victoria [1995, pp.4-5], the term *practicable* refers to a situation when coordinated marks exist within 1 km of the survey or when a mark can be reached using less than three instrument set-ups. (This explanation clearly refers to surveys conducted using conventional terrestrial survey means). With the use of GPS technology, however, practicable reach may be extended beyond 1 km, with minimal loss of time.
- Government policy towards reducing the emplacement and coordination of ground marks.
- The operational capabilities of real time kinematic survey systems, which generally are limited to 10 km.

From the above discussions, this thesis recommends that the spacing between the tertiary network stations should be less than 10 km. The recommendation is made with reference to the use of GPS, and not conventional terrestrial survey means, for connecting surveys to the geodetic network. The hierarchy for the geodetic networks is shown in Figure 6.7.

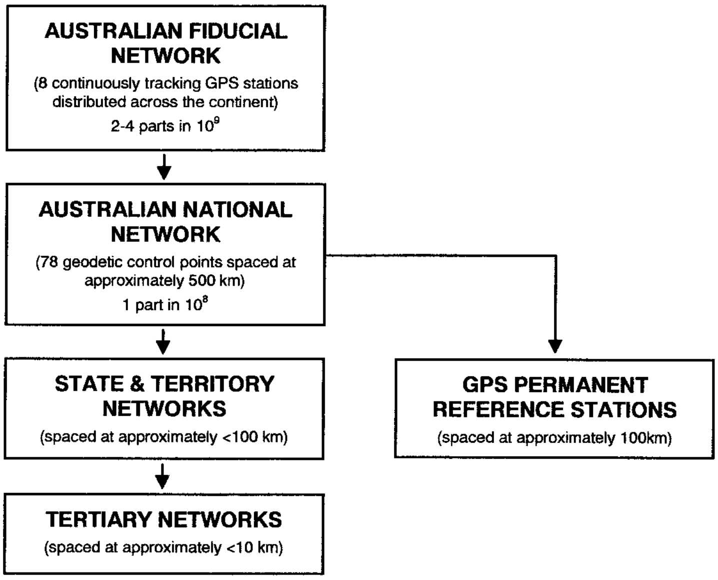


Figure 6.7. The hierarchy of the national geodetic networks shown in descending order.

The foregoing paragraphs have described the Australian geodetic networks in a hierarchical manner, classified according to their degrees of accuracy. Traditionally, such a hierarchy has been necessary due to economic and pragmatic constraints; however, the advent of GPS has made possible the measurement of short and long baselines with almost equal precision and costs. In the future, as the networks become homogeneous, the need for subdivision the network into some form of hierarchy should be obviated. For the near future, the geodetic network is most likely to comprise two levels only; the higher order being the AFN and ANN and the lower being the State and Territory networks comprising the *high precision GPS networks* and GPS permanent reference stations.

6.5.2 Traceability of GPS positions

The positions of survey marks are legally traceable to the recognized-values of the positions of the AFN geodetic stations by virtue of the provisions of the National Measurement Act, in particular s.8A and s.10 (*vide* Section 6.5). Figure 6.8 illustrates the manner in which GPS positions can be traceable to the recognized-value standards of measurement of position. This scheme follows the conventional hierarchical comparison method (Figure 2.1 and Figure 2.2 *vide* Section 2.4.4).

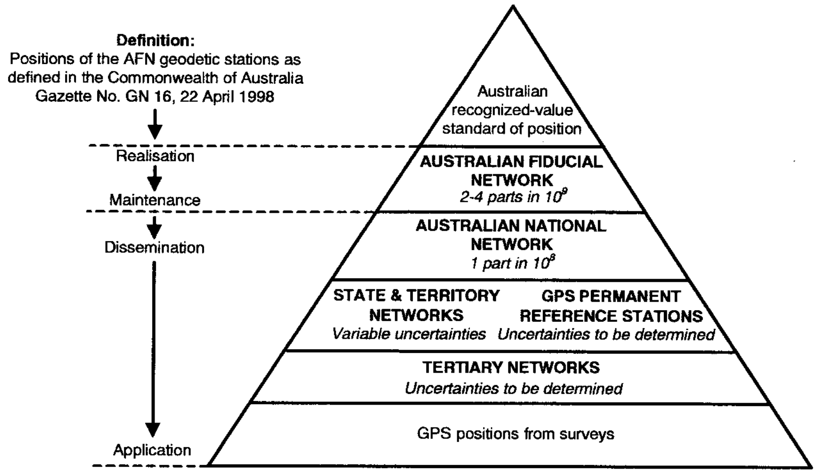


Figure 6.8. Traceability of GPS positions to the recognized-value standards of measurement of position.

