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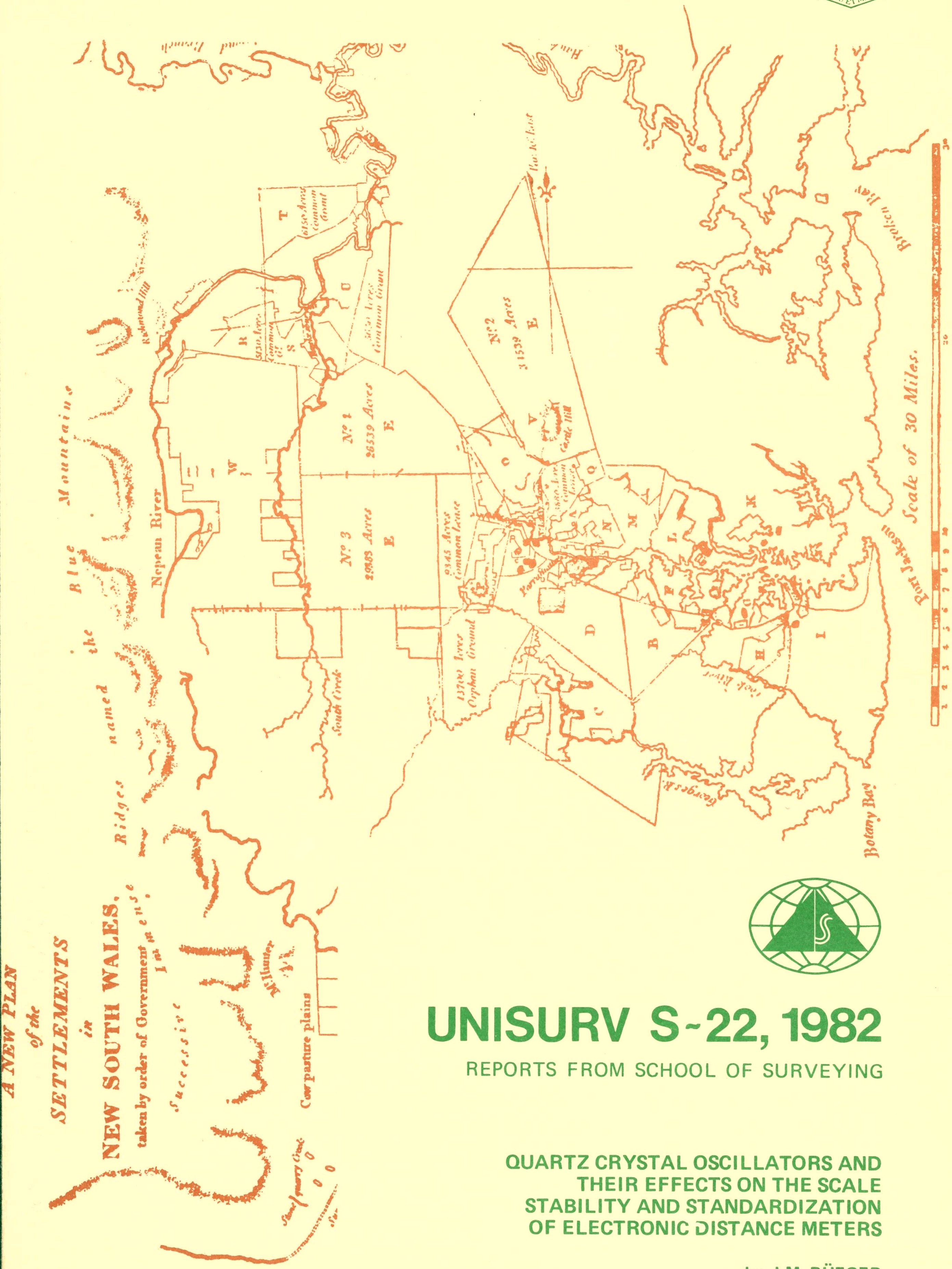

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QUARTZ CRYSTAL OSCILLATORS AND THEIR EFFECTS ON THE SCALE STABILITY AND STANDARDIZATION OF ELECTRONIC DISTANCE METERS

by J.M. RÜEGER

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ABSTRACT

This study examines the effects of quartz crystal oscillators on the stability and the calibration of scale (standardization) of short-range electronic distance meters. A wide range of parameters which cause changes and instabilities in the oscillator frequency (and thus in the metric scale of distance meters) is investigated. The magnitude of these effects is determined and the ultimate accuracy of laboratory calibration techniques evaluated.

To establish a list of parameters affecting quartz crystal oscillators, the construction and properties of such devices is reviewed in detail with respect to room temperature crystal oscillators and temperature controlled crystal oscillators commonly employed in short-range distance meters. Several frequency measuring techniques are investigated and their results compared. A photodetector unit was constructed to allow indirect frequency measurement. Eight different distance meters of the types AGA Geodimeter 14, Hewlett-Packard HP 3800B, HP 3805A, HP 3820A, Kern DM 501 and Topcon DM-C2 were tested in the laboratory for the temperature characteristic, the warm-up effect, the non-linearity of ppm-dials, ageing, retrace, hysteresis and electromagnetic interference. Calibration values for the various oscillator effects were derived from these tests and were field tested in the case of four instruments against direct frequency measurement in the field. This established the validity of laboratory standardization data for the correction of distances measured in the field.

The largest errors measured were a 0.6 ppm cable loading effect, a 0.46 ppm/^{o}C temperature drift, a 5.2 ppm warm-up effect, a 4 ppm non-linearity of a ppm-dial, a 0.8 ppm/year ageing rate, a 1.1 ppm retrace effect and a 0.7 ppm hysteresis effect. Electromagnetic interference of transceivers and electric motors caused maximum errors of 2700 ppm and 160 000 ppm respectively. A frequency change of 1.4 ppm between still air and ventilated air operation of an oscillator was recorded.

Retrace and hysteresis were found to be the ultimate limitations of scale stability in EDM; they cannot be predicted and may cause errors of up to 1.1 ppm. In cases where these errors are insignificant, laboratory standardization of simple and inexpensive short-range distance meters enable the correction to true scale of field distance measurements with an accuracy of ± 0.5 part per million.

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1. INTRODUCTION

The method of *electronic distance measurment* (EDM) has been generally adopted by the surveying profession during the last ten years, replacing other means of distance measurement such as graduated steel bands or tapes. The acceptance of EDM by surveyors coincides with the introduction of *short range electro-optical distance meters* on the surveying equipment market. Such EDM instruments typically measure distances of up to 1000 m with a precision of ± 10 mm and are much smaller, lighter (approx. 2 kg) and particularly cheaper than earlier types of EDM instruments.

To measure a distance, the distance meter is set up over one terminal of the line to be measured and a reflector, which reflects the rays emitted by the distance meter back to the distance meter, over the other terminal of the line. The distance meter emits, through the transmitter optics, an amplitude modulated and continuous infrared beam and receives the same beam, after reflection by the reflector, through the receiver optics. The EDM instrument determines the length of the line between the instrument and the reflector by measuring the phase difference between the transmitted and the received modulation signal and by addition of a number of full wavelengths of the modulation signal. As the signal travels twice over the distance (forward and backward) a division by two is executed before the result of the distance measurement is displayed. The distance as displayed by the distance meter is therefore effectively determined in terms of the modulation wavelength imprinted on the infrared beam by counting the number of full wavelengths spaced over the line and by measuring the remaining fraction of the modulation wavelength. Because of the double measurement of the distance and the required division by two, it is usually said that the EDM instrument determines a distance in terms of its *units length*, being the exact half of the modulation wavelength. The unit length is typically 10.0 m, which means that all measurements involve the measurement of the number of multiples of ten metres in a distance and the remaining fraction of the 10 m unit length.

After this short review of the working principle of a short range distance meter (for more details, see e.g. RÜEGER, 1980), the importance of the unit length of an EDM instrument becomes clear. The *standardization* of an EDM instrument can now be defined as the measurement of the length of its unit length in terms of the international standard of length, the metre. The standardization will therefore tell the exact length of the "yard stick" with which the instrument measures a distance. If the "yard stick" is too short, all distances will be measured too long; if the "yard stick" is too long, all distances will become too short. Errors in the length of the "yard stick" lead to errors in distance, which increase or decrease with distance and which are often referred to as *scale errors*. The standardization will determine a scale factor, which, when multiplied by the distance values as displayed by an EDM instrument, converts displayed distances into distances based on the international unit of length or, simply, into truly metric distances.

The standardization of a distance meter forms part of a full *calibration* of a distance meter. A calibration comprises the measurement of all errors present in measurements executed with a particular instrument, and not solely the error in its unit length. The standardization however is a very important part of a calibration, as it ascertains that all measurements are in conformity with the standard of length. This is particularly so in countries, such as Australia, where surveys are normally not tied into higher order survey networks and where scale errors would pass unnoticed if not eliminated by standardization. Furthermore, standardization is of prime importance in countries such as Australia, where surveyors are required by law to comply with the (national) standard of length (RÜEGER, 1980b). In Australia, for example, stringent rules on standardization of steel bands and tapes have been in force for years (RÜEGER, 1980b) and the techniques are well established. Due to the relative novelty of electro-optical short range distance meters and due to their use as a "black box" producing a result upon pressing a button, the standarization techniques for such instruments are not well established and the accuracy of standardization is not well known.

Two distinct techniques are being used to standardize distance meters, namely the *baseline technique* and the *frequency measurement technique*. In a first approximation, both methods produce equivalent results. In the baseline technique, several lines of known length are measured with the distance meter and the scale error correction is derived from the difference between measured and known lengths.

It is interesting to note that the baseline technique has been used in the past to determine the velocity of light (SANDERS, 1965; FROOME & ESSEN, 1969). In fact, one apparatus developed for this purpose later became the first commercial electro-optical distance meter.

The second standardization technique relies on the measurement of the frequency which modulates the infrared beam of the distance meter. As the modulation wavelength is directly related to the unit length of the distance meter, the modulation frequency is also a measure of the unit length. The modulation frequency is derived from the resonance frequency of a quartz crystal oscillator and can be determined, for example, by connecting a frequency counter to appropriate points of the circuitry of the distance meter. The scale error correction is derived in this case from the ratio of the measured to the nominal frequency. It is evident that the baseline technique is a field technique, while the frequency measurement techniques is a laboratory one, thus adding a further distinction to the two methods.

In this study, only the frequency measuring technique in standardizing short range distance meters is investigated. The technique is and has been employed for a long time to standardize long range distance meters. However, the techniques has been applied only recently to short range distance meters, where it requires more sophistication because of the simpler design of the oscillators involved and because of the lack of frequency output sockets.

In addition to legal and quality control aspects, the improvement in accuracy is an aspect of standardization which is becoming increasingly important, particularly in the area of precise engineering surveys. Over one kilometre, the oscillator's specification contributes typically 50 percent of the error budget (5 mm + 5 mm/km). Over two kilometres the oscillator's contribution has already reached 75 percent! By standardizing a short range distance meter to an accuracy of much better than 5 mm/km, its performance is greatly improved. One of the aims of this work is to demonstrate to what level of accuracy standardization may be achieved.

Another aim is the evaluation of the potential, problems and limitations of frequency standardization of short range distance meters. This necessitates a detailed knowledge of the characteristics of quartz crystal resonators and oscillators. These components are therefore reviewed to allow a better understanding and prediction of the various effects which can be expected during practical frequency measurements. A description of the different techniques of frequency measurement follows, then extensive frequency tests on eight short range distance meters are discussed. The validity of this laboratory frequency standardization is finally demonstrated on the basis of tests on an EDM baseline where predicted standardization parameters are compared with field-measured frequency data.

2. QUARTZ CRYSTAL OSCILLATORS

2.1 Introduction

LAURILA (1976) defines an oscillator as 'circuitry that converts direct current (DC) drawn from an energy source (battery) into alternating current (AC) where the electromagnetic energy alternates at the radio frequency'. The frequency of an oscillator circuit can be stabilized at a fixed value by placing a resonating quartz crystal resonator at the appropriate position in the circuit. The resulting circuit is called a quartz crystal (controlled) oscillator.

Quartz crystal oscillators relate in many ways to the problem of standardization of EDM instruments. Firstly, as already mentioned, the modulation frequency and thus the unit length is derived from a quartz crystal oscillator, in all instruments. The unit length is therefore locked to the frequency of the oscillator. Secondly, the time bases in frequency counters, which are employed for the measurement of the modulation frequencies of distance meters, are again quartz crystal oscillators. The accuracy of measurements executed with frequency counters is directly related to the accuracy of the built-in quartz crystal oscillator. Thirdly, frequency standards, against which the frequency counters (and sometimes the EDM instruments themselves) are calibrated, are also based on quartz crystal oscillators, either on their own or combined with and stabilized by a caesium beam standard or a rubidium vapour standard (HEWLETT-PACKARD, 1974). Because quartz crystal oscillators are very important in the context of the standardization of EDM instruments, a detailed review of such devices is required.

The vibrator quality of quartz crystals is based on the *piezoelectric effect*. CADY (1946) defines a piezoelectric crystal 'as a crystal in which "electricity" or "electric polarity" is produced by pressure' or as one 'that becomes electrified on squeezing'. This is referred to as the *direct* piezoelectric effect. The deformation of a piezoelectric crystal whilst in an electric field describes the *converse* piezoelectric effect. A more stringent definition of the direct effect is given again by CADY (1946) as 'electric polarization produced by mechanical strain in crystals belonging to certain classes, the polarization being proportional to the strain and changing sign with it'. The converse effect causes 'a piezoelectric crystal to become strained when electrically polarized by an amount proportional to the polarizing field'.

Piezoelectricity was discovered by the brothers Pierre (1859-1906) and Jacques (1855-1941) Curie in 1880, the former being well known for his work on radioactivity. Development of piezoelectric resonators commenced around 1918, followed by applications as stabilizers, oscillators and filters. Although many crystal materials exhibit the phenomenon of piezoelectricity, quartz (silicondioxide SiO_2) was soon found to be the most suitable material because of its almost ideal elastic qualities, small hysteresis, great mechanical strength and stability and excellent chemical stability. Quartz crystals exhibit a sharp resonance, an excellent temperature stability and allow the construction of resonators of convenient size covering the frequency range from 50 Hz 300 MHz.

The resonance frequency and other properties of a quartz crystal resonator are determined by the size, shape and angle of cut (relative to the three crystal axes of the mother quartz) of the quartz bar or plate. The problem of poor temperature stability of early cuts (X-cut, Y-cut) was overcome in 1934 with the discovery of the so-called AT-cut (LACK, WILLARD & FAIR, 1934). Because of the good temperature stability and convenient resonant frequencies ranging from 0.5 to 250 MHz (GERBER & SYKES, 1966), AT-cuts are used for a wide range of applications ranging from radio transmitters and receivers to wrist watches, microprocessors and EDM instruments. The GT-cut discovered in 1940 (MASON, 1940) exhibits an even better temperature stability, but is restricted to frequencies between 100 kHz and 1 MHz (CADY, 1946). The SC-cut (SC for stress-compensated) was introduced in 1974 (HOLLAND, 1974) and is now used in frequency standards (ADAMS & KUSTERS, 1981). The principle and properties of quartz crystal resonators are now discussed in more detail.

2.2 Quartz Crystal Resonators

2.2.1 Construction

CADY (1946) defines a piezoelectric resonator as 'an elastic solid body consisting partly at least of piezoelectric crystalline material, capable of being excited to resonant vibration by an alternating electric field of the proper frequency. In its simplest form it is a single piece of crystal, usually cut to prescribed size, shape and orientation. The electric field is applied by means of electrodes, so situated that the field will be in the proper direction to excite the desired mode of operation.' The electrodes are deposited directly on the polished (lapped) crystal plate by vapour deposition. The electrodes may cover the central area of the quartz disc or two opposite parts of the circumference depending on the desired mode of vibration and the design. A typical 10 MHz resonator may have a diameter of 12 mm and a thickness of 1.06 mm (HEWLETT-PACKARD, 1978). The quartz plate is supported at two or more points with low damping tension wires or ribbons which act also as leads and which are fixed to a ceramic header. The mechanical support should be positioned in such a way that avoids any inhibition of the desired vibration. It may even be optimized to suppress unwanted vibrations of the quartz plate. A typical mounting system is depicted in Figure 2.2.1 (QUARZ AG).

To guarantee a clean environment for the quartz, the resonator is enclosed in a sealed metal or glass container of flat rectangular or cylindrical shape. Typical dimensions are (FRERKING, 1978):

13.5 x 10.2 x 3.8 mm
19.7 x 18.4 x 8.0 mm
ø 8.3 mm; 6.7 mm high

The housings of the resonators are either evacuated or filled with inert gases to maintain a clean environment. All-glass holders are always evacuated. In the case of metal housings, the method of fixing the cover to the base is very important, because the sealing method may destroy the clean environment inside the case. Solder sealed and cold-welded cans are different, the latter being the preferred type because less impurities get into the case during the sealing process. The cold-weld technique can be used in a vacuum after a high temperature bake-out of the resonator for pre-ageing purposes (GERBER & SYKES, 1967). More information on the manufacture of quartz plates and resonators can be found in the book by HEISING (1952).