Section 5.9 has established that the most appropriate and practical means for verifying GPS results from the connection of a survey to the *geodetic network* (also see Table 5.2). Connection to at least three known points, which have been independently determined, enables the survey to be verified in terms of scale and orientation. (The space and control segments are verified implicitly, since an accurate set of results indicates that the measuring system must have operated properly). Inadequacies in the geodetic network coverage and coordinate homogeneity would require the implementation of an integrity monitoring system. Some of the advantages of using the geodetic network as part of a verification process are (*vide* Section 5.9):

- the results of *each* survey are **verified during the survey**, rather than at regular intervals (hence, temporal and geographical aspects of GPS errors are accounted for during each survey);
- **all three GPS segments would be verified**, therefore obviating the need for implementing an integrity monitoring system;
- the approach **obviates the need to make special verification excursions**, because verification is performed during the conduct of a survey;
- the **objectives of survey coordination can be achieved**, because surveys can be rationalised based on a common spatial referencing system; and
- the option is **technology-independent**, i.e. any measurement technology, including EDM, can be deployed for verification purposes.

The recognized-value standards of measurement of position can be disseminated in the same manner as in the current scheme (*vide* Section 2.7). Essentially, Surveyors General, as *verifying authorities* appointed by the NSC, would issue certificates attesting to the verification of a standard of measurement in pursuance of r.80 of the National Measurement

Regulations. Such a certificate, according to r.80A(1), *is evidence of the matters stated in it* and is admissible as evidence in legal proceedings. The proof of legal traceability of measurements to the national standards is through certificates issued by the verifying authorities following the appropriate verification process. Approved methods of verification are prescribed by the NSC in the Verifying Authorities Handbook [NSC., 1994].

In this model, cadastral surveys conducted using GPS are required to be connected, using recommended guidelines, to at least three control points in a tertiary network, which have been certified pursuant to r.80. The control points can be in the form of ground marks or GPS permanent reference stations. Following the completion of the survey, the network solutions from the survey are compared with the values of the control points constituting a tertiary network. Upon satisfying the tolerances, the results of the survey can be declared as acceptable, as well as traceable to the standard of measurement of position, being the AFN.

In summary, this section has described a model for establishing the legal traceability of GPS derived positions in pursuance of the provisions of the National Measurement Act. The basis of the model is the verification of cadastral survey results, determined using the GPS measuring system, by connection to control points constituting the tertiary network, which, in turn, is linked to the AFN. Hence, GPS derived positions are traceable to the recognized-value standards of measurement of position, being the AFN.

6.6 An integrity monitoring system for the purposes of legal traceability of GPS measurements

The function of the integrity monitoring system is to warn users when not to use GPS or when not to use a specific GPS satellite. Such warnings are issued when the GPS satellites are not operating according to specified tolerances, due to various factors, such as malfunctions, degraded satellite ephemeris or anomalous signals (*vide* Section 5.5). The operational specifications for GPS are provided in two publications, namely *Interface Control Document* [Anon., 1995b] and *Global Positioning System Standard Positioning Service signal specification* [Anon., 1995a]. The warnings are applicable only to those satellites within the coverage area.