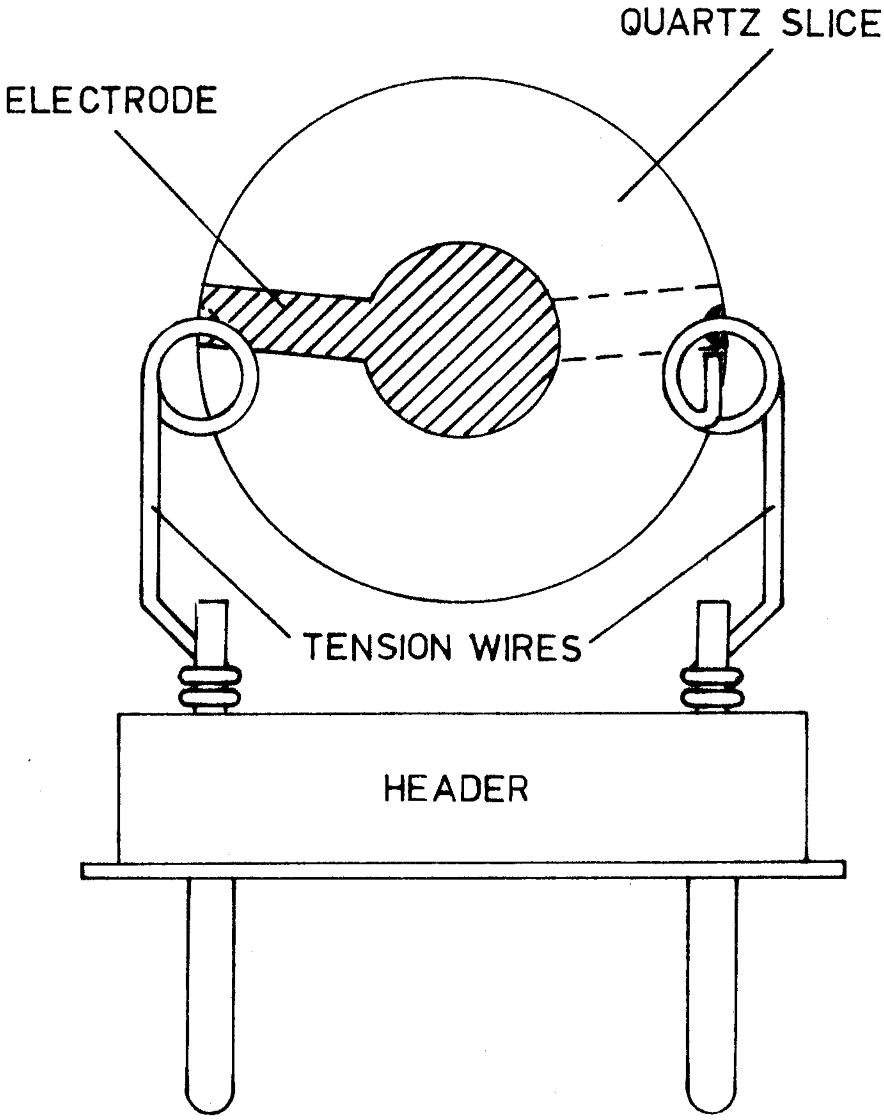

Fig. 2.2.1 Mounting of a quartz crystal resonator

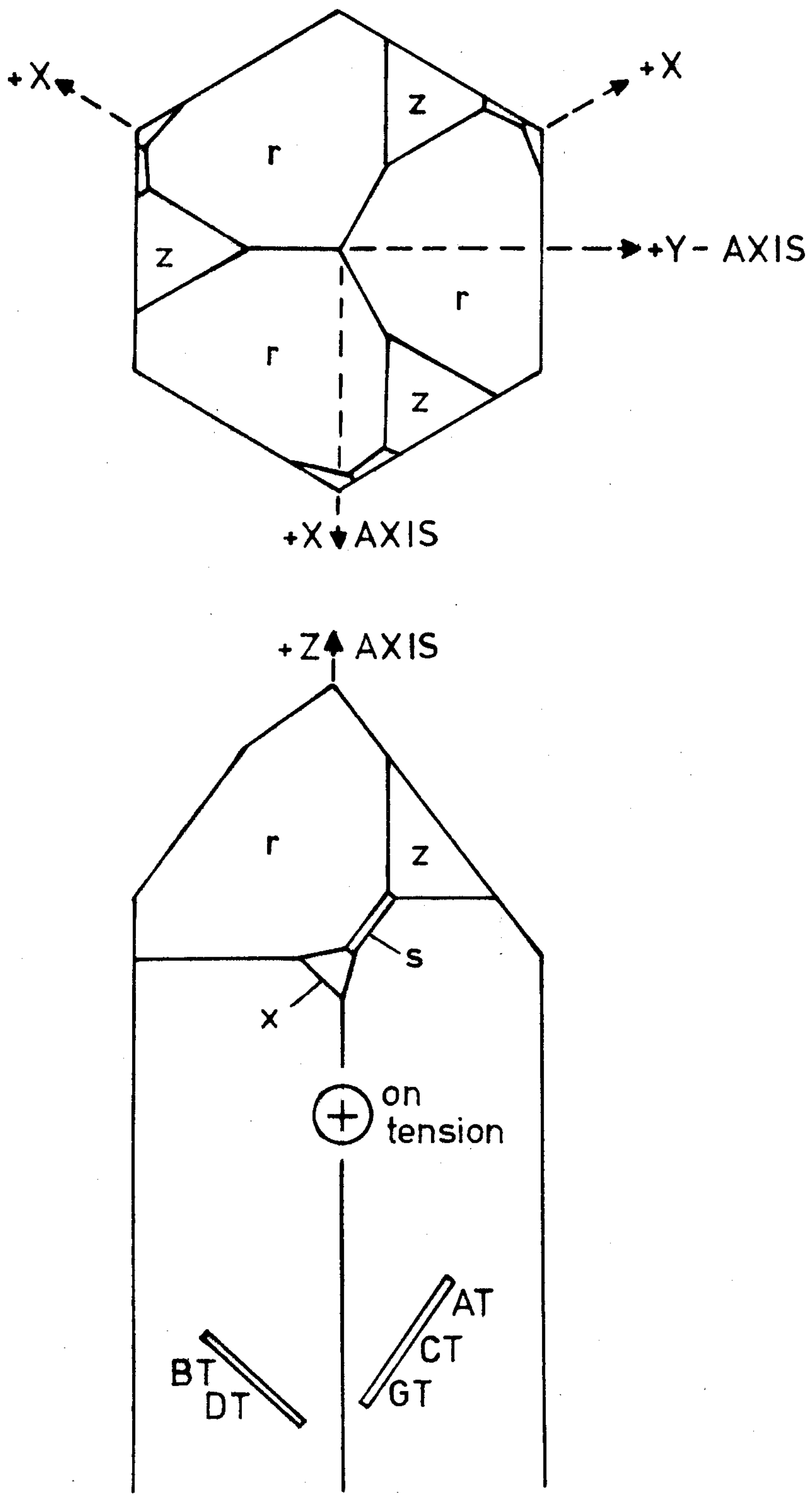

Fig. 2.2.2 Quartz crystal: Axes and cuts

2.2.2 Quartz Cuts and Modes of Vibrations

As the various crystal properties depend on the orientation of the quartz plate relative to the three crystal axes of the mother quartz, the mode of vibration, the resonant frequency and its properties, such as the temperature characteristics, also follow from the orientation of the crystal plate in the coordinate system. In fact, there are 18 possible relations between the mechanical and electrical states of the crystal, which can be expressed by the 18 piezoelectric constants (CADY, 1946). The orientation of an oblique plate can be defined by up to three rotations of the crystal coordinate system X, Y, Z as defined in Figure 2.2.2 for right-handed quartz (IEEE, 1978). The Z-axis is the polar axis, the X-axis one of the three diagonal axes. When comparing Figure 2.2.2 with figures in references, it should be noted that the definition of the X-axis was changed in the 1978 standard as compared to earlier standards (IEEE, 1949; IRE, 1949; ANSI, 1951). The presently accepted notation for the description of quartz plates is defined by the *Standards on Piezoelectricity* (IEEE, 1978) and is basically in agreement with the definition given in earlier standards (IEEE, 1949; IRE, 1949; ANSI, 1951), the only difference being the different signs of the rotation angles. The definition differs distinctly however from even earlier notations (CADY, 1946; HEISING, 1952). A specific triple-rotation cut may have the notation (YZ twl) $30^{o}/15^{o}/40^{o}$. As the "old" standard (IRE, 1949) explains the notation in more detail than the "new" standard (IEEE, 1978) the definition of the former is given here:

A. The first two letters of the symbol (bracket term) indicate the initial orientation used.
   - (a) The *first* letter is X, Y or Z, and indicates the direction of the plate *thickness* before any rotations have been made.
   - (b) The *second* letter is X, Y or Z, and indicates the direction of the plate length before any rotation.
   - (c) These two letters completely specify unrotated plates.

B. The remaining letters of the symbol indicate the plate edges used as axes of rotation.
   - (a) The *third* letter of the symbol is t, l or w, according to whether the thickness direction, length direction or width direction is the axis of first rotation. If one

rotation suffices (single-rotation cut) there are only three letters in the symbol.

(b) The *fourth* letter is t, l or w according to the edge used for the second rotation. If two rotations suffice (double-rotation cut) there are only four letters in the symbol.

(c) The *fifth* letter is t, l or w according to the edge used for the third rotation (triple-rotation cut). There need be no more than five letters in the symbol.

C. The symbol is to be followed by a list of rotation angles phi, theta, psi; angles negative in sense will be indicated by a negative sign.

(a) A positive angle means rotation counter-clockwise as seen looking toward the origin from the positive end of the axis of rotation.

(b) The positive ends of the axes t, l, w are the ends that initially pointed in the positive directions of the three coordinate axes X, Y and Z.

The cuts mentioned earlier in section 2.1 are now defined in Table 2.2.2.1

CUT	DEFINITION
X	(XY), (XZ)
Y	(YX), (YZ)
AT	$(YX\ell)-35.25^{o}$
BT	$(YX\ell)+49^{o}$
GT	$(YX\ell t)-51^{o}/-45^{o}$
SC	$(YXw\ell)-21.93^{o}/-34.11^{o}$

Table 2.2.2.1: Definition of Quartz Cuts, conforming to the ANSI/IEEE Standard 176-1978.

The mode of motions which can be excited in a bar or plate of quartz depends on its dimensions, its cut relative to the crystal axes (see Table 2.2.2.1) and the direction and frequency of the electrical field applied. Three basic types of motion can be distinguished (HEISING, 1952):

* flexural
* extensional
* shear

In the *flexure* mode a *quartz bar* vibrates about two or more nodal points; its centre line does not change length. If the motion is about two nodes, the bar vibrates in the fundamental mode. The second and third mode exhibit three and four nodes respectively. Similarly, a *quartz plate* can vibrate in the flexure mode. The vibrations about the length and width dimensions may not be of the same order, and thus may exhibit a different number of nodal points. The location of nodal points must be considered when designing the support of the vibrator. The vibrator is ideally supported at nodal points to avoid interfering with the vibration.

The fundamental *extension mode* of a bar consists simply of the extension and contraction of the bar around its centre. In the case of higher order modes, certain parts of the bar will be expanding whilst other parts will be contracting. The extension mode of a bar is sometimes called the *longitudinal mode*. In plates, three extensional modes are possible due to the three dimensions, the *thickness vibration* being a very important mode of operation.

Two cases of the *shear mode* of plates must be considered, namely the face shear and the thickness shear modes. The *face shear* mode may be explained by a simple case where the two diagonals of the length-width plane expand and contract out of phase. This shear mode is sometimes referred to as low frequency shear. In the high frequency *thickness shear* mode, the top face of the plate moves in one direction and the bottom face in the opposite direction. In this mode, only odd harmonics can be obtained, notably the third and the fifth overtone. (Illustrations of the thickness shear mode may be found in the books by KAHMEN (1977) and ZETSCHE (1979)).

The velocity of wave propagation c in a crystal can be defined in terms of the effective stiffness elastic constant q and the density ρ (CADY, 1946)

$$c = \left(\frac{q}{\rho}\right)^{0.5} \qquad (2.2.2.1)$$

Considering the fundamental equation

$$c = \lambda f \qquad (2.2.2.2)$$

where the wavelength and the frequency are denoted by λ and f respectively, and the relationship (fundamental mode)

$$\lambda \; = \; \sim 2e \qquad (2.2.2.3)$$

in the case of thickness and thickness shear vibration in a plate of thickness e, the velocity c yields

$$c \; = \; \sim 2ef \qquad (2.2.2.4)$$

For the fundamental mode, the frequency of a vibrating plate in the thickness or thickness shear mode becomes:

$$f \; = \; \sim \frac{1}{2e} \left(\frac{q}{\rho} \right)^{0.5} \qquad (2.2.2.5)$$

In the case of higher order modes or overtones the frequency may be expressed as

$$f_h \; = \; \sim \frac{h}{2e} \left(\frac{q}{\rho} \right)^{0.5} \qquad (2.2.2.6)$$

or using the wave constant H = fe (CADY, 1946)

$$f_h \; = \; \sim \frac{hH}{e} \qquad (2.2.2.7)$$

It must be noted that an overtone frequency f_h will never be an exact multiple of the fundamental frequency f because of the boundary conditions of a finite plate and coupling with shear modes in other directions and with flexure modes (MASON, 1950).

In addition to the fundamental frequency (and its overtones) a quartz crystal will always exhibit a number of other frequencies, called *spurious responses*. These are caused by modes of vibration, other than the response of interest, which are possible in any quartz plate. Most spurious responses have a higher resistance (smaller amplitude of vibration) and a higher frequency than the main response (FRERKING, 1978). The presence of a spurious response of low resistance (large amplitude of vibration) close to the main response could make an oscillator circuit operate on the frequency of the spurious response rather than the main response. This would be unacceptable. Unwanted responses can be suppressed by *contouring* of the plate (e.g. plano convex shape) and/or by varying the diameter and thickness of the electrodes *(energy trapping)* (GERBER & SYKES, 1966). Examples of frequency responses of quartz plates may be found e.g. in KUSTERS, ADAMS, YOSHIDA & LEACH (1977), KUSTERS & LEACH (1977) and FRERKING (1978).

Summarizing, some common cuts of quartz plates are described in terms of mode of vibration, wave constant H, and frequency range, in Table 2.2.2.2.

Cut	Mode of vibration	H kHz•mm	Frequency MHz
X	extensional (thickness)	2870	ultra-sonic
X	extensional (longitudinal)	2700	LF
Y	thickness shear	1954	high
Y	face shear		low
AT	thickness shear	1622	0.5-250
BT	thickness shear	2549	1.0-30
GT	extensional (thickness)	3292	0.1-0.5
SC	thickness shear		HF

Table 2.2.2.2: Data of quartz cuts

The data in Table 2.2.2.2 have been taken mainly from CADY (1946), MASON (1950) and GERBER & SYKES (1966). Overtone operation is commonly used in thickness shear cuts and exhibits higher response, better ageing, improved electrical stiffness and mechanical stability (FRERKING, 1978). A typical 10 MHz 5th-overtone AT-cut vibrator has a diameter of 12 mm and a thickness of 1.06 mm. Considering Eq. 2.2.2.7 and the wave constant of 1662 kHz mm (AT-cut) in Table 2.2.2.2, the thickness of a 10 MHz fundamental mode vibrator would yield 0.17 mm. As thin quartz plates are very fragile, FRERKING (1978) does not recommend fundamental mode AT-cut resonators for frequencies above 30 MHz (thickness = 0.06 mm). Common 10 MHz AT- and GT- resonators are therefore designed as third or fifth overtone units (KUSTER & LEACH, 1977, FRERKING, 1978).

2.2.3 Frequency Stability

The stability of the frequency of quartz crystal vibrators is very important in the context of EDM instruments and their standardization by the frequency measurement technique. The stability depends on many environmental factors, the effects of which are discussed in detail below.

2.2.3.1 Dependence on Temperature

The temperature dependence of quartz crystal resonators can be easily explained by considering two parameters of Eq. 2.2.2.5, namely the density and the thickness of the quartz plate. A direct temperature effect is caused by the temperature dependence of the density of quartz (CADY, 1946). An indirect effect is due to the coefficient of thermal expansion, which changes the thickness of the quartz plate according to temperature.

The non-rotated X and Y-cuts have very large temperature coefficients, namely -20 to -22 ppm/^{o}C for X-cuts and + 60 to + 90 ppm/^{o}C for Y-cuts, and are not suitable for applications where good temperature stability is important. Quartz cuts of better temperature stabilities were found as early as 1934 and are of the singly or doubly rotated type (see Table 2.2.2.1). The temperature characteristic of most of these *zero temperature coefficient quartz cuts* is parabolic. This applies for example for the BT, CT and DT-cuts. The inflection point of the parabola can be placed anywhere in the temperature range of interest by slight changes in the cutting angle of the quartz plate. The temperature characteristic of AT, GT and SC-cuts follows a polynomial of the third order. In the case of the widely used AT-cut, the two points of zero temperature coefficient (turning points) are nearly symmetrical about room temperature (25^{o}C). The slope at 25^{o}C and the position of the two turning points are controlled by the cutting angle of the quartz plate and is zero for $\theta = 35^{o}17'$ (MASON, 1950). A change of plus three minutes of arc in the cutting angle produces a negative temperature coefficient of one part per million (ppm) (MASON, 1950). The SC-cut exhibits a similar pattern around a temperature of +97^{o}C (KUSTERS & LEACH, 1977). Generally, the frequency versus temperature characteristic can be expressed by the following equation (FRERKING, 1978)

$$\frac{f-f_o}{f_o} = A_1 (t-t_o) + A_2 (t-t_o)^2 + A_3 (t-t_o)^3 \qquad (2.2.3.1.1)$$

where f is the frequency at a temperature t and f_o is the frequency at the temperature t_o of the "symmetry point". For the single-rotation cuts AT, BT, CT, DT, t_o is 25^{o}C. The coefficients A_1

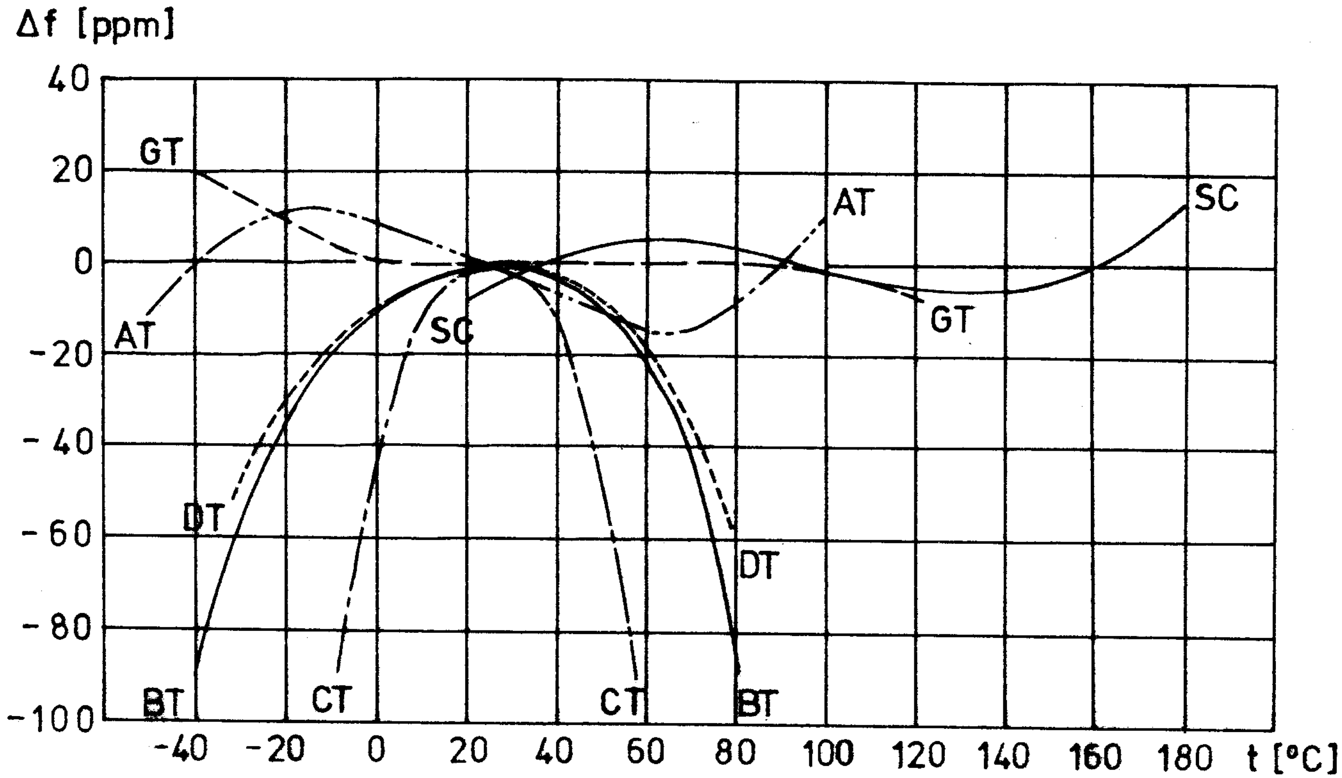

Fig. 2.2.3.1 Frequency versus temperature characteristics of a few "zero temperature coefficient" quartz crystals

and A_3 are zero for BT, CT and DT-cuts, and the coefficient A_2 is zero for AT, GT and SC-cuts. The temperature characteristics of a few cuts are depicted in Figure 2.2.3.1 (MASON, 1950; GERBER & SYKES, 1966; KUSTERS & LEACH, 1977).

As the curves follow quadratic or cubic equations, it is not possible to completely avoid frequency changes over a wide range of temperatures. The frequency changes may be reduced by narrowing the temperature range, or may be eliminated to a large extent by controlling the ambient temperature. Another aspect to be considered is the manufacturing tolerance of the cutting angle of the quartz plate, particularly in large scale production. Small variations of the cutting angle lead to changes in the temperature characteristics, so that each quartz crystal resonator exhibits a different temperature behaviour.

2.2.3.2 Long-Term Dependence on Time (Ageing)

The long-term dependence on time (or ageing) of a quartz crystal resonator can be defined as the gradual drift of the average frequency. Superimposed on the gradual drift are short-term fluctuations which will be discussed later. The physical and mechanical processes causing the ageing of thickness shear resonators (e.g. AT-cuts) can be given as follows (GERBER & SYKES, 1966)

* temperature gradient
* stress relief
* change of mass
* structural changes

Temperature gradient effects can last from several minutes to several hours after a thermal disturbance. Thermal disturbances may be caused by on/off switching of the unit, or other events. Stress relief effects depend on the previous thermal history and can last from three days to three months. Stress relaxation effects may also be caused by a change of the physical properties of the crystal mount and/or the electrodes as well as by a loss of gases from the can.

The change-of-mass effects are caused by a gain or a loss of mass on the crystal surface and can last for a period of several weeks to several years. Adsorption and desorption of gases is behind the change of mass of the crystal plate and is largely dependent on the type of casing and sealing used. Solder sealed metal holders exhibit the worst performance, with changes of 5 to 7 ppm/year. All-glass holders and cold-welded metal holders perform better, with ageing rates of 1 to 3 ppm per year (KRISTALLVERARBEITUNG GMBH). Long-term effects can also be attributed to structural changes in the quartz, caused by imperfections in the crystal lattice. An exit of excess vacancies to the crystal surface would cause a change of density and, thus, of frequency. Impurities in the quartz also affect the frequency stability. The ageing rate of quartz crystal resonators is most pronounced after manufacture, and levels out over the years. It can be said that it follows a logarithmic function. The pronounced ageing after manufacture can be accelerated by repeated heating and cooling or by the high temperature bake-out mentioned earlier in connection with cold-welded resonators. As ageing is also dependent on the drive current and the operating temperature, the two parameters should be mentioned in connection with any ageing specification. One may even distinguish two ageing patterns, *active ageing* and *passive ageing*, depending on whether the unit is operating or not.

Quartz crystal resonators age either up or down and will not change their ageing pattern. According to FRERKING (1978), glass-enclosed units will age up (that is, there will be a gradual increase of frequency) because of an apparent reduction in the mass of the crystal. Metal-enclosed units will age down (with a gradual decrease of frequency), because impurities, enclosed in the can, settle on the crystal, thus increasing its mass. In the case of EDM instruments, a downward ageing pattern can be predicted because of the predominant use of metal-enclosed resonators.

In the fields of electronic distance measurement and frequency measurement (frequency counters), ageing is not a critical factor, as it is a gradual and long-term effect, which can be easily monitored. If required, ageing can be compensated by adjustment. As an adjustment of the quartz crystal resonator is not possible after manufacture, the task has to be achieved by the circuitry of the oscillator, which includes the resonator.

2.2.3.3 Short-term Dependence on Time

Short-term fluctuations of the frequency about the average frequency are again caused by adsorption and desorption of gases by the crystal as well as the build-up and relaxation of stresses between the quartz and its electrodes, particularly in the case of switching the resonator on and off and abrupt but small temperature changes. In the short-term domain, frequency fluctuations caused by the entire oscillator circuit will be more pronounced than those of the crystal resonator alone. The effect will therefore be discussed in more detail in the context of oscillators.

2.2.3.4 Dependence on Stress, Vibration and Acceleration

Vibration and acceleration, the latter including gravitational forces, are related to stress as they change the loading on the quartz plate, for example due to a deformation of the mounting structure. Vibration and shock do not usually lead to a catastrophic failure of a unit but rather cause frequency shifts (up to 1 ppm) and changes in the resistance (up to 10 percent) (FRERKING, 1978). The mounting structure of the crystal unit must have a resonance frequency well above the frequency of mechanical vibrations, to prevent deterioration of the frequency stability. The sensitivity to static acceleration and dynamic acceleration (shock or vibration) depends on the orientation of the quartz plate relative to the direction of the acceleration. The sensitivity is typically 1 part in 10^9 per 9.81 m/s^2 in the case of AT-cuts. The newer SC-cuts exhibit a better performance (KUSTERS, ADAMS, YOSHIDA & LEACH, 1977). Experiments with AT-cuts have shown that the frequency changes due to tensile forces depend largely on the amount, direction and point of attack of the forces. The frequency change is linear with the force and can amount to up to 44 ppm/N (GERBER & SYKES, 1966, 1967). The effect can be used to compensate for the frequency drift with temperature, by designing an appropriate mounting structure (GERBER & SYKES, 1966).

In the context of EDM, the effects discussed above are sufficiently small to be safely ignored unless the mounting structure becomes permanently deformed and causes a permanent frequency "jump". However such events may be detected by periodic monitoring of the frequencies.

2.2.3.5 Dependence on Drive Level

The power dissipation in the quartz crystal, caused by the AC current used to exite the quartz vibrations, is proportional to the square of the amplitude of the current (drive level) and leads to self-heating of the crystal, to temperature gradients between the vibrating region and the periphery of the quartz plate (FRERKING, 1978) and to changes in the elastic properties of the quartz (QUARZ AG). GERBER & SYKES (1966) report on an almost linear change of frequency with power of 1 part in 10^9 per µW (1 ppm between 1 µW and 1 mW) in an AT-cut resonator. The operating current is therefore usually kept as low as possible. The amplitude of the drive current also affects the ageing pattern of a resonator, for example from 1 part in 10^{10} per month to 15 parts in 10^{10} per month, for a change in current from 75 µA to 750 µA (GERBER & SYKES, 1966).

2.2.3.6 Dependence on Nuclear Radiation

A few experiments carried out with quartz crystal resonators under the influence of pulsed nuclear radiation have been reported by GERBER & SYKES (1966). Permanent frequency changes of up to 10 ppm and post-irradiation ageing of up to 0.5 ppm per week have been found. Although the effects of nuclear radiation are very large, they are unlikely to be of importance in the domain of electronic distance measurement, because the operator of EDM instruments could not be exposed to such radiation levels.

2.3 Quartz Crystal Oscillators

After having discussed quartz crystal resonators and their properties, the complete assembly, namely the quartz crystal oscillator, needs to be examined. Again, the properties of such units will be the main interest.

2.3.1 Working Principles

A quartz crystal oscillator is basically a closed loop system composed of an amplifier (usually a transistor), a resonator (containing the crystal) and a feedback network. The amplitude of the oscillation builds up to the point where the returned energy equals the input energy of the amplifier, necessary to produce the required output energy. If the feedback energy is too small, an increase in the output energy of the amplifier results.

The frequency adjusts itself until the total phase shift around the loop is 0^o (or 360^o). If the circuit can operate as an oscillator, even after the quartz crystal resonator has been removed, it is called a *quartz crystal controlled oscillator*. If the circuit ceases to work as an oscillator after a removal of the quartz crystal resonator, it is termed simply a *quartz crystal oscillator* (HEISING, 1952). The latter type is used predominantly, and may require only resistances and/or inductances and/or capacitors in addition to the transistor and the quartz crystal resonator.

A number of suitable quartz crystal oscillator designs have been developed over the years. A comprehensive and up-to-date discussion of these circuits may be found in FRERKING (1978). The resonant frequency of an oscillator circuit will not coincide exactly with the resonant frequency of the quartz crystal resonator. The parameters of the other components used in the oscillator (resistors, capacitors, inductances, transistor) will affect the resonant frequency of the entire oscillator due to the self-adjusting properties of the circuit, mentioned above. It is therefore necessary to build a tuning element into the circuit, to allow an adjustment of the oscillator resonant frequency to the required value. This is usually achieved by placing a variable capacitor in the circuit, sometimes in series with the quartz crystal resonator. The tuning range must be such to cover not only the manufacturing tolerances but also the predicted ageing rate over the lifetime of the unit.

2.3.2 Types of Quartz Crystal Oscillators

The frequency drift of quartz crystal resonators, with temperature, is by far the largest source of error in these units. (See section 2.2.3 for details). After the addition of an oscillator circuit to a quartz crystal resonator, the frequency stability will be further decreased, because of the large number of components involved and the change of their design parameters with temperature. The temperature coefficient of the circuitry of a typical 10 MHz oscillator would be in the vicinity of 2 parts in 10^8 per ^oC (FRERKING, 1978). A large demand for more precise oscillators has led to the development of specialized oscillators exhibiting greatly reduced sensitivity to changes in ambient temperature. Two types of oscillators evolved and are discussed below, together with the class of unimproved oscillators (RTXO).

2.3.2.1 Room Temperature Crystal Oscillators (RTXO)

Room temperature crystal oscillators operate at the ambient temperature of the unit ("room temperature") and incorporate quartz crystal resonators of minimum frequency change over a temperature range which is usually quite large. High frequency oscillators employ AT-cut crystals and may exhibit a frequency stability of ± 20 ppm from $-55^{\circ}C$ to $+105^{\circ}C$ and ± 5 ppm from $-20^{\circ}C$ to $+70^{\circ}C$ (GERBER & SYKES, 1978). Further limitation of the temperature may lead to a stability of ± 2.5 ppm between $0^{\circ}C$ and $50^{\circ}C$ (HEWLETT PACKARD, 1978). The specifications define the *maximum* deviation of the frequency from the centre frequency in the temperature interval given, but do not give any information on the shape of the frequency versus temperature curve in the same interval. In the specified temperature range, the temperature characteristic may be a straight line (horizontal or with a positive or negative slope) or may follow the cubic equation with a maximum below and a minimum above $25^{\circ}C$. (As mentioned earlier in section 2.2.3.1, the curves of AT-cuts are symmetric with respect to the $25^{\circ}C$ point). This indicates that the actual frequency versus temperature characteristic can be much better than the specification. The specifications (or tolerances) include the tolerance for calibration, which means that the temperature component alone is slightly better (FRERKING, 1978).

The term "room temperature" may be somewhat misleading in the context of EDM instruments and frequency counters, where the oscillator is usually enclosed in a large instrument. The decisive parameter is the temperature inside the oscillator rather than the temperature outside the instrument, the former being usually larger than the latter due to power dissipation in the oscillator and in the entire instrument.

Room temperature crystal oscillators are employed in some short range distance meters as well as in low-priced frequency counters.

2.3.2.2 Temperature Controlled Crystal Oscillators (TCXO)

After the development of stable thermistors, simple temperature compensating networks became feasible. The so-called *analogue temperature compensation* is achieved external to the crystal resonator by placing capacitors and thermistors having opposite temperature coefficients in the circuit. Alternatively, a voltage tuned capacitor (varactor) may be placed in the oscillator circuit. Its voltage is controlled by a voltage divider network, incorporating thermistors and resistors, to provide the voltage versus temperature function needed to compensate for the temperature drift of the oscillator (FRERKING, 1978; HEWLETT-PACKARD, 1978). The temperature characteristic of a TCXO is typically five times better than that of a RTXO. To achieve compensation to ± 5 to 10 ppm, a fixed compensating network with carefully selected specifications of component parameters can usually be used. For tolerances in the 5 to 0.5 ppm range, an individual adjustment of the component parameters is required (FRERKING, 1978). The smaller the required tolerance and the larger the temperature range, the more sophistication is required in the compensative network. For a small tolerance of ±1 ppm in a relatively small temperature range (0-50^{o}C) or a tolerance of ± 2 ppm in a temperature range of -20^{o}C + 70^{o}C, three-point compensation may be sufficient. In this case the frequency versus temperature curve will cross the 25^{o}C frequency three times in the specified temperature range and will maintain the form of a cubic equation. To get a tolerance of ± 1 ppm in a range of -20^{o}C to +70^{o}C, five-point compensation may be required, thus leading to a curve having a minimum and a maximum on each side of the 25^{o}C point. The frequency versus temperature cuve in this case takes the form of a polynomial of fifth order with five crossings of the 25^{o}C frequency (KRISTALL-VERARBEITUNG).