In the context of surveying, Manning and Harvey [1994, p.31] suggest that the permanent tracking GPS receivers which constitute the AFN will provide: *Essential information relating to the integrity of individual GPS satellite and to the integrity of GPS system as a whole;...* . This thesis agrees with the foregoing suggestion that the AFN should be used as a basis for an integrity monitoring system for the following reasons: the physical infrastructure for the

AFN is in place and several sites within the Australian Regional GPS Network (ARGN), of which the AFN is a part, namely Casey, Davis, Macquarie Island, Cocos Island, and Hobart, are International GPS Service (IGS) Stations, which provide *continuous tracking using high accuracy receivers and have data transmission facilities allowing for a rapid (at least daily) data transmission to the data centers* [IGS Central Bureau, 1998]. Data from any of the IGS Stations could be used to process information regarding the operational status of satellites. An example of an analysis centre, which provides information regarding satellite performance using data from IGS Stations, is that of the Jet Propulsion Laboratory (JPL) Fiducial Laboratories for an International Natural Science Network (FLINN) Analysis Center (milhouse.jpl.nasa.gov/eng/jpl_hp2.html).

The AFN comprises eight sites, namely Alice Springs, Darwin, Karratha, Yaragadee, Ceduna, Hobart, Tidbinbilla and Townsville (Figure 6.9). The rise and set times for all the satellites passing over individual AFN site at 5° elevation mask were used to determine the minimum number of monitoring stations required adequately to monitor the operational performance of the GPS satellites. As a result, several sites, namely Darwin, Hobart, Karratha, Townsville and Yarragadee have been found to be either the initial or last sites to track the satellites. These sites are called *primary monitor stations*. The remaining sites, namely Alice Springs, Ceduna and Tidbinbilla, are considered as *redundant* sites, because the satellites tracked by these sites are already being tracked by the primary monitor stations. The current AFN configuration is capable of providing adequate coverage for monitoring the performance of all 26 GPS satellites.

Figure 6.9. The Australian Fiducial Network sites.

Section 5.5 has reviewed and described the characteristics of some of the existing integrity monitoring systems implemented for aviation navigation, in particular the Wide Area Augmentation System (WAAS), which has a network of permanent ground monitoring stations with precisely known locations, to verify the integrity of GPS. Some elements in the

WAAS can be adopted and applied in the AFN, which comprises geodetic stations equipped with permanent tracking GPS receivers, to form an integrity monitoring system. Following the WAAS concept, a basic configuration of an integrity monitoring system for the purpose of establishing the legal traceability of GPS measurements could comprise the following elements:

- a network of ground monitoring stations equipped with permanent tracking GPS receivers;
- central processing facilities;
- communication links, dissemination means and an archival system;
- GPS satellites; and
- the user.

The designated AFN sites are responsible for collecting pseudorange measurements from all GPS satellites in view. The data are sent via any convenient communication link, such as telephone, radio or satellite, to a central site for processing to determine the integrity of each satellite. Typically, the integrity of GPS is appraised based on the residuals determined by comparing the estimated pseudoranges to the measured pseudoranges. Residuals lying within the specified tolerance would indicate that the satellites are healthy, while large or rapidly varying residuals would indicate otherwise. This information can be either posted on the internet or disseminated to GPS users via any convenient communication link. Additional facilities for archiving integrity data are required because the integrity information is an important piece of evidence that could be used in future litigation to ascertain the integrity of the measuring system during a particular survey. Figure 6.10 illustrates the basic configuration of an integrity monitoring system.

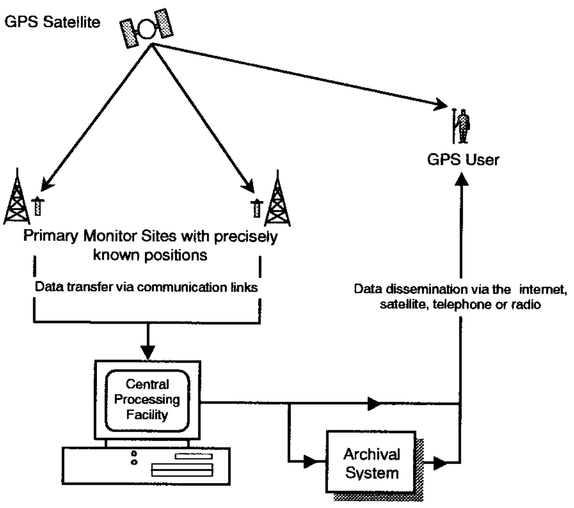


Figure 6.10. The concept of an integrity monitoring system.