Analogue temperature compensation beyond a tolerance of ± 0.5 ppm is very difficult to achieve, because of the small component tolerances involved, particularly in mass production. Using *digital temperature compensation with a microprocessor*, tolerances of ± 0.05 ppm may be realized (FRERKING, 1978). In this technique a voltage tuned capacitor (varactor) is again placed in the oscillator circuit. The temperature is sensed by a thermistor network, which supplies the information through an analogue-digital converter to the microprocessor. The microprocessor calls the necessary varactor voltage from a programmable read-only-memory (PROM), using an interpolation technique for the stored discrete values (temperature-voltage pairs), and controls the varactor voltage through a digital-analogue converter. The data stored in the PROM must be evaluated from a measurement of the oscillator frequency over the desired temperature range. FRERKING (1978) uses the following measurement cycle to derive the voltage versus temperature data later to be stored in the PROM. The unit is first stabilized at room temperature for 10 hours (continuous operation of the oscillator is assumed) and is then stabilized at temperatures from $-40^{\circ}C$ to $+80^{\circ}C$ in 4-$5^{\circ}C$ steps for a shorter time, before the temperature and voltage data are read. The time required for a measurement from $-40^{\circ}C$ to $+30^{\circ}C$ in $4^{\circ}C$ steps is 2 days. The unit has to be tested again in the same way after the data have been stored in the PROM.

Microprocessor-controlled digital temperature compensation is still in the development stage but may be considered in EDM applications in future, at least in special cases, as most modern EDM instruments already incorporate a microprocessor for other tasks. In fact, the method could be greatly simplified in the case of EDM instruments: the PROM would contain a table of temperatures and ppm corrections. The ppm corrections would be applied directly in digital form to the measured distances thus eliminating the varactor in the oscillator circuit and a second digital-analogue converter. To allow standardization of such an instrument, it should be possible to display the ppm correction as derived from the PROM table at any time.

The widely used crystal oscillators with analogue temperature compensation have many advantages over the next class, the oven controlled crystal oscillators, because they require little additional power (as compared to RTXOs), because they exhibit a lower ageing rate (due to their operation at ambient temperature) and because they require no warm-up (GERBER & SYKES, 1966). The last criterion means that TCXOs do not require a warm-up to become operational. It does however not mean that there is no initial frequency drift after the unit is switched on. Commercially available TCXOs typically have dimensions of 50 x 50 x 13 mm (KRISTALL-VERARBEITUNG) which often preclude them from use in compact short range distance meters. Lower priced frequency counters may incorporate TCXOs, sometimes however as an optional item only. In EDM, TCXOs are employed in some short and medium range instruments.

2.3.2.3 Oven Controlled Crystal Oscillators (OCXO)

Oven controlled crystal oscillators employ a controlled environment for the quartz crystal resonator and, possibly, for the entire oscillator circuitry, by operating at an elevated temperature, namely 15° to 20°C above the highest temperature to which the instrument is likely to be exposed. Typical operating temperatures vary between 65° and 85°C (WILLRODT, 1973; FRERKING, 1978). The least sophisticated OCXOs employ a solid state oven, which clamps over the quartz crystal resonator, and an oscillator circuit external to the oven. Frequency stabilities of ± 0.5 ppm can be achieved with such an arrangement. For more precise units, the quartz crystal resonator and the oscillator circuit are packaged in an oven and the temperature of the oven is controlled by a thermistor. Such oven controlled crystal oscillators may be stable to ± 0.01 ppm over a temperature range from -55°C to +75°C (FRERKING, 1978). To obtain even better stabilities, a double oven can be used, where the outer oven controls the temperature to ± 1°C and the inner oven to ± 0.01°C. Double oven units may exhibit stabilities in the order of 1 part in 10^{10} (FRERKING, 1978).

To obtain an optimal result, the oven temperature has to coincide with the temperature of a (or the) turning point of the frequency versus temperature characteristic of the quartz crystal oscillator. The slope of the temperature curve is then zero in the vicinity of the oven temperature. Depending on the curvature of the frequency curve at the oven temperature, some crystal cuts are better suited than others. Commonly used cuts are the AT, BT and SC (KUSTERS et al, 1977).

The temperature control of the oven can be of the *switching* or the *proportional* type. The former switches the heating element on whenever a lower temperature limit is reached, and off whenever the upper limit is attained. This leads to a temperature cycle inside the oven and thus to a cycling of the output frequency between a lower and upper limit. OCXOs with switching controllers have been used in earlier EDM instruments. MECKENSTOCK (1963) reports on a frequency cycle of 3.3 ppm (peak-to-peak) for a Geodimeter NASM 4 due to the temperature cycle of the oven. SCHNÄDELBACH (1980) found a similar effect of 0.2 ppm (peak-to-peak) in a Tellurometer MA 100. Ovens of the proportional type are employed whenever a high frequency stability is required. The oven is operated continuously but the power supplied is regulated on the basis of the thermistor output, namely proportional to the heat loss. As mentioned before, highest performance is achieved with proportionally controlled double ovens.

Oven controlled crystal oscillators are widely used in high precision frequency counters and frequency standards as well as in some long range EDM instruments.

2.3.3 Performance of Quartz Crystal Oscillators

The performance of quartz crystal oscillators is mainly but not solely determined by the frequency stability of the quartz crystal resonator (see section 2.2.3). In the discussion of the properties of the entire oscillator, the contribution of other parts of the circuit must be considered. In addition, some commonly experienced effects have to be discussed. The most important stability parameter is temperature which has already been treated in section 2.3.2.

2.3.3.1 Long Term Stability (Ageing)

This gradual drift of the average frequency is caused by the ageing of components, notably the quartz crystal (section 2.2.3.2). The long-term stability is specified for a certain time interval, namely years, months or days, depending on the type of oscillator. RTXOs and TCXOs cannot be specified in terms of days because effects caused by small temperature variations are too large to allow the measurement of the long-term drift in such a short time span. Extrapolation of ageing rates from smaller to larger time spans is permissible, but not in the reverse sense. Typical ageing rates are given in Table 2.3.3.1.

	Ageing rate		
	per day	per month	per year
RTXO	-	3×10^{-7}	3×10^{-6}
TCXO	-	1×10^{-7}	1×10^{-6}
OCXO	5×10^{-10}	1.5×10^{-8}	2×10^{-7}

Table 2.3.3.1: Typical ageing rates (HEWLETT-PACKARD, 1978)

The ageing rates of oven controlled crystal oscillators are measured after the initial warm-up period and are based on continuous operation and sometimes optimum environment. GERBER & SYKES (1966) report weekly ageing rates of as little as 1 part in 10^9 in the case of U.S. Navy VLF transmitters. Although ageing is the second largest error of frequency it can be accounted for easily by frequent frequency adjustment or monitoring.

2.3.3.2 Short Term Stability

The short-term stability is defined as the frequency fluctuation for a specific average time. To eliminate the effects of ageing, the so-called Allan-Variance is used to compute the short-term stability (FRERKING, 1978):

$$\sigma(\tau) = \left\{ \frac{1}{2N} \sum_{i=1}^{N} (f_{2i} - f_{2i-1})^2 \right\}^{\frac{1}{2}} \qquad (2.3.3.2)$$

where τ is the measuring time (counting interval) for each frequency reading with no dead time between the readings,
N the number of measured pairs,
f is the measured frequency, and
$\sigma(\tau)$ is the short term stability for the counting interval τ.

Useful counting intervals range from 1 ms to 100 s. Specifications are typically given for a one second counting interval. It is obvious that the short-term stability improves with an increase in the length of the counting interval.

The short-term fluctuations are caused by thermal and shot noise perturbing the oscillations, - a shot noise is a noise voltage produced by statistical fluctuations in the electron current because of random variations in the number of electrons - by additive noise of accessory ciruits, not perturbing the oscillations but adding to the signal, and by fluctuations of the oscillator frequency due to parameter changes of the crystal or of other circuit components (GERBER & SYKES, 1966). The interaction of the desired signal with the unwanted signals can lead to a simple superposition, to amplitude modulation (AM), to frequency modulation (FM), to phase modulation (PM) or to any combinations thereof, of the oscillator's output frequency (FRERKING, 1978).

Additional short-term fluctuations may be caused by interference from sources outside the oscillator circuit. The physical location of an oscillator must therefore be carefully chosen (HEWLETT-PACKARD, 1978). Typical short-term stability specifications are listed in Table 2.3.3.2.

Type of oscillator	Short-term stability (1 s average)
RTXO	2×10^{-9}
TCXO	1×10^{-9}
OCXO	5×10^{-10}

Table 2.3.3.2: Typical short-term stability specifications (HEWLETT-PACKARD, 1978)

High performance OCXOs may have stabilities of 1 part in 10^{11} (HEWLETT-PACKARD, 1978) or even 3 parts in 10^{12} (GERBER & SYKES, 1966).

When investigating the short-term stability of EDM instruments, the averaging time of the distance meter during a phase measurement at a particular frequency, either internal path or external path (via reflector) must be considered. This phase measurement sampling time is 2 s for a KERN DM 501 distance meter, for example. For more recent instruments, the relevant phase measurement time is between 0.1 and 1.0 s. The short-time stabilities listed above would have to be multiplied by a factor of approximately four (HEWLETT-PACKARD, 1978) to relate to a 0.1 s average time. In all cases, the expected short-term stability of EDM instruments will be well below the distance measurement accuracy of these instruments and need not to be considered any further.

In the case of frequency measurements of the modulation frequencies of EDM instruments, the counting interval will be probably 1 s or 10 s which indicates that the short-term stability of the frequency counter's oscillator will also be of little consequence.

2.3.3.3 Line Voltage Effects

A change in the line voltage may change the power consumption of the power supply and thus result in a change of temperature inside the instrument. In addition, the voltage in the oscillator circuit will change, leading to changes in the drive level of the quartz crystal resonator (see section 2.2.3.5), to phase changes in the feedback loop and in the case of TCXOs to changes in the varactor voltage. In all these cases, the output frequency will be affected.

Considering frequency counters with AC line supply power, typical voltage specifications are given in Table 2.3.3.3.

Type of oscillators	Frequency change due to 10% line voltage change
RTXO	$< 1 \times 10^{-7}$
TCXO	5×10^{-8}
OCXO	1×10^{-10}

Table 2.3.3.3: Typical frequency versus voltage specifications (HEWLETT-PACKARD, 1978).

In battery operated field instruments, such as electronic distance meters, the aspect of a change in the supply voltage becomes more pronounced. The effect has been investigated by a few researchers and their results will be summarized here. MECKENSTOCK (1963) found a change of frequency of 1.3 ppm in a Tellurometer MRA2, for a voltage change from 100% to 20% on the ammeter. MEIER-HIRMER (1974) reported on another microwave distance meter (Tellurometer CA 1000) which showed a 0.2 ppm frequency change for a voltage drop from 12.5 to 10.5 V. RÜEGER et al (1975) published results on tests with two Wild Distomat DI 10 and one Kern DM 500 distance meters. The former two instruments exhibited a frequency change of 0.1 ppm for a voltage drop from 13.5 to 11.0 V, and the latter 2.2 ppm from 5.5 to 4.25 V. HERZOG (1978) reported on a frequency change of 0.1 ppm from 6.0 to 9.5 V change, in a Zeiss ELDI 2. With respect to the AGA Geodimeter 8, tests were carried out by MAIER (1977) and RICHTER (1978). The former measured frequency drifts between 0.5 and 1.8 ppm for a voltage drop from 13.0 to 11.0 V, depending on the chosen frequency (f1, f2 or f3). Much larger frequency drifts were experienced at lower temperatures, the largest being 3.5 ppm at -28°C for a voltage change from 13.0 to 11.5 V. RICHTER found much smaller values of 0.03 to 0.20 ppm from 12.5 to 11.0 V, again depending on the use of the f1, f2 or f3 frequency. In this case the frequency versus voltage curves showed a parabolic rather than the usual linear trend. All results given above refer to room temperature measurements unless specified otherwise. It becomes evident that the voltage dependency of the frequency is much larger in the case of battery operated EDM instruments than in the case of line operated frequency counters, to which Table 2.3.3.3 above refers. It follows that the effect cannot be ignored in the context of the standardization of EDM instruments.

2.3.3.4 Warm-up Effect

The warm-up effect is not really a separate effect but rather a special temperature effect (see section 2.3.2). It is caused by the temperature rise from the time the oscillator (as well as the instrument) is turned on to the time a stable operating temperature is reached. The warm-up effect is therefore also a time effect. The temperature rise is brought about directly by power dissipation in the oscillator or indirectly by the generation of heat of the circuitry of the entire instrument.

The effect is very pronounced in OCXOs, where the oscillator is brought to an elevated temperature by design. In these cases, a (minimal) warm-up time is specified to allow for the rise of temperature from ambient (at turn-on) to the oven temperature and thus for the necessarily large frequency change. A typical warm-up time is 20 minutes for AT and BT cuts (HEWLETT-PACKARD, 1978). The newer SC-cut requires only 10 minutes (BURGOON & WILSON, 1981). For a complete levelling out of the warm-up effect, the unit must be operated for a much longer time span. The warm-up frequency drift rate for a 10 day period may decrease from 2 parts in 10^{10} after 15 days of operation to 1.5 parts in 10^{11} after 195 days (GERBER & SYKES, 1966, 1967). OCXOs used as frequency standards are therefore kept in continuous operation, because a temporary shut-down requires another lengthy warm-up period. During the warm-up, the frequency approaches the final value in form of an exponential curve (MEIER-HIRMER, 1975, 1978) but may "over-shoot" the final value initially. AT-cuts are known for "over-shooting"

(WILLRODT, 1973; KUSTERS et al, 1977; HEWLETT-PACKARD, 1978). For EDM instruments incorporating OCXOs, a warm-up time is specified by the instrument manufacturer. The prescribed warm-up time must be closely adhered to as a minimum and it should be considered that a longer warm-up time may be required at extremely low temperatures (MAIER, 1977). The "over-shoot" effect is not critical in EDM instruments, as may be seen in figures published by RÜEGER et al (1975), MAIER (1977) and RICHTER (1978), for example.

No warm-up times are specified for RTXOs and TCXOs, because the frequency drifts due to warm-up effect will not exceed the value of the frequency stability specification given for a specific temperature range and oscillator, as long as the operating (crystal) temperature remains inside this temperature range. The actual time required to reach a stable frequency is much longer for RTXOs and TCXOs and may be in the 3 hour range for stabilities of 1 part in 10^8 (HEWLETT-PACKARD, 1978). HEWLETT-PACKARD (1978) give the following typical sample values for 3-hour warm-up drifts: TCXO -0.3 to -1.1 ppm, RTXO +3.2 ppm. The frequency versus temperature curve during warm-up is again basically an exponential curve, but may be preceded by a trend in the opposite direction for say the first 5 to 10 minutes, leading up to a turning point. If the drift curve is purely exponential, the largest frequency rise or drop will occur immediately after turn-on when, in the case of EDM instruments, most distance measurements are executed. The warm-up effect can thus be of significance in EDM, depending on the length of lines measured and the magnitude of the total frequency drift due to warm-up.

2.3.3.5 Retrace and Hysteresis

Retrace and hysteresis describe permanent or temporary changes to the average frequency of an oscillator. When an oscillator (RTXO, TCXO or OCXO) is shut down after continuous operation for some length of time, a new stabilization period is required, after which the stable frequency of the previous run will not be reached exactly. The remaining permanent offset is termed *retrace* and is generally caused by a component such as a resistor or a capacitor not repeating its value with temperature (FRERKING, 1978). – PELZER (1968) used the term "insufficient representativeness" to describe the retrace effect . — Similarly, if an RTXO or TCXO is exposed to various temperature cycles as, for example, the measurement of the frequency versus temperature characteristic, the stable frequency at one and the same temperature will not repeat itself exactly. The effect is called *hysteresis*.

Allowing for insufficient stabilization time during temperature cycles with RTXOs or TCXOs may lead to a so-called *apparent hysteresis* (FRERKING, 1978), which is not of a permanent nature. Apparent hysteresis can be avoided by allocating sufficient time for stabilization. The 30 minutes suggested by FRERKING (1978) may have to be extended in the case of EDM instruments.

Retrace and hysteresis are a measure of the repeatability of the oscillator's frequency at a particular ambient temperature and after a specific warm-up time. They indicate the ultimate limitations of the accuracy of the oscillator frequency in EDM instruments, which are not kept in continuous operation over the years. They also determine the limits of accuracy with which the frequencies of EDM instruments should be evaluated; accuracies of standardization better than the magnitude of retrace and hysteresis would be of little use.

The only way to offset retrace and hysteresis effects is to run the oscillator continuously over the years, which may be practical for standard oscillators but not for EDM equipment, or to monitor the frequency in the field during the EDM measurements, which is in most cases, not practical either. The topic of retrace and hysteresis will be reconsidered later on the basis of actual measurements.

2.3.3.6 Electromagnetic Interference (EMI)

The term "interference" may be defined as any signal disturbance other than the desired signal (BURT & BAKER, 1972). Three forms of interference are discussed below:

* radiated interference
* conducted interference
* common-mode interference

The interference may occur between one or more part(s) of an instrument and the oscillator (and naturally any other part of the instrument). It may also be caused by outside sources, such as auxilliary equipment of the instrument. In the case of standardization of EDM instruments, it may affect the EDM instrument and/or the frequency counter in use.

Radiated interference describes a signal transmitted from one point to another point (e.g. oscillator) with no apparent connection between the two points (BURT & BAKER, 1972). It can be of the type of a magnetic interference (due to stray magnetic fluxes) or a plane wave interference (due to an electromagnetic field). Common sources for the former and latter type are power transformers and radio transmitters respectively.

Conducted interference is caused by direct coupling of signals through wires and components (BURT & BAKER, 1972) with the oscillator (or other instrument components). Again the source of interference may be located within or outside the instrument.

Common-mode interference is a conducted interference caused by voltage drops across wires (usually ground) which are common to two circuits (e.g. oscillator and one or more other circuit(s) of the instrument) or even two instruments (BURT & BAKER, 1972). Poor grounding is a common source which leads to ground loops.

Sources of *continuous interference* (BURT & BAKER, 1972) are radio and television transmitters (narrowband signals) and arcs (broadband signals) from three sources namely high-voltage power lines, neon or mercury vapour light fixtures and rotary machines, such as electric motors and generators. The interference signal is usually picked up by a cable or lead of appropriate length, acting as a radio signal antenna. Another type of interference source is *impulse noise* (BURT ¢ BAKER, 1972), which is generated whenever the magnitude of a (large) current changes abruptly. Common sources are again electric motors and generators, but also car ignition systems. The interference signal is broadband and is transferred by radiated or conducted interference to the instrument.

The effects of electromagnetic interference (EMI) must be considered in the design stage of the instrument, whether an electronic distance meter or a frequency counter. It is good practice to place oscillators well away from fans and transformers (HEWLETT-PACKARD, 1978). In addition, EMI must be taken into account during distance or frequency measurements in the field or in the laboratory. Field measurements are generally less prone to EMI, due to greater distances from interference sources and due to the battery operation involved. However, FRÖHLICH (1979) reported on interference of radar devices during microwave distance measurements, and NASH (1978) on the effects of transceivers on electro-optical distance meters.

2.4 Typical Specifications of Quartz Crystal Oscillators

The specifications of oscillators of equipment used in the context of this investigation are listed in Table 2.4, as far as the information is known. It can be seen that the performance of the oscillators listed is consistent with "typical" data supplied in section 2.3.3. The specifications refer to the oscillator of a particular instrument only.

2.5 Adjustment of Oscillators

All oscillators are adjustable (tunable) so that the output frequency can be set to the design value. The tuning range has to cover the manufacturing tolerances of the quartz crystal resonator and oscillator circuit alike, as well as the expected ageing over a number of years. The conditions under which the tuning should be executed differ necessarily with the type of oscillator and the intended mode of operation.

OCXOs will have to be adjusted after the initial warm-up period of say 20 minutes. Continuously operated OCXOs may even be adjusted after the full warm-up has been taking place as, for example, after one month or even after six months of operation. High precision OCXOs are likely to be operated in a controlled environment (air-conditioned laboratory) in which case the frequency versus temperature characteristic need not to be considered. OCXOs in EDM instruments are subject to different ambient temperatures during practical applications and could be adjusted at a temperature which corresponds to an average frequency in the desired temperature range. Alternatively, the unit may be tuned at room temperature (25°C) to a frequency slightly offset from the desired one, to achieve the same effect (HEWLETT-PACKARD, 1978).

Most RTXOs and TCXOs employ AT-cut quartz crystals and exhibit a frequency versus temperature characteristic which is symmetric with respect to the 25°C point (see section 2.2.3). Instruments equipped with RTXOs and TCXOs are operational almost immediately after turn-on and are commonly used in this fashion. The instrument is turned off whenever a measurement is completed, basically to make the charge of the battery last longer. The frequency of such instruments, which are expected to operate over a wide temperature range, should be adjusted at 25°C, after approximately two minutes of operation (QUARZ AG).

Instrument	Oscillator Type	Ageing Rate	Short Term (1 s average)	Temperature Stability	Voltage Change %	Reference
EDM Instruments						
AGA Geodimeter 14	TCXO			± 2 ppm 0-40°C ± 5 ppm(-20)-(+50)°C		AGA, 1979
Hewlett-Packard HP 3820A	RTXO			± 3-4 ppm(-10)-(+40)°C		GORT, 1978, 1980
Kern DM 501	RTXO	2 in 10^7/month	< 1 in 10^8	± 5 ppm 0-40°C ±15 ppm(-20)-(+50)°C	± 5 ppm (5%)	KERN, 1977a,b
Plessey Tellurometer CA 1000	RTXO			± 3 ppm 0°-50°C		PLESSEY, 1978
Frequency Counters						
Hewlett-Packard HP 5300B	TCXO	< 1.2 in 10^6/year		± 5 in 10^7 0-50°C	< ± 5 in 10^8 (10%)	HP, 1975
Hewlett-Packard HP 5315A	TCXO	< 1 in 10^7/month		± 1 ppm 0°-40°C	< 1 in 10^8 (10%)	HP, 1979
Hewlett-Packard HP 5343L	OCXO	< 3 in 10^9/day	< ±2.5 in 10^{10}	< 1.5 in 10^8(-20)-(+55)°C	< 5 in 10^{10} (10%)	HP, 1973
Standard Oscillator						
Racal 9420	OCXO	± 5 in 10^{10}/day		± 6 in 10^{10}(-10)-(+60)°C	± 5 in 10^9 (10%)	RACAL

Table 2.4: Specification of oscillators in instruments relevant to this investigation.

FRÖHLICH (1978) suggests that the frequency be measured in a time interval after turn-on similar to the measuring time of a distance to avoid warm-up effects. The instrument should be stored at 25°C for a few hours prior to the frequency tuning, to ensure that the entire instrument has adapted to this temperature. Such a procedure ensures minimal frequency deviations in a temperature range symmetric to 25°C.

Instruments employing RTXOs or TCXOs and being exclusively used in a controlled (temperature) environment (air-conditioned laboratory) may be adjusted after a full warm-up period of 1 to 2 hours (or more), if the instrument will be used subsequently under the same conditions or even in continuous operation over the years. The frequency stability of such units with regard to temperature will naturally be much better than the specified temperature stability given for a wide temperature range.

For special purposes, field equipment subjected to different ambient temperatures may also be used solely after a full warm-up of the built-in RTXO or TCXO. An adjustment at 25°C ambient temperature would mean that the oscillator is tuned for an oscillator temperature significantly above 25°C and that it would no longer exhibit a frequency versus temperature behaviour symmetric to this point. Based on the knowledge of the actual frequency versus temperature characteristic (after warm-up!), the oscillator frequency may be set at 25°C ambient temperature at an offset from the nominal frequency or at another carefully selected ambient temperature to the nominal frequency, to ensure minimal frequency change in the desired temperature interval of the field operations.

In the majority of frequency measurements with frequency counters and distance measurements with EDM instruments, oscillators adjusted to the nominal frequency will be preferred. There is however no real need for an adjustment, as small frequency offsets from nominal can be corrected for by computation (RÜEGER, 1980a).

3. TECHNIQUE OF FREQUENCY MEASUREMENT

The performance of the key component, the oscillator, of frequency counters and EDM instruments being known, the principles of frequency measurement may now be discussed. The measurement of the oscillator frequency of EDM instruments is one of the two possible techniques for their standardization. As the working principle of frequency counters has not been mentioned before, a short introduction to such instruments is given first.

3.1 Frequency Counters

Conventional frequency counters can usually execute various measurement functions, two of which are of main interest here. The measurement principle in these modes is explained briefly.

3.1.1 Modes of Operation

In the *frequency measurement* mode, the input signal is conditioned before entering the gate, the opening and closing of which is controlled by another signal derived from the frequency counter's own oscillator (time base). The gate time can be varied in decade steps, usually 10 s, 1 s, 0.1 s and so forth. Whilst the gate is open for a time span equivalent to the set gate time, the pulses of the input signal flow through the gate and are accumulated in the counting register. During the measurement of a 15 MHz input frequency with a gate time of 1 s, the counting register will record 15 million pulses and the display will indicate 15 MHz, being 15 million cycles per second. The frequency measuring routine resembles the technique of digital phase measurement used in modern EDM instruments. For gate times other than 1 s, the decimal point has to be shifted to the appropriate position in the display. Because the gate time is controlled by the frequency counter's internal oscillator, the accuracy of the frequency measurement depend entirely on the performance of this oscillator. Some frequency counters allow a by-passing of the internal oscillator, to permit the use of a more stable external time base for higher accuracy. This technique has been used for some field tests, which will be discussed later.

Another mode of measurement is the *period measurement*, in which the time equivalent to a full cycle of the input signal is measured. In this case, the gate is opened and closed by the input signal and the counting register accumulates the pulses from the internal oscillator whilst the gate is open. Assuming a 10 MHz time base for the frequency counter, the counting register would record 10 000 pulses during a full cycle of a 1 kHz input signal. The period of a time base pulse being 0.1 μs, the period displayed would yield 10 000 x 0.1 μs or 1.0000000 ms. To obtain higher resolutions, the gate can be kept open during a number of cycles of the input signal. This technique is known as *multiple period averaging*. The Hewlett-Packard 5302A Universal Counter averages up to 1 000 periods, for example. To obtain frequency information from period measurement the following equation may be used:

$$f = \frac{1}{p} \qquad (3.1.1)$$

where f is the frequency in Hertz (Hz), and
p is the period in s.

The period and period average modes are advantageous for the measurement of low frequencies where they provide a higher resolution than the direct frequency measurement mode.

3.1.2 Measurement Errors

The accuracy of measurements executed with a frequency counter depends largely on the stability and state of adjustment of the built-in oscillator. As these aspects have been dealt with before, they need not be discussed again. Another important source of error is the electromagnetic interference (EMI), which can affect the input signal and/or the frequency counter. Frequency counters and EDM instruments are usually equipped with metal cases to reduce the effects of EMI (BAND, JEKAT & MAY, 1971). The distance meter TOPCON DM-C2 even features two metal cases, one inside the other, for optimal shielding. Further limitations are introduced by the so-called "± one count error" and the "trigger error" (HEWLETT-PACKARD, 1978b).

3.1.2.1 The ± One Count Error

This error refers to the ± one count ambiguity in the least significant digit of the measurement. It is caused by the phase of the input signal relative to the gate time signal. Considering the frequency measuring mode, a small shift of the gate interval in time may lead to the inclusion of another pulse into the counting interval. Alternatively, one count may be "lost", when "shifting" the gate interval.

The relative frequency error caused by the ± 1 count error amounts to:

$$\frac{\Delta f}{f} = \pm \frac{1}{f_i} \qquad (3.1.2.1)$$

where f_i is the frequency of the input signal and the relative error in a (single) period measurement is:

$$\frac{\Delta T}{T} = \pm \frac{t_c}{T_i} \qquad (3.1.2.2)$$

where t_c and T_i are the periods of the internal (time base) and the input signals respectively (HEWLETT-PACKARD, 1978b). In the multiple period averaging mode, the relative period error becomes

$$\frac{\Delta T}{T} = \pm \frac{t_c}{nT_i} \qquad (3.1.2.3)$$

where n is the number of periods averaged. The "± one count error" can be a serious limitation in frequency measurement if a counter is not operated properly. According to the frequency of the input signal, frequency, period or period average modes have to be used to minimize the effect of the ± one count error. Some frequency counters (proportional counters) will make that decision for the operator to achieve highest resolution in all cases.

3.1.2.2 The Trigger Error

The trigger error is effective in period and multiple period averaging measurements only, because the input signal controls the opening and the closing of the gate in this case. The error is of random nature and is caused by the noise of the input signal and input channel (of the counter) alike. Slight variations in the length of the gate time interval result and cause slight variations in the result of the period measurement. The trigger error is reduced in the period average mode by a factor n, n being the number of periods averaged. A period average measurement therefore provides advantages similar to the repetition method in angular measurement in surveying, where an angle is averaged over a multiple of the angle without recording more than two circle readings.

The trigger error standard deviation may be computed from (HEWLETT-PACKARD, 1978b)

$$\text{trigger error} = \pm \frac{1.4 \quad (x^2 + e^2)^{\frac{1}{2}}}{(\Delta V/\Delta T)} \text{ seconds} \qquad (3.1.2.4)$$

where x is the noise contributed by the counter's input channel,
e is the noise in the input signal and
($\Delta V/\Delta T$) is the slew rate (slope) at the trigger point of the input signal.

For the Hewlett-Packard Electronic Counter 5243L, the trigger error is specified as

$$\text{trigger error} < \pm \frac{0.3\% \text{ of one period}}{\text{number of periods averaged}} \qquad (3.1.2.5)$$

for input signals with a signal to noise ratio of better than 40 db. In measuring the period of a 1 kHz signal over 1000 periods, the trigger error would be less than ± 3 ns or ± 3 ppm.

It becomes evident that great attention must be paid to the shape, noise and amplitude of all signals to be measured, in order to keep the trigger error in period measurements to a minimum.

3.1.3 Types of Counters

Two types of frequency counters may be distinguished (HEWLETT-PACKARD, 1978b):

* conventional counter
* reciprocal counter

The principle of operation of the former has already been discussed in section 3.1.1. When using conventional counters it is up to the operator to decide on the measuring mode. High frequencies have to be measured in the frequency mode, and low frequencies in the period or period averaging mode to ensure the highest possible resolution.

The new conventional counters allow the direct measurement of frequencies over the entire range of frequencies specified for the counter, without a need to switch to the period mode at lower frequency. All frequencies lower than the frequency of the internal oscillator will be measured in the period or period average mode but displayed as a frequency, a process which may be called "frequency averaging" (HEWLETT-PACKARD, 1978b). This procedure has the advantage that the resolution of the frequency (averaging) measurement becomes independent of the input frequency. For input frequencies higher than the frequency of the internal oscillator, most reciprocal counters switch to the normal frequency measuring mode to take advantage of its higher resolution in this frequency range.

The working principle of a reciprocal counter differs from a conventional counter in so far as two counters are used. During the open sequence of the gate, the "time counter" and the "event counter" accumulate the pulses coming from the internal clock and the input signal respectively. The average period is then obtained as

$$\text{AVE PER} = \frac{(\text{CLOCK PERIOD})*(\text{CLOCK COUNT})}{(\text{EVENT COUNT})} \qquad (3.1.3.1)$$

and the average frequency as

$$\text{AVE FREQ} = \frac{(\text{EVENT COUNT})}{(\text{CLOCK PERIOD})*(\text{CLOCK COUNT})} \qquad (3.1.3.2)$$

where the clock count refers to the number of pulses recorded by the time counter and the clock period to the length of time of a full cycle of internal oscillator or time base. The gate time interval can be varied (continuously) by the user. Again, the procedure resembles very much the one used in digital phase measurement in EDM.

Apart of the higher resolution at lower frequencies, the reciprocal counter has another advantage which can be very important in measuring modulation frequencies of EDM instruments. The techniques called "external arming" or "external gating" allow the measurement of frequency of pulsed signals. An external signal which coincides with the starting of a pulse is applied to the counter and the gate time is set in such a way that it is shorter than the length of the pulse. MAURER & SCHNÄDELBACH (1978) use this technique in conjunction with a Hewlett-Packard HP 5345A 500-MHz counter to monitor the (pulsed) modulation frequency of the Kern

Mekometer ME 3000. This particular counter even allows the determination of an average frequency over a number of pulses.