6.7 Summary

This chapter has identified **time, relative positions and baseline vectors** as meaningful and practical measurements for cadastral surveying. Subsequently, two models for establishing the legal traceability of GPS measurements for the purposes of cadastral surveying have been developed.

The first model treats **time** as the most basic measurable quantity in GPS. The satellite atomic frequency standards have dual roles; they are used to define the system time scale, namely GPST, as well as for generating timed signals. GPST is directly linked to UTC(USNO), which is a primary time standard, and UTC, which is the legal basis for international civil time. Since all GPS measurements are derived from time, they should be traceable to UTC. However, currently, this model is not tenable within the provisions of the National Measurement Act, which require measurements to be related to Australian standards of measurement. There is no provision within the Act for the recognition of international standards of measurement. This situation may change in the near future, due to demands of international trade, particularly that of the removal of technical barriers to trade, which include the differing national standards of measurement.

The underlying assumption in the **first model** is that in GPS, all time-based quantities can be determined within the accuracy requirements of cadastral surveying through the correct determination of time. In order for this assumption to be valid, the operational domain of the GPS measuring system must perform at acceptable or specified tolerances. An integrity monitoring system is required to monitor and verify the operation of the control and space segments. The user segment must be controlled by ensuring that the responsible surveyor is both sufficiently competent and is in compliance with best practice guidelines for cadastral surveying with GPS. In this model, GPS measurements are traceable to the satellite atomic frequency standards and eventually to UTC. More importantly, traceability of measurements is achieved *during* a survey. The implementation of the four principal requirements for achieving the traceability of time in the Global Positioning System is shown in Table 6.2.

Requirement	Time in GPS
Physical quantity	Time
Unit of measurement	The *second*. The *metre* is implied by virtue of the speed of light being a physical constant.
Standard of measurement	UTC as realised by the atomic frequency standards from around the world.
Means of relating a measurement at the working level to the standard of measurement	GPS measurements are derived directly from satellite atomic frequency standards, which are also used to define GPST. GPST is linked to UTC.

Table 6.2. The traceability of time in the Global Positioning System.

The **second model** has been developed for establishing the legal traceability of GPS derived positions in pursuance of the provisions of the National Measurement Act. In this model, **position is established as a physical quantity**. In Australia, the positions of the AFN geodetic stations have been determined by the NSC as the recognized-value standards of measurement of position. **Hence, the value of any GPS derived position can be traceable to the AFN through a hierarchy of national geodetic networks**. The means for relating GPS positions to the AFN is by comparing the network solutions from a survey with the values of the control points constituting a tertiary network. Due to the existence of inadequacies in the geodetic network coverage and coordinate homogeneity, use of an integrity monitoring system is recommended as an interim measure. The role of the integrity monitoring system is to ensure that the GPS is performing according to specifications. In this way, the cause of any disagreements between network solutions from a survey and the values of the control points can be isolated. More importantly, the traceability of measurements is achieved *during* a survey. The implementation of the four principal requirements for achieving the traceability of GPS positions is shown in Table 6.3.

Requirement	Position
Physical quantity	Position
Unit of measurement	The *metre* and/or angular units.
Recognized-value of standard of measurement of position	The values of the positions of the AFN geodetic stations.
Means of relating a measurement at the working level to the standard of measurement	GPS positions are directly related to the AFN through a hierarchy of national geodetic networks.

Table 6.3. The traceability of GPS positions.

7. CONCLUSIONS AND RECOMMENDATIONS

The aim of this thesis has been to develop a model for establishing the legal traceability of GPS measurements, pursuant to the provisions of the *National Measurement Act 1960* (Cwlth), for cadastral surveying in Australia. In order to achieve this aim, the following research objectives have been set:

- Examine and describe the national measurement system in order to determine the principles for achieving the legal traceability of measurements (Chapter 2).
- Examine and describe the cadastral survey system in order to elicit statutory requirements for ensuring legal traceability of measurements (Chapter 3).
- Describe and analyse the risk factors, and their management, associated with using GPS for cadastral surveying (Chapters 4 and 5).
- Based on the foregoing objectives, develop a model for achieving legally traceable GPS measurements (Chapter 6).