3.1.4 Calibration of Frequency Counters

The aim of the standardization of EDM instruments is to determine their unit length in terms of the national standard of length. If frequency measurement is the chosen technique, then the frequency counters used must conform with the national standard of time. All frequency counters must therefore be tested against a more precise frequency standard. This can be simply done by measuring the output frequency of a frequency standard (such as an atomic clock) with the counter concerned. Alternatively, frequency transfer techniques may be employed. Some transfer methods are listed below (HEWLETT-PACKARD, 1976):

* VLF radio: standard frequency broadcasts, OMEGA navigation system
* LF radio: standard frequency broadcasts, LORAN-C navigation system
* HF/MF radio: standard frequency broadcasts, LORAN-C navigation system
* VHF/SHF: television broadcasts

Other transfer techniques make use of satellites (e.g. TRANSIT), microwave links or VLBI (very long baseline interferometry). A table of the standard frequency or time signal transmitters of the world is given by HEWLETT-PACKARD (1974). In Australia, two transmitters are located at Exmouth (North West Cape, W.A.) and Lyndhurst (Victoria). The former station (NWC) broadcasts on 22.3 kHz (VLF), the latter (VNG) on 4.5, 7.5 or 12.0 MHz (HF). No LORAN stations are located in Australia, but an OMEGA station entered into service recently. In the table above, all but the HF/MF radio broadcasts provide a transfer accuracy of 1 part in 10^{11} for day to day measurements (HEWLETT-PACKARD, 1976). The same reference states an accuracy of 1 part in 10^7 for HF/MF transfers.

All counters used in the experiments to be discussed later were measured against the reference counter (HP 5243L) of the Sydney County Council Measurement Laboratory, School of Electrical Engineering, University of New South Wales, Sydney. The reference frequency is known to better than 2 parts in 10^8 (KINARD, 1977) from periodic (passive) television signal transfers (for details, see for example, HEWLETT-PACKARD (1976)).

It may be mentioned that frequency transfer techniques can be incorporated in frequency counters to enable high precision frequency measurements under permanent control even in the field. The Australian LAB-TRONICS EDM Frequency Counter has been developed for this purpose; it runs on 12 V and derives its standard frequency from the 4.5, 7.5 or 12 MHz transmission of the time signal transmitter VNG, Lyndhurst (Australia) with an accuracy of at least 1 part in 10^8 (PERRY, 1980).

3.2 Direct Frequency Measurement

A direct measurement of the modulation frequency of an EDM instrument requires a temporary or permanent attachment of one terminal of a co-axial cable to an appropriate point (test point) in the circuitry of the EDM instrument and the other terminal to the input socket of a frequency counter. In the case of a permanent attachment, a co-axial socket is mounted on the instrument panel, which can be connected easily (and without opening of the EDM instrument) to the frequency counter.

3.2.1 Test Points

Very few distance meters are equipped with factory fitted frequency output connectors. Such instruments are the Plessey Tellurometer MA 100, the Kern Mekometer ME 3000 and the Keuffel & Esser Ranger V/V-A and Rangemaster II/III, for example. Of those, only the first instrument belongs to the group of infrared short range distance meters, which is to be considered here. Hewlett-Packard equip their instruments with frequency sockets on request (SOBOTTA et al, 1975). The instruments Kern DM500, 501 and 502 feature a test point which is accessible (through a screw hole) without opening the instrument (RÜEGER et al, 1975).

In all other cases, the instrument must be opened to allow a direct frequency measurement. In these cases it is advisable to contact the manufacturer or their local agent to obtain information on the test point to be used and the nominal value of the frequency at that point. (The frequency measured at a test point may be different from the oscillator frequency, depending

on the part of the circuit where the test point is located.)
Other relevant information is the shape of the signal and the voltage level; these two parameters can be easily established by the user, if necessary.

As it is cumbersome to open EDM instruments for the purpose of repeated frequency tests, the fitting of permanent frequency output sockets and their connection to the test points mentioned before may be an advantage, particularly if frequency measurements under field conditions are anticipated. In the context of this study, two HP 3800B, two HP 3805A and one AGA Geodimeter 14 distance meters were modified in this way.

3.2.2. Measurement Procedures

Considering the errors of frequency counters as outlined in section 3.1.2, the type of counter, the mode of operation (frequency or period measurement) and the gate time (0.1 s, 10 s, 10.0 s) must be carefully selected to achieve the highest possible resolution in the measurement of a particular frequency. Sometimes it is possible to vary the output frequency of the EDM instrument, thus providing a further parameter in the optimization of the frequency measurement. This is only valid if all output frequencies are derived from the same main oscillator and/or if they are in a fixed relationship. This aspect will be discussed in more detail later, with respect to specific EDM instruments. Usually the best resolution is achieved when measuring the highest output frequency, which coincides often with the oscillator frequency of the EDM instrument. This oscillator frequency is typically 15 MHz at present and produces the 10 m unit length for the fine measurement of distance (RÜEGER, 1980a).

For practical reasons, the maximum gate time which can be selected on frequency counters, is 10 s. Because of the "± one count error" in frequency measurement, the best resolution is achieved with this gate time. In some instruments, (e.g. HP 3805A) this gate time cannot be used because the frequency to be measured is not available for that time span at the test point. Another consideration to be taken into account when selecting the gate time is the time involved in one sequence of the measurement of distance, a sequence being either an internal or external path measurement at one frequency only. It may be advisable to execute frequency measurements not only with the largest possible gate time, but also with one smaller than the time span of a sequence of distance measurement (e.g. 0.1 s) to obtain information on the relevant short-term stability of the oscillator. The short-term stability is however unlikely to be critical, as discussed in section 2.3.3.2.

In the following sections, the details of the direct frequency measurement are given for the group of EDM instruments which have been used in the tests.

3.2.3 AGA Geodimeter 14

The AGA Geodimeter 14 measures all distances with the modulation wavelengths equivalent to unit lengths of 10 m and 1000 m (ZETSCHE, 1979). The nominal oscillator frequency is 14 985 528 Hz. The low frequency, corresponding to the 1000 m unit length, is obtained by dividing the high frequency by 100. Its nominal value is therefore 149 855.28 Hz. Both frequencies are available at the test point, depending on the distance measuring cycle. In the "AUTO" mode of distance measurement, the following cycles are executed:

* internal path, at low frequency, 2.5 s (approx)
* internal path, at high frequency, 2.5 s (approx)
* external path, at low frequency, 2.5 s (approx)
* external path, at high frequency, 2.5 s (approx)

After having placed a reflector in front of the instrument and having initialized a measurement by pressing the "START" button, the frequencies will appear on the frequency counter in the sequence listed above. With a selected gate time of one second at least one and possible two proper frequency counts are obtained for each of the cycles. To get a continuous HF signal, the reflector has to be removed during the fourth cycle. The instrument is programmed to transmit the HF signal to the reflector during this cycle so that a removal of the reflector prior to the completion of the cycle effectively blocks the instrument on this frequency. This is achieved by trial or by observing the signal strength meter. In the latter case, the beam should be interrupted at the fourth quick needle deflection after pressing the start button.

The low frequency (LF) is available upon turning the distance meter on and whenever a distance measurement is completed. The same LF may be obtained by removing the reflector during the third cycle of a distance measurement.

In monitoring the HF and the LF frequency with a Hewlett-Packard Universal Counter HP 5313A on a gate time of approximately 10 s, the frequencies are resolved to 0.1 Hz and 0.001 Hz respectively. The ± one count resolution is ± 0.007 ppm and is sufficient in all cases. With the conventional counter HP 5302A, the HF resolution is the same, the LF resolution, however, is not. In the frequency mode, the LF can be resolved to only 0.7 ppm This shows clearly the advantage of a reciprocal counter such as HP 5315A. When using this counter, either of the frequencies can be monitored. Experiments have shown that the same frequency information and the same precision is obtained. This indicates that the trigger error (see section 3.1.2.2) is of little importance during the LF measurement. If a conventional counter similar to the HP 5302A is employed and if a precision better than 0.7 ppm is sought, the HF has to be measured; this requires an interruption of the beam during the fourth cycle.

3.2.4 KERN DM 501

Like the previous instrument, the Kern DM 501 employs two unit lengths of 10 m and 1000 m to determine a distance. The nominal high frequency is 14 985 400 Hz and coincides with the oscillator frequency. A 1:100 divider produces the low frequency of nominally 149 854.00 Hz (MÜNCH, 1974; ZETSCHE, 1979; RÜEGER, 1980a). The instrument measures distances in four cycles (MÜNCH, 1974; RÜEGER, 1980b):

* HF, external path, 2 seconds
* HF, internal path, 2 seconds
* LF, external path, 2 seconds
* LF, internal path, 2 seconds

The frequency test point on the circuitry is accessible from outside after removing a screw (RÜEGER et al, 1975). After switch-on of the EDM instrument, an intermediate frequency (IF) of approximately 150 kHz can be measured. This IF frequency is the mixer product of the frequency of an auxilliary oscillator (14.835 MHz) and the high frequency (HF) signal and is used for the phase measurement of the external and internal path measured with the high modulation frequency.

The IF frequency is not stable because the auxilliary oscillator is not quartz crystal controlled. Drifts of this frequency of 125 ppm over one hour have been measured. To measure the low frequency (LF) continuously, a reflector must be placed in front of the instrument, a measurement started and the reflector removed during the third measurement cycle. (The third cycle is announced by the second "click" of the two shutters which switch from external to internal path and vice-versa). The IF is available during the first two (HF) cycles, and the LF during the last two cycles for approximately 4 s each. Because the test point is located after the mixer stage, the high frequency cannot be measured directly.

As in the previous section, the best resolutions of the LF are 0.7 ppm and 0.007 ppm for the counters HP 5202A and HP 5315A respectively for a gate time of 10 s. To achieve such a precision, the reflector has to be removed during the third cycle of a distance measurement. During test measurements it has been found that the frequency measurement precision coincides with the ± one count error; this indicates that the trigger error is not critical. This LF measurement is also employed by the manufacturer to adjust the frequency to its nominal value.

3.2.5 Hewlett-Packard HP 3800B

This instrument features four unit lengths of 10 m, 100 m, 1000 m, and 10 000 m (McCULLOUGH, 1972; ZETSCHE, 1979; RÜEGER, 1980a). The 10 m unit length is produced directly by the oscillator with a nominal frequency of 14 985 454 Hz (HEWLETT-PACKARD, 1976b). The other frequencies are derived in decade steps by three "divide by ten" integrated circuits. All four modulation frequencies are available continuously at the test point, depending on the setting of the slide switch on the front panel. From left to right, the first, second, third, fourth and fifth positions provide frequencies of 15 kHz, 150 kHz, 1.5 MHz, 15 MHz and 15 MHz respectively. When measured with the reciprocal counter HP 5315A (10 s count), the resolution of all four frequencies was ± one count or ± 0.007 ppm. Comparisons of the LF measurements against the HF (15 MHz) revealed however maximal differences of 1.0 ppm, 0.4 ppm and 0.1 ppm for the 15 kHz, 150 kHz and 1.5 MHz frequencies respectively.

The measurement of the high frequency (15 MHz) is therefore to be preferred. This coincides with the procedure suggested by the manufacturer (HEWLETT-PACKARD, 1976b).

During frequency measurements in the field, it was found that distances could not be measured while a co-axial cable was attached to the frequency output socket. The errors in distance were in excess of 0.1 m.

3.2.6 Hewlett-Packard HP 3805A

This distance meter features two unit lengths of 10 m and 2000 m. The oscillator frequency of nominally 14 987 103 Hz is 110 ppm higher than the frequency equivalent to the unit length of 10 m (HEWLETT-PACKARD, 1976b). This has the advantage that all ppm-corrections, which are applied by the dial on the front panel, get a negative sign in the computations executed by the instrument's microprocessor. The high frequency is reduced to the low frequency LF (nominally 74 935.515 Hz) by two 1:10 dividers and one 1:2 divider.

The low frequency is available at the test point as soon as the instrument is switched on. To obtain a high frequency reading, the balance control has to be turned fully counter clockwise and the power switch to "self check" (and then released) (HEWLETT-PACKARD, 1976b). After a while, the HF appears on the counter; on completion of the self test, the counter display returns to the LF again. Following this procedure, the HF can be measured during approximatively 2-3 seconds. Alternatively, the balance control may be turned fully clockwise and the "self check" started. This procedure allows a measurement of the HF for up to 30 seconds.

With the reciprocal counter HP 5315A, the resolution is 0.01 ppm (10 s gate) and 0.07 ppm (1 s gate) for the LF and HF respectively. For the conventional counter HP 5302A, the corresponding values are 1.3 ppm and 0.07 ppm. The measurements of LF and HF disagree by 0.3 and 0.6 ppm for the two instruments tested, the LF giving lower readings in both cases. To eliminate trigger errors, the HF measurement is preferred.

3.2.7 Hewlett-Packard HP 3820A

Because of its longer range capabilities, the HP 3820A electronic tacheometer employs three unit lengths: 10 m, 400 m, 40 km. A high frequency of 14 985 439 Hz would correspond to the 10 m unit length. For reasons given before, the actual oscillator frequency is again chosen at + 110 ppm (the maximum offset of the ppm dial) or 14 987 087 Hz (GORT, 1978, 1980). The lower frequency of 375 kHz is produced by a 1:40 divider, the 3.75 kHz signal by a subsequent 1:1000 divider. All frequencies are therefore derived from one and the same HF oscillator.

At the test point suggested by the instrument manufacturer (GORT, 1979), none of the above three frequencies is present. The test point supplies (continuously) a very low frequency (VLF) of nominally 374.677175 Hz, which is derived by another 1:10 divider from the 3.75 kHz signal. The VLF frequency is used for the phase measurement of the distance meter, the two circles and the level sensors (GORT, 1978).

With the reciprocal counter HP 5315A, this frequency has been measured directly to 0.03 ppm corresponding to the ± one count error for a 10 s gate time. With the conventional counters HP 5302A and HP 5243L, precisions obtained in the period average mode (10 s count) have been 0.4 ppm and 0.04 ppm respectively.

3.2.8 Topcon DM-C2

As in the HP 3805A, two unit lengths of 10 m and 2000 m are used. The high frequency (HF) is nominally 14 985 437 Hz (TOPCON, 1979). This value is in agreement with information provided by the brochure on the instrument and by the Australian supplier; it differs however from the value given in the instrument's handbook (14 985 413 Hz). The former value has been accepted as being more reliable.

The test point suggested by the manufacturer delivers a continuous high frequency signal of nominally 7 492 718 Hz. It has to be assumed that this signal is derived from the oscillator frequency by a 1:2 divider. During the frequency tests, another test point, providing a continuous very low frequency signal (VLF) of 1.5 kHz was used because the manufacturer's recommendations were not received in time. Comparative measurements indicate that the

7.5 MHz signal is an exact multiple of the 1.5 kHz signal. As the VLF test point is easier to access, it will be used in future, as it has been used in the past.

Using the reciprocal counter HP 5315A, the resolutions of the 7.5 MHz and the 1.5 kHz signals are 0.013 ppm and 0.007 ppm respectively (10 s gate time). The measurements of both signals agree within the limits of ± one count error. With the conventional counter HP 5302A, the VLF frequency resolution is only 1.5 ppm in the period average mode; in this case, the measurement of the 7.5 MHz signal is of advantage.

3.2.9 Closed Case versus Open Case Measurements

The direct measurement of frequencies in EDM instruments usually requires the removal of the instrument's case. Because of the reflection properties of metal cases, the frequencies measured without the case may differ from those measured with the case. The effect has been investigated for the AGA Geodimeter 14, where the modulation signal can be easily recovered from the transmitted infrared beam using an optical coupler technique. (This technique will be discussed later in greater detail). From a total of 12 measurements of the optical modulation (HF) signal in the sequence case on, case off, case on, ..., ten differences of the two HF frequencies have been obtained. A mean difference of 6.22 Hz (0.42 ppm) has been obtained, the "case off" frequency being higher than the "case on" frequency. The standard deviation and the 95% confidence interval (2-tailed test) of the mean difference being ± 0.1 Hz and ± 0.23 Hz respectively, the difference of the two frequencies is significantly different from zero.

SOBOTTA et al (1980) reported differences of up to 10 Hz (0.67 ppm) for similar tests and attributed the differences to the differing operating conditions, namely the electric shielding provided by the case and changes in the ambient temperature of the oscillator. The latter effect is an unlikely contributor in the tests described above, as the "open box" and "closed box" measurements were executed in quick succession.

As the case is always fitted during EDM observations, the "case on" frequency is relevant. Frequencies measured with the case removed must therefore be reduced by 0.42 ppm to obtain the relevant "case on" frequency of the AGA Geodimeter 14 tested.

Alternatively, EDM instruments may be equipped with permanent frequency output sockets, thus rendering the removal of the case unnecessary.