Successive chapters, as indicated, have sought to meet the above objectives and, finally, the aim.

Legal traceability of measurements refers to that property of the result of a measurement or value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties, pursuant to the provisions of the measurement legislation of a nation. Unlike traceability of measurements *per se*, which can be achieved through several routes, legal traceability of measurements can be achieved only under the force of the law. In Australia, the main measurement legislation which prescribes the principles for achieving the legal traceability of measurements is the National Measurement Act. The four principal requirements for establishing legal traceability, contained in s.10 of the Act, are:

- A measurement must be of a physical (measurable) quantity.
- Australian legal units of measurement for the sought-after measurement must be prescribed.
- Appropriate Australian standards of measurement must be available.
- The methods or means for relating measurements to the appropriate standards of measurement must be available.

The concept of legal traceability and its four principal requirements form the basis of this thesis. The main point of note is the requirement for measurements to be traceable to Australian standards of measurement. There appears to be no specific provision for traceability to *international standards of measurement*, i.e. either those standards recognised globally as the best approximation of the SI units or equal standards held by other national metrology institutes. This has significant ramifications for the traceability of GPS measurements to the standards of measurement for the Global Positioning System, which are maintained in the U.S.

The National Measurement Act provides the administrative and legislative framework for the Australian measurement system, which is the infrastructure that supports measurement activities in the country. The national measurement system is part of the wider international measurement system. International traceability of measurements is achieved by way of *international comparisons* of national standards of measurement. In addition, the International Bureau of Weights and Measures (BIPM) has proposed the concept of *international equivalence of national measurement standards* for ensuring international traceability of measurements; this concept aims to provide for a more systematic and transparent approach for undertaking international comparisons through the adoption of BIPM guidelines for *key comparisons*. This drive for international traceability of measurements, consequent on the demands of global commerce, particularly those relating to the removal of technical barriers to trade, is anticipated to result in an amendment of the National Measurement Act so as to recognise international standards of measurement. As a result of such an amendment, GPS measurements would acquire a legal basis by virtue of their traceability to international standards of measurement.

In Australia, legal traceability can be required for measurements carried out for any legal purpose, such as agreements, contracts and court proceedings, as well as measurements which are subject to regulation by law or government decree. Consequently, any survey conducted for legal purposes, such as a cadastral survey, could be required to prove the basis of its measurements. Currently, a surveyor can prove the legal basis of measurements simply by demonstrating that the measurements have been related to the appropriate standards of measurement pursuant to the provisions of the National Measurement Act; production of the appropriate certificates constitutes proof of such compliance.

In Australia, the primary function of cadastral surveying is to define and demarcate parcel boundaries in support of the processes of alienation of Crown land and the subdivision and conveyance of freehold land. In order to preserve the integrity of the cadastral system, survey laws have been enacted, essentially, so as to control the quality of surveyors and surveys. The goal of the laws is to minimise financial risk to the public. Part of the risk management scheme is the requirement for survey measurements to be traceable to national standards of measurement.

Cadastral surveyors, when carrying out measurements, have a statutory responsibility, as prescribed in survey legislation, to ensure that the results of the measurement are a matter-of-fact. Furthermore, by law, cadastral surveyors owe a duty of care to their clients and the general public, who may rely and/or act upon the information or advice provided. In this regard, adherence to statutory requirements, such as use of Australian legal units of measurement, calibration of survey equipment, and prescribed accuracy standards for survey measurements, is required. Current survey legislation prescribes the requirements necessary for ensuring legal traceability of measurements; these requirements apply to the whole *measurement process*, which includes the surveyor, the instrument, the procedures and the accuracy standards. Surveyors are required to prove their competency in the field of cadastral surveying before they can be allowed to practise as cadastral surveyors. In order to ensure the legal traceability of measurements, survey equipment used for a cadastral survey is required to be calibrated and standardised. In most jurisdictions, detailed survey methods are outlined in complementary publications, such as manuals and handbooks. Compliance with the accuracy standards prescribed for cadastral surveys is compulsory. The main requirement which prevents the use of GPS for cadastral surveying is that pertaining to equipment calibration; in other words, the need for measurements to be legally traceable to their standards of measurement.

The GPS measuring system differs in principle from conventional terrestrial survey technology, such as the EDM. The differences include, *inter alia*, the types of measurement, the definition of scale, the user's ability to control the operation of the measuring system, and the characteristics of the factors which affect the accuracy of the measurements. Consequently, calibration, in the conventional sense, cannot be applied to GPS. This realisation is the basis for the departure from the current perception of calibration. GPS measurements must be verified and, hence, made traceable to their standards of measurements *during* the actual survey and not pre- or post-survey. Such an approach would lead to the realisation of the objective of legal traceability, i.e. *each* measurement result has its own associated uncertainty specific to the circumstances in which it was obtained. Verification schemes need not detect and identify individual errors; however, they must be able to indicate whether a GPS survey has complied with the required accuracy specifications for achieving traceability under the current legislation.

In GPS, most of the accuracy degrading factors are either eliminated or significantly reduced in relative positioning through the use of differencing techniques. However, this is possible only when certain equipment, processing and operational strategies have been either adopted or applied. This thesis has outlined various options that can be used to manage GPS measurement biases and errors.

The user's *inability* to control the operation of GPS is a significant limitation, because GPS comprises separate but interdependent control, space and user segments. The space and control segments are not infallible. Integrity lapses in these segments have occurred, and will continue to occur, and their detection and prevention have been difficult, and will continue to be so. Many of the anomalies are quite rare and obscure, and their effects on the user segment are not always well understood. Further, other anomalies that have not been anticipated by the systems designers may yet occur. Therefore, implementing verification measures for the user segment only, whilst ignoring the control and space segments, is not recommended; confirmation that the latter pair are operating according to specified tolerances could be achieved through the implementation of an integrity monitoring system, which should be an important part of the overall verification scheme for establishing legal traceability of measurements. As a result, the integrity of GPS can be *independently* verified in Australia and should obviate the need for dependence on an unreliable external source.

Several methods are available for testing and verifying the elements of the Global Positioning System. These methods have been reviewed and compared in order to ascertain the most appropriate option for the purposes of achieving the legal traceability of GPS measurements. As a result, a decision-making matrix for designing appropriate verification methods was developed. The *geodetic network* option is recommended to be the most appropriate and practical, because verification is performed during the actual survey. The option requires the connection of a GPS survey to at least three known points, which have been independently determined. This enables the survey to be verified in terms of scale and orientation. Further, the space and control segments are verified implicitly, since an accurate set of results indicates that the measuring system must have operated properly.

Based on the four principal requirements for establishing legal traceability, contained in s.10 of the National Measurement Act, two models for establishing the legal traceability of GPS measurements for the purposes of cadastral surveying have been recommended.

The first model treats time, which has the *second* as its unit of measurement, as the most basic measurable quantity in GPS. The *metre* is implicitly defined by virtue of the adoption of the speed of light as a physical constant. The satellite atomic frequency standards have dual roles; they are used to define the system time scale, namely GPST, as well as for generating timed signals. GPST is directly linked to UTC(USNO), which is a primary time standard, and UTC, which is the legal basis for international civil time. Since all GPS measurements are derived from time, they should be traceable to UTC. However, this model is not tenable within the provisions of the current National Measurement Act, which require measurements to be related to Australian standards of measurement. In order to implement this model in Australia, the Act must be amended to recognise international standards of measurement.

The underlying assumption in the first model is that in GPS, all time-based quantities can be determined within the accuracy requirements of cadastral surveying through the correct determination of time. In order for this assumption to be valid, the *operational domain* of the GPS measuring system must perform at specified tolerances. An integrity monitoring system is required to monitor and verify the operation of the control and space segments. The user segment must be controlled by ensuring that the responsible surveyor is both sufficiently competent and is in compliance with best practice guidelines for cadastral surveying with GPS. In this model, GPS measurements are traceable to the satellite atomic frequency standards and eventually to UTC.