3.2.10 Cable Effects

Using again the AGA Geodimeter 14 and the optical coupler technique, the loading effect of a co-axial cable (2 m long, 52 ohm) when attached to the test point on the printed circuit board has been investigated. From a total of 14 measurements, alternating between a "cable attached" and a "cable off" state, 12 differences of the HF signal have been obtained. The mean difference of the HF signal yielded 2.97 Hz or 0.20 ppm, the "cable attached" measurement being the higher one. The standard deviation and the 95% confidence interval (two-tailed test) of the mean difference were ± 0.10 Hz and ± 0.22 Hz respectively. The difference is again significantly different from zero, although sufficiently small to be ignored in most cases.

Measuring the HF signal of a Kern DM 501 through an optical coupler, with an without a co-axial cable attached to the test point, yielded a 0.97 Hz or 0.065 ppm higher value in the case of an attached cable. The standard deviation of this mean difference was ± 0.04 Hz or 0.0024 ppm. Again, the difference of the two frequencies measured is so small that it can be ignored.

The results are consistent with tests executed by other researchers. SOBOTTA et al (1980) published a value of 3 Hz (0.2 ppm) for similar experiments.

3.3 Indirect Measurement of Frequency

The techniques of indirect frequency measurement are defined as being techniques which do not require the removal of the case of the EDM instrument for the purpose of a measurement of the modulation frequency. The techniques offer some advantages such as not requiring a removal of the instrument's case (which can be time consuming and can cause a loss of the sealing properties of the case) and rendering the attachment of cables to the circuitry unnecessary. The possibility of damaging an EDM instrument through improper connection is therefore effectively removed. An owner of an EDM instrument is likely to favour indirect frequency measurement for this very reason, in particular, if the measurements are executed during the warranty period after purchase of an instrument. An additional advantage is the absence of the effects discussed in sections 3.2.9 and 3.2.10.

3.3.1 Induction Loops

The external sources of electromagnetic interference (EMI) and their effect on EDM instruments, frequency counters and cables (connecting the two) have been discussed previously. EMI can however be useful, if caused by the distance meter and if carrying the modulation signal to be measured to the exterior of the instrument.

Assuming that a magnetic field B is produced by the EDM instrument, such that:

$$B = \hat{B} \sin\omega t \qquad (3.3.1.1)$$

and that a loop-shaped stationary conductor is placed in the magnetic field, the magnetic flux yields (BOSSE, 1967):

$$\Phi = \hat{\Phi} \sin\omega t \qquad (3.3.1.2)$$

Both the magnetic field and the magnetic flux change sinusoidally with time (t). The angular velocity (ω) derives from the frequency (f) as follows (RÜEGER, 1980a):

$$\omega = 2 \pi f \qquad (3.3.1.3)$$

The voltage induced in the loop can be written as (BOSSE, 1967):

$$U = - \hat{\Phi}\omega\cos\omega t \qquad (3.3.1.4)$$

or, in the case of n loops in series as:

$$U = - n\hat{\Phi}\omega\cos\omega t \qquad (3.3.1.5)$$

The induced voltage is therefore a function of the number of loops. In the case of an homogeneous magnetic field and a conductor loop perpendicular to it, the magnetic flux and field relate in the following way (BOSSE, 1967):

$$\Phi = B \cdot A \qquad (3.3.1.6)$$

where the area enclosed by the loop is denoted by A. The induced voltage depends therefore on the area of the loop and, naturally, on the strength of the magnetic field (B).

The phenomenon of electromagnetic induction can be used for indirect frequency measurement, if a magnetic field carrying the modulation frequency is detectable on the instrument's case. A loop is then fixed with a tape to the instrument and the two terminals attached to the frequency counter. Should the voltage level be insufficient, an amplifier would have to be inserted between the loop and the counter.

This method was successfully used by SOBOTTA, SCHWARZ & WITTE (1980) in connection with a Zeiss ELDI distance meter. The loop was attached near the battery enclosure in this case. Although outside the scope of this section, it may be mentioned that the induction technique can also be used to pick up the modulation signal inside the instrument and to feed it to a permanent frequency output socket on the instrument's case (RÜEGER et al, 1975).

3.3.2 Optical Couplers

In the correct sense, optical couplers consist of a light (or infrared) emitting device and a photodetector separated by a few millimetres. A signal is transmitted from the former to the latter device, without any electric connection. A perfect electric (voltage) isolation is achieved (MYERS & O'BRIEN, 1969). To bridge larger distances, the two devices (usually diodes) may be connected by a thin glass fibre. This technique is often used in EDM instruments to achieve wire free connections between different parts of the instrument.

In connection with frequency measurement of EDM instruments, an optical coupler may be defined as a device which focusses the emitted ray bundle onto a photodetector and which amplifies the detected signal to a level sufficient for frequency measurement with a counter. Such an optical coupler is identical to the first stages in the receiver section of an EDM instrument, namely the receiver optics, the photodiode (in the focal point of the lens system), the preamplifier and the amplifier stage (RÜEGER, 1980a). The amplitude modulated infrared beam produced by the distance meter is detected and the optical modulation signal converted in an electrical signal, a process which may be termed "direct demodulation" (RÜEGER, 1980a). The photodetector of the optical coupler must have an optimal response for the carrier wavelength of the infrared radiation emitted by the EDM instrument. The carrier wavelengths of infrared distance meter range presently from 820 nm to 930 nm, which makes either silicon p-i-n photodiodes or silicon avalanche photodiodes (APD) suitable for the purpose (MELCHIOR, 1972).

For a frequency measurement of the modulation signal of a distance meter, the optical coupler is set up in front of the transmitter optics of the distance meter and aligned so that the optical axes of EDM instrument transmitter and optical coupler are parallel. This arrangement corresponds to the collimation technique in surveying, assuming that both optics are set at infinite focus; the surface of the infrared emitting diode is projected onto the surface of the photodiode in the optical coupler. The alignment of the two optics can be optimized by monitoring the level of the output signal of the optical coupler either with the trigger level knob of the counter or with a display on an oscilloscope. Although the former method is practicable the latter is more convenient.

Optical couplers have been used for EDM instrument frequency testing at the WILD factory in Switzerland for many years (RÜEGER et al, 1975; ZEISKE, 1980). An unsuccessful attempt of building an optical coupler was reported by DODSON (1977, p. 67); however subsequent development led to a device working successfully (ASHKENAZI et al, 1979). From Germany, optical coupler measurements were reported by WITTE & SCHWARZ (1979), SOBOTTA et al (1980) and JACOBS (1980).

The problems encountered whilst using an optical coupler for the frequency monitoring of the instruments mentioned in sections 3.2.3 to 3.2.8 will be discussed later.

3.4 Construction of an Optical Coupler

For the purpose of indirect measurement of frequencies in EDM instruments, an optical coupler was designed and built by the author. The three components (lens, photodetector unit and dc-dc converter) are built into an aluminium tube of 275 mm length and 80 mm diameter. For laboratory use, the unit is supported by a small stand sitting on a bench. The selection and specifications of the three components are now discussed in detail.

3.4.1 Lens

The aperture of the lens, which collects the infrared rays transmitted by the EDM instrument and focusses them onto the photodetector, had to match the aperture of the transmitter optics of the EDM instrument if no loss of energy is to occur. The distance meters to be tested feature lens diameters ranging from 28 mm (Kern DM 501) to 70 mm (HP 3820A). Considering the second requirement - a short focal length to keep the coupler as short as possible - a plano-convex lens made of crownglass featuring a diameter of 60 mm and a focal distance of 90 mm was finally selected (SPINDLER & HOYER, 1977, No. 03 1726). The transmittance of this uncoated lens is 90 percent approximatively and is linear for radiation wavelengths from 450 nm to 1800 nm. The 10 percent loss in transmittance is caused by reflexion losses on the two air/glass surfaces (SCHRÖDER, 1977). The selection of a plano-convex lens has the additional advantage of a minimal spherical aberration in the case of parallel incident rays (SCHRÖDER, 1977).

The change of the focal length due to chromatic aberration can be calculated as follows (SCHRÖDER, 1977):

$$f_3 - f_2 = - f_1 (n_1 - 1) \left(\frac{1}{n_2 - 1} - \frac{1}{n_3 - 1}\right) \quad (3.4.1)$$

where the focal lengths f_i and the refractive indices n_i (of glass) refer to the respective radiation wavelengths λ_i.

i	λ	n	f	Reference
1	546.1nm	1.51872	90mm	(SPINDLER & HOYER, 1977)
2	633nm	1.5147		(RÜEGER, 1980a)
3	900nm	1.5090		(RÜEGER, 1980a)

Table 3.4.1: Refractive index versus wavelength data of crownglass BK7

Using the data of Table 3.4.1 the difference of focal lengths $f_3 - f_2$ yields + 1.0 mm. The lens' focal length is therefore 1 mm longer for an infrared radiation (λ = 900 nm) than for the radiation emitted by a Helium-Neon-Laser (λ = 633 nm). This effect may require an adjustment of the photodetector relative to the lens, if the coupler is also used to monitor the modulation frequencies of laser distance meters.

3.4.2 Photodetector Unit

An EMI 536/12 photodetector unit has been chosen for incorporation into the optical coupler. In order to demonstrate the suitability of the unit for the purpose, to assess some limitations and to compare a number of predicted with measured parameters, the main specifications of the unit have to be discussed in detail.

The selected unit is packaged into a cylinder of 137 mm length and 35 mm diameter and incorporates a silicon avalanche photodiode (EMI S 30512), a bias controller (the bias voltage of approx. 180 V must be varied with temperature to maintain a constant gain or avalanche multiplication of nominally 100), a dc-dc converter, a preamplifier and a drive circuit (amplifier). The expitaxially grown silicon avalanche photodiode (LUCAS, 1974, 1976) features a sensitive area with a diameter of 0.25 mm, an operating range from - 70°C to + 125°C and a photocurrent multiplication of typically 150 (minimum 100) (EMI, 1976). The (fast component) rise time is given as 0.5 ns (EMI, 1976) and corresponds to the time lapse between the 10% and 90% points of the output waveform for a step input (square wave) of radiant flux (RCA, 1974). The typical spectral responsivity or sensitivity for the fast component is dependent on the wavelength of the incident radiation (EMI, 1976, 1977) and is given in Table 3.4.2.1 for a gain (multiplication) of 100.

Wavelength	Sensitivity	Radiation Source
nm	A/W	
633	8.5	HeNe laser
820	25.0	Topcon DM-C2
910	18.0	HP 3800B, HP 3805A, AGA 14

Table 3.4.2.1: Fast component sensitivity versus wavelength of incident radiation of EMI 536/12 photo-detector unit.

The *sensitivity* (or responsivity) is the ratio of the output current (in amperes) to the input flux (in watts) (RCA, 1974). The sensitivity versus wavelength curve (fast component) is bell shaped, with the peak at 820 nm. As the diode is used for the detection of high frequency signals, only the fast component characteristic is of interest. The pulse width at 15 MHz for example amounts to 67 ns only.

Another important aspect is the *noise equivalent power* (NEP) of the diode. The NEP is the radiant flux (in watts) incident on the diode which gives a signal-to-noise ratio of unity (RCA, 1974). It is specified as $1 \cdot 10^{-13}$ W/Hz$^{0.5}$ (EMI, 1976) and is dependent on the frequency of the incident signal. Table 3.4.2.2 gives the details.

Modulation frequency	NEP
15.0 MHz	$3.9 \cdot 10^{-10}$ W
1.5 MHz	$1.2 \cdot 10^{-10}$ W
150 kHz	$3.9 \cdot 10^{-11}$ W
75 kHz	$2.7 \cdot 10^{-11}$ W

Table 3.4.2.2: Noise equivalent power (NEP) versus modulation frequency of incident signal.

As electro-optical short range distance meters feature transmitting powers of 10 µW to 200 µW, the signal-to-noise ratio will be sufficiently large in all cases. The above NEP are valid for incident radiation of 900 nm wavelength. A more serious limitation of the photodiode is the so-called "gain-bandwidth product" at high frequencies of the incident signal (MELCHIOR, 1972). This parameter indicates that the current gain (avalanche multiplication) decreases with an increase in the modulation frequency of the incident signal due to transit time effects of electrons in the photodiode material. The gain-bandwidth product is not specified for the diode in question. The minimum bandwidth of the entire photodetector unit is however specified as 55 MHz at - 3 db. For equal incident radiant flux, the unit delivers for a modulation frequency of 55 MHz only half the voltage it delivers for a lower modulation frequency of say 10 MHz.

The characteristics of the entire photodetector unit EMI C536/12 are listed in Table 3.4.2.3 (for a wavelength of 900 nm, a load resistance of 50 ohm and a gain of 100).

Parameter	Specification
operating temperature	$-40^{o}C$ to $+60^{o}C$
supply voltage	12-15 V dc
minimum bandwidth (-3 db)	55 MHz
typical responsivity	$6 \cdot 10^5$ V/W
rise time (maximum)	5 ns

Table 3.4.2.3: Specifications of photodetector unit EMI C536/12

The avalance gain of the unit can be varied by applying a dc voltage between 0 V and 5 V, which allows a reduction of the output voltage by up to 40 db (or 10 000 times). No use has been made of this facility. The output voltage versus modulation frequency of radiant input is linear between 800 Hz and 10 MHz approximatively with -3 db (50%) points at 40 Hz and 55 MHz. The reason for the drop of the curve at the upper end of the frequency range is caused by the gain-bandwidth product limitation of the diode and/or bandwidth of the amplifier.

Whilst detecting the modulation frequencies of infrared distance meters, it was found that the unit worked at any supply voltage between 12 and 15 V dc. For distance meters HP 3800B and HP 3805A only, the output voltage was slightly higher at 13 V supply as compared to 12 V supply. The unit works even at lower supply voltages (11 V, 10 V) satisfactorily, although with reduced output level.

The value given for the typical responsivity may be used to predict the output level of the unit, based on the radiated power of EDM instruments and assuming no loss of radiated power in the EDM instrument and in the optical path of the coupler. Responsivities of 9 V and 120 V are calculated for a radiated power of 10 μW and 200 μW respectively.

As the photodetector unit provides only the ac component of the incident radiation, the actual output of the unit is likely to be much smaller than the computed responsivities depending on the depth of modulation (amplitude of ac component versus level of dc component of current driving the infrared emitting diode in the distance meter) in the incident radiation. Furthermore, the amplifier stages in the unit are likely to limit the output voltage to a certain level, although this is not mentioned in the specifications. The highest output voltage ever measured did not exceed 3.6 V (peak-to-peak). This is well below the damage levels of the frequency counters used (6 V rms for HP 5315A and 10 V rms for HP 5302A) but also well above the minimum input senitivities of these counters (25 mV for HP 5315A (at 10 MHz) and 100 mV for HP 5302A (at 50 MHz)).

The rise time of the photodetector unit (5 ns) is noticeably longer than the rise time of the diode (0.5 ns). This can be attributed to the bandwidth limitation of the amplifier employed in the unit (LUCAS, 1974, 1976).

3.4.3 DC-DC Converter

To enable the use of the optical coupler under field condition (viz. from 12 V car batteries), a 12 V/15 V dc converter has been incorporated. A DATEL BPM-15/165-D12 converter has been chosen for the purpose. It delivers an output current of 165 mA at 15 V; this is well above the power consumption of the photodetector.

The converter module has a size of 51 x 51 x 19 mm and fits into the aluminium tube of the coupler which has a diameter of 80 mm.

For laboratory use, the dc-dc converter is by-passed and the optical coupler run from a regulated, variable dc power supply, which provides voltage levels between 5 and 15 V dc.

3.4.4 Optical Alignment

The cylindrical photodetector unit inside the optical coupler is supported by four screws at both ends each, allowing an adjustment in both x and y direction, with the z-axis being the longitudinal axis of the coupler. Adjustment along the z-axis is achieved by pulling or pushing, after losening the x and y support screws. To bring the photodiode of the photodetector in to the focal point of the plano-convex lens of the coupler, the optical coupler is set up in front of an infrared distance meter and the coupler's output fed into an oscilloscope. The output signal is then optimized by shifting the photodetector along the optical axis (z-axis) by hand and laterally (in x and y direction) by means of the four adjustment screws next to the photodiode end of the photodetector.

If the optical coupler is to be used for testing different types and makes of infrared distance meters, some thought must be given to the carrier wavelength of the distance meter used in the alignment. To offset the effect of chromatic aberration, an adjustment for a mean radiation wavelength would be appropriate. Within the range of the instruments tested, a wavelength of 865 nm would have been midway between the shortest wavelength (TOPCON DM-C2, 820 nm) and the longest wavelength (e.g. HP 3805A, 910 nm) encountered. As the focal length changes only by 0.26 mm (Eq. 3.4.1) for radiation with wavelengths ranging from 820 nm to 910 nm it was felt that the aspect of chromatic aberration could be ignored in this context. A more important effect is the wavelength dependency of the responsivity (see section 3.4.2). As the responsivity at 910 nm is only 70% of the maximum at 820 nm, the optical coupler was aligned for the former wavelength.

3.4.5 Output of Optical Coupler

The output levels of the different modulation signals of all distance meters tested are listed in Table 3.4.5. The voltages are given peak-to-peak and were measured with an oscilloscope TEKTRONIX 7603.

Distance meter	Modulation frequency	Output voltage
AGA Geodimeter 14	150 kHz	3.6 V
S/N 14075	15 MHz	1.4 V
Hewlett-Packard 3800B	15 kHz	0.9 V
S/N 1141 A 00110	150 kHz	1.0 V
	1.5 MHz	1.1 V
	15 MHz	1.4 V
Hewlett-Packard 3800B	15 kHz	0.9 V
S/N 1226A00368	150 kHz	0.9 V
	1.5 MHz	1.1 V
	15 MHz	1.2 V
Hewlett-Packard 3805A	75 kHz	1.6 V
S/N 1338A00123	15 MHz	1.2 V
Hewlett-Packard 3805A	75 kHz	2.8 V
S/N 1440A01439	15 MHz	1.5 V
Hewlett-Packard 3820A	375 Hz	3.5 V
S/N 1650A00131	3.75 kHz	2.0 V
	375 kHz	3.3 V
	15 MHz	1.8 V
Kern DM 501	150 kHz	3.4 V
S/N 250942	15 MHz	2.6 V
Topcon DM-C2	75 kHz	3.4 V
S/N 911266	15 MHz	2.4 V

Table 3.4.5: Output levels of the optical coupler for different distance meters and modulation frequencies.

For all distance meters except the HP 3800B instruments, the signal level at the high frequency of 15 MHz is lower than at lower frequencies due to the bandwidth of the photodetector unit. However all HF signal amplitudes exceed the minimum sensitivities of the frequency counters mostly used in the experiments (HP 5302A and HP 5315A) by a factor of at least ten. The optical coupler and the frequency counters are therefore well matched.

3.5 Frequency Measurements Using Optical Couplers

Because different types and makes of EDM instruments employ different distance measurement cycles, the technique of optical coupler measurement must vary accordingly. Two main groups of infrared distance meters can be distinguished:

* continuous beam instruments
* pulsed beam instrument

The first group of continuous beam instruments measure the reflector (external) and the internal path for each of the measuring modulation frequencies in independent cycles. This means that the modulation frequency can be detected in the reflector path continuously and uninterruptedly for the full length of an external measurement cycle. The length of such cycles have been listed in sections 3.2.3 and 3.2.4 for instruments AGA Geodimeter 14 (2.5 s) and Kern DM 501 (2.0 s). This group of instruments features also a transmission of an uninterrupted modulation signal upon switching on, which is available indefinitely. This property is particularly useful if the signal transmitted is the high frequency (HF) signal. This facility is available in instruments such as the Keuffel & Esser Autoranger, Wild DI 3S (SOBOTTA et al, 1980), Wild DI 3 (RÜEGER et al, 1975) and Kern DM 501. In other instruments such as the AGA Geodimeter 14, a continuous HF transmission is obtained for an indefinite period after placing a reflector in front of the instrument, initiating a measurement and removing the reflector during the appropriate measurement cycle.

The second group of pulsed beam instruments features measuring cycles at different modulation frequencies which combine external/internal measurements. Within each measurement cycle, internal and external path measurement follow in quick succession. Despite the fact that the emitting diode transmits continuously, the signal in the reflector path will be present in pulsed form only. Pulsed LF and HF signals cannot be measured directly. The special techniques required will be discussed below. Instruments of the second group transmit also a pulsed modulation signal upon switching on which is available for indefinite periods. For example, the Hewlett-Packard HP 3800B, HP 3805A, HP 3820A and the Zeiss ELDI (SOBOTTA et al, 1980) belong to this second group.

The test arrangements are now discussed in more detail with special reference to the instruments tested in the context of this study.

3.5.1 Continuous Beam Instruments

3.5.1.1 Introduction

On a bench, the distance meter (possibly attached to a theodolite) and the optical coupler are set up at a distance which allows the placement of a reflector in between. The optical axes of the distance meter's transmitter and the optical coupler should be horizontal and at the same height. For convenience, the co-axial frequency output cable of the coupler is attached to a cathode ray oscilloscope and the two axes made parallel by adjusting the coupler and/or the slow motion screw (horizontal and vertical) of the distance meter. Both units are switched on for this purpose. The alignment is complete as soon as the amplitude of the signal displayed on the oscilloscope is at the maximum. In addition, the shape of the output signal may be optimized, if necessary, by adjusting the external gain control of the coupler (see section 3.4.2) or by a small misalignment of the two optical axes. The co-axial cable is then attached to the input socket of the frequency counter and the frequency monitoring can commence. Should the desired modulation frequency not be already on display, a reflector must be placed between EDM instrument and coupler, a distance measurement started and the reflector removed during the appropriate distance measuring cycle.

Instead of using an oscilloscope, the alignment of EDM instrument and optical coupler may also be achieved and optimized with the aid of the sensitivity or trigger level controls of the frequency counter. This is quite feasible, if the output waveform is known in advance from previous experiments.

3.5.1.2 Testing the AGA Geodimeter 14

Upon switching on, the instrument transmits continuously and indefinitely the low frequency of approximately 150 kHz. As the LF is produced by a digital divider (1:100) from the HF signal of the oscillator, the transmitted signal is no longer a sine wave but rather a square wave. The HF signal may be detected after placing a reflector in front of the EDM instrument, initiating a distance measurement and removing the reflector in the fourth distance measuring cycle (see section 3.2.3). The (sine wave) HF signal is then available continuously and indefinitely, because the AGA Geodimeter 14 has no mechanism to abort a distance measurement after a lengthy beam interruption.

3.5.1.3 Testing the Kern DM501

After switching on the instrument, the high frequency signal of approximatively 15 MHz is transmitted continuously and indefinitely. As in all instruments, this HF signal is a sine wave. The low frequency signal of approximatively 150 kHz and square wave shape may be detected, after setting up a reflector in front of the distance meter, pressing the start button and removing the reflector in the third distance measuring cycle (see section 3.2.4). The LF signal is then available continuously and for as long as required for reasons outlined in section 3.5.1.2.

3.5.2 Pulsed Beam Instruments

The optical axes of distance meter and optical coupler are aligned as described in section 3.5.1.1. Because most frequency counters are not able at all to measure the modulation frequencies of signals inside pulses or, alternatively, not with sufficient resolution, special techniques and/or equipment are required to test pulsed beam instruments. Some feasible options are described below, followed by a discussion of the output signals of the distance meters tested.

3.5.2.1 Phase Locked Loop (PLL) Technique

A testing facility based on this technique has been described by SOBOTTA, SCHWARZ and WITTE (1980). The phase locked loop circuit contains a phase discriminator and a voltage controlled quartz crystal oscillator (VCXO). The (pulsed) output of the optical coupler is fed into the phase discriminator, which derives a voltage from the phase difference of the VCXO and the optical coupler signal. The resulting voltage tunes the VCXO until both signals are of identical frequency. The VCXO frequency, which is continuously available, is then easily measured with a frequency counter. Naturally, the PLL circuit must be designed in such a way, that it maintains the synchronisation in between pulses. The disadvantage of this method lies in the necessarily limited tuning range of the VCXO. SOBOTTA et al (1980) report on PLL's for the measurement of 15 MHz (10 m unit length) and 7.5 MHz (20 m unit length) signals. A wide band coupler with PLL (4 to 100 MHz) has been developed since (WITTE & SCHWARZ, 1982).

The PLL technique has also been used for some measurements in the context of this study. Instead of constructing a specialized device, readily available commercial equipment has been employed, namely an Adret Electronique (AE) frequency generator-syntheziser "Codasyn 201" (frequency range 0.1 Hz to 2 MHz) together with an Adret Electronique phase comparator model 295 (frequency range 10 Hz to 2 MHz) (ALDRET ELECTRONIQUE, 1969). The system is operational as soon as the phase comparator is connected to the synthesizer and the optical coupler to the phase comparator. No frequency counter is required as long as the offset of the synthesizer's oscillator is known or a standard frequency (1 MHz) is fed into the synthesizer. The expected frequency is set on the synthesizer to as many digits as are likely to be unaffected by frequency drifts and offsets. The synthesizer then provides the offset frequency of the optical coupler signal from the preset value, which can be measured with a frequency counter. The phase comparator indicates if a phase lock is obtained or not. The advantage of this equipment is that it enables the measurement of any modulation signal detected by the optical coupler, even if different frequencies appear sequentially. The limitation is the upper frequency limit of 2 MHz. Thus it does not allow the measurement of high frequencies in the 15 MHz region. However, with a model 202 synthesizer and a model 296 phase comparator, this would have been feasible, the upper frequency limit of this equipment being 60 MHz (ADRET ELECTRONIQUE, 1966).

The frequencies successfully measured by the author with the PLL technique and the equipment listed above are listed in Table 3.5.2.1.

Instrument	Approx. frequency	Date
HP 3800B S/N 1226A00368	150 kHz	28.1.1981
	15 kHz	28.1.1981
HP 3805A S/N 1440A01439	75 kHz	28.1.1981
HP 3820A S/N 1650A00131	375 Hz	29.1.1981
TOPCON DM-C2 S/N 911266	75 kHz	12/13.5.1980

Table 3.5.2.1: Modulation frequencies successfully measured by the PLL technique.

The measurement of the 1.5 MHz signal with the HP 3800B failed. Inspection of the coupler output signal at this frequency revealed later that the amplitude of a 15 MHz noise signal on top of the 1.5 MHz square wave signal is particularly large at this (1.5 MHz) frequency and may have caused triggering problems and thus a failure of the PLL measurement.

3.5.2.2 External Gating of Frequency Counter

The facility of external gating together with the frequency average mode is available in more sophisticated reciprocal counters (see section 3.1.3) such as the Hewlett-Packard HP 5345A electronic counter. The technique has been successfully used by MAURER & SCHNÄDELBACH (1978) and JACOBS (1980) for frequency measurements of the Kern Mekometer ME 3000 and short range distance meters respectively. The gating signal is applied in such a way that the counter starts counting as soon as a pulse starts and stops counting before a pulse ends. This sequence continues until a full 1 s or 10 s count is completed. The start signal for the gate is obtained from an oscilloscope and the length of the gate time from a separate pulse generator. The measuring time for a 1 s count is approximately 5 minutes in the case of Mekometer frequency measurements (MAURER & SCHNÄDELBACH, 1978). Short range distance meters have a much better duty cycle, requiring less measuring time. Taking the Hewlett-Packard HP 3800B as an example, it transmits pulses of 16.67 ms length and has a dead time of another 16.67 ms between pulses (McCULLOUGH, 1972), it would take only a little more than 20 s to get a full 10 s count.

It should be mentioned that the 500 MHz counter HP 5345A also provides the facility for external and even automatic internal arming (see section 3.1.3). Considering again the HP 3800B distance meter with a pulse width of 16.67 mn and assuming the measurement of the 15 MHz frequency, this counter would provide a least count resolution (Eq. 3.1.3.2) of 0.2 ppm for a count of one pulse width only. External gating may therefore not be necessary in most cases, making the procedure much simpler and requiring less equipment.

3.5.2.3 Other Methods

A number of other methods are suitable for precise frequency intercomparisons and may also be used to determine the modulation frequency of pulsed signals. HEWLETT-PACKARD (1976) list the following procedures amongst others:

* oscilloscope Lissajous patterns
* oscilloscope pattern drifts
* frequency comparison with vector voltmeter
* frequency comparison with phase comparator

All four procedures require a separate frequency source such as a fine-tunable frequency generator or synthesizer, with the capability of producing a stable and continuous signal comparable to the frequency to be measured.

In the case of *Lissajous patterns,* one frequency is applied to the horizontal input and the other to the vertical input of a suitable oscilloscope. If the two signals are of almost identical frequency, the trace on the cathode ray tube will be elliptical. The ellipse will roll through 360° as long as the two frequencies are not the same. The frequency of the synthesizer may then be adjusted until the ellipse remains stable. The frequency corresponding to the EDM instrument's signal may then be read off the synthesizer. As soon as the optical coupler supplies pulsed signals of more than one frequency, Lissajous patterns of all frequencies will appear simultaneously. Experiments with the HP 3820A electronic tacheometer have shown that it is possible to measure any of the frequencies present. Using this EDM instrument in the tracking mode for the slope distance, the 375 Hz and the 375 kHz signals were easily measured. The 15 MHz signal could not be monitored directly, due to the 2 MHz upper limit of the synthesizer used (Adret Electronique, Model 201). A comparison with a synthesizer signal ten times smaller (viz. 1.5 MHz) however would have been possible. (The use of the tracking mode is possible in this case, because the photodiode of the optical coupler reflects enough light to allow a distance measurement to it).

To make use of the oscilloscope *pattern drift technique,* the output of the optical coupler is displayed normally and the synthesizer output is used to externally trigger the oscilloscope. As long as the two frequencies are not the same, the display pattern will move either to the right or to the left. The frequency output of the synthesizer may then be adjusted until there is no apparent movement on the cathode ray tube display. Using the 2 MHz synthesizer Adret Electronique Model 201, a 15 MHz coupler output signal may be triggered by a 1.5 MHz signal from the synthesizer, thus rendering the measurement of the HF signal of most infrared distance meters possible.

When employing the *vector voltmeter method,* the output signals of both the optical coupler and the synthesizer are fed into the vector voltmeter, which provides a voltage output which is proportional to the phase meter reading. This output may be displayed on a strip chart recorder, thus providing a phase versus time curve. Again, the frequency of the synthesizer may be adjusted until the phase becomes constant.

Instead of a vector voltmeter, a *phase comparator* may be used, which produces a dc signal proportional to the phase difference of the two signals. Recording this output on a strip chart recorder leads again to a curve of phase difference versus time. The phase difference may be kept constant by adjusting the frequency of the synthesizer.

For all four methods, it has been suggested that the frequency of the synthesizer be adjusted to stabilize the trace on the cathode ray tube or on the strip chart recorder. An alternative method is to keep the synthesizer output constant and to determine the frequency offset by computation. The relevant equations may be found in the literature (e.g. HEWLETT-PACKARD, 1976).

3.5.2.4 Hewlett-Parckard HP 3800B

The operation of this distance meter during distance measurements requires manual switching from one modulation frequency to the next. This has the advantage that the infrared beam is modulated with one signal only at any time. The transmitted beam is however pulsed at a rate of 30 Hz, with pulse lengths of 16.67 ms (McCULLOUGH, 1972). Displaying the coupler outputs of two such instruments on an oscilloscope reveals that all but the high frequency signals are square waves. It is interesting to note, though of no consequence, that the (sine wave) HF signal of 15 MHz is superimposed on all other signals of 1.5 MHz, 150 kHz and 15 kHz. (The amplitude of the superimposed HF signal varies between 40 and 50 percent of the amplitude of the lower frequency signal). In any of the four frequency switch positions, the pulsed signals are available for as long as required, which simplifies considerably the frequency measurement by any method.

3.5.2.5 Hewlett-Packard HP 3805A

After switching on this type of distance meter, the low frequency of approximately 75 kHz is indefinitely transmitted to the reflector in pulsed form. The pulse rate is 5 Hz approximately, with pulses and blackouts of 100 ms length each. The LF is again a square wave. Without executing a distance measurement, the (sine wave) high frequency signal may be obtained in the output of the optical coupler after turning the relevant knob to the self-check position and releasing it. After a while, the HF signal, again in pulsed form, is detected by the optical coupler for time periods up to 30 s, depending on the position of balance knob (see section 3.2.6). On completion of the self test, the LF signal transmission is restored. As only the LF signal is available indefinitely, it may be advantageous to measure the 75 kHz signal rather than the 15 MHz signal.

The alternative of measuring the frequencies in the distance measuring mode, does not provide any benefits, as the instrument provides no tracking mode. It has therefore not been investigated if the photodiode in the optical coupler, acting as a reflector, would return enough signal to allow a distance measurement.

3.5.2.6 Hewlett-Packard HP 3820A

The coupler output signal of this instrument has been investigated for three operational modes:

* aiming (signal available upon switching on)
* single slope distance
* tracking of slope distance

The transmitted beam is pulsed in all three cases at a rate of 10 Hz (GORT, 1980) which gives a pulse width of 50 ms. After having switched on the instrument, square pulses of 120 μs width (approx.) are transmitted at a frequency of 375 Hz for indefinite periods. This very low frequency (VLF) signal, otherwise used in the instrument for the circle and level sensor reading systems, is employed to derive the signal strength information whilst pointing to the reflector. Due to the slow repetition rate, the power consumption is effectively reduced as compared to the power consumption during actual distance measurements with higher frequencies. The VLF of 375 Hz is the same frequency as used during direct frequency measurements at the test point inside the instrument and can be easily measured from the optical coupler