The second model has been developed for establishing the legal traceability of GPS derived positions in pursuance of the provisions of the National Measurement Act. In this model, position is established as a physical quantity. In Australia, the positions of the AFN geodetic stations have been determined by the NSC as the *recognized-value standards of measurement of position*. Hence, the *value* of any GPS derived position can be traceable to the AFN through a hierarchy of national geodetic networks. The means for relating GPS positions to the AFN is by comparing the network solutions from a survey with the values of the control points constituting a tertiary network. However, due to inadequacies in the geodetic network coverage and coordinate homogeneity, the implementation of an integrity monitoring system is recommended.

The first model is the preferred option because of its simplicity. Essentially, the only major difference between this model and current measures for ensuring legal traceability of measurements is the integrity monitoring system, which serves to safeguard the proper operation of the Global Positioning System. Verification measures, such as independent verification methods, which should be outlined in best practice guidelines, are an extension of current survey practice. However, the most significant change, introduced by the model, is the traceability to international standards of measurement rather than to Australian standards of measurement. Following the recognition of international standards of measurement in the National Measurement Act, links, i.e. standards of measurement and uncertainties, between the measurements and the standard of measurement must be formalised so that the GPS measurements can be given a legal basis.

The second model is a practical solution and its implementation should be familiar to surveyors. However, the underlying concepts which form the basis of the model are relatively novel. For the first time, a position is recognised as a physical quantity in the National

Measurement Act. Position *per se* is not an unfamiliar concept in surveying, as evidenced in the accuracy standards specified for positions in survey legislation.

Both models extend the current philosophy of *calibration* by verifying and, hence, establishing traceability of measurements during the actual survey. However, according to the requirements of the current National Measurement Act, only the second model provides a basis for achieving the legal traceability of GPS measurements.

7.1 Recommendations

This thesis recommends the following:

1. In order to achieve the legal traceability of GPS derived positions, the *position-based model* should be implemented. However, upon the eventual recognition of international standards of measurement in the National Measurement Act, the *time-based* model should then be adopted.
2. In order to ensure that GPS measurements are traceable to their standards of measurement, all three segments of the Global Positioning System must be treated as an integrated measurement system. The user segment, in particular, should include the surveyor, survey equipment, survey observation techniques and procedures, data processing software and methods, and verification mechanisms.
3. In order to ensure the proper operation of GPS, specifically the control and space segments, an integrity monitoring system should be implemented. In this regard, some of the geodetic stations in the Australian Fiducial Network should be considered as *monitor sites*, due to its existing infrastructure.
4. In order to provide proof of operational status or integrity of the measuring system during a particular survey, an archival system should be included in the integrity monitoring system.
5. In order to manage the factors which degrade the accuracy of GPS measurements, the GPS measuring system must be verified *during* a survey. In this regard, verification schemes need not detect and identify individual errors; however, they must be able to indicate whether a GPS survey has complied with the required accuracy specifications for achieving measurement traceability under the current legislation.
6. In order to manage effectively the factors which degrade the accuracy of GPS measurements, *best practice guidelines* must specify GPS equipment, processing and operational strategies outlined in Chapter 4.

7. In order to ensure that the results of a GPS survey are commensurate with the accuracy standards stipulated in survey legislation, the overall model for verifying GPS measurements must include some means for assessing a surveyor's competency, particularly in the area of measurement science. Surveyors should be required to demonstrate that they have a basic understanding of, and are sufficiently proficient in, the application of the technology, in which professional knowledge and practical skills are important for its proper application and operation, and the attainment of appropriate high quality results.

7.2 Future research

As corollaries to this thesis, potential areas for further research include:

- The investigation and development of specifications, requirements and costs of establishing and maintaining a geodetic network for measurement traceability purposes.
- The development of appropriate accuracy standards for GPS surveys. Existing accuracy standards favour conventional terrestrial survey technology and, in many cases, are inappropriate for GPS. Appropriate accuracy standards, in the context of this thesis, are important because they are the basis for the determination of measurement uncertainties, which in turn form the links in the traceability chain. Appropriate accuracy standards can be determined from statistical analysis of a large sample of surveys conducted in a variety of conditions and with different techniques, such as static, kinematic and real time kinematic. More importantly, however, a survey of community expectations should be conducted in order to elicit practical accuracy standards.
- The development of efficient and effective independent verification methods for GPS surveys. Many of the existing methods, such as re-occupation, can be considered to be uneconomical. Current research into areas pertaining to the integration of terrestrial and space-based positioning technologies should be extended to include the possibility of providing a means for comparing measurements obtained from the two independent positioning modes. Upon the eventuality of such a technology, angles and lengths determined by a total station could be verified by those determined by GPS. Through such a technology, the calibration of EDM devices could possibly be conducted by direct comparison with the satellite atomic frequency standards, rather than on the conventional EDM calibration baselines.

- Investigation of the use of GPS permanent reference stations for measurement traceability purposes. Issues such as separation and coverage of installation sites should be considered with the object of facilitating optimum implementation schemes. Measurement uncertainties associated with the reference stations should then be determined in order to place them in the appropriate level in the hierarchy of standards of measurement.
- Investigation of the *test network* option, albeit not recommended for measurement traceability purposes, as a facility for the accreditation of GPS surveyors, and the comparative evaluation of GPS survey systems and methodology. In particular, the network's suitability for testing different techniques, such as static and post-processed or real time kinematic should be examined.

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APPENDIX - DERIVATION OF COSTS ASSOCIATED WITH VERIFICATION METHODS

Labour costs

Derived from: Guide for Survey Fees for Consulting Surveying Services, 1998, Association of Consulting Surveyors (Victoria) Inc., Melbourne, Victoria, January, 22 pp.

Suggested Charge Out Hourly Rate for:

Professional Surveyor/Licensed Surveyor (Level 3)	$78
Survey Technician (Level 8)	$62

Assumptions:

A surveyor has a pair of survey grade GPS receivers and a copy of GPS processing software

Test Data for Software

Assumption:

Each test requires approximately 1 hour to perform

Professional Surveyor/Licensed Surveyor	$78	(Surveyors costs)

Zero Baseline Test

Assumption:

Each test requires approximately 2 hours to perform

Professional Surveyor/Licensed Surveyor	$156	
Hire of antenna splitter for one day	$30	
Total costs	$186	(Surveyors costs)

EDM Calibration Baselines

Infrastructure:

EDM Calibration Baselines currently exist

Initial survey to determine coordinates of points

Assumption:

Each Calibration Baseline requires approximately 1 day (8 hours) to survey using static GPS

Professional Surveyor/Licensed Surveyor	$624	
Survey Technician	$496	
Total survey costs for 1 Calibration Baseline	$1,120	
Total establishment costs for 1 Calibration Baseline	$1,120	(Institutional cost)
Annual maintenance costs (resurveys)	$1,120	(Institutional cost)

Costs to the surveyor for conducting the test

Assumption:

Each Calibration Baseline requires approximately 1 day (8 hours) to survey using static GPS

Professional Surveyor/Licensed Surveyor	$624
Survey Technician	$496
Survey costs	$1,120 (Surveyors costs)

Test Network

Assumption:

A network comprises 5 survey marks (the longest baseline is 10 km)

Infrastructure

Permanent Survey Mark in situ casting according to Schedule 1 of the Survey Co-ordination (Surveys) Regulations 1992

Survey Mark (Brass Plaque)	$8
Concrete ($5.50/bag x 3)	$17
Labour for 1 hour (Technician)	$59
Total cost for placing each mark	$84
Total cost for placing 5 marks	$418

Initial survey to determine coordinates of points

Assumption:

Each network requires approximately 2 days (16 hours) to survey using static GPS

Professional Surveyor/Licensed Surveyor	$1,248
Survey Technician	$992
Total survey cost for 1 network	$2,240
Total establishment costs for 1 network	$2,658
Annual maintenance costs (resurveys)	$2,240 (Institutional cost)

Costs to the surveyor for conducting the test

Assumption:

Each network requires approximately 2 days (16 hours) to survey using static GPS

Professional Surveyor/Licensed Surveyor	$1,248
Survey Technician	$992
Survey costs	$2,240 (Surveyors costs)

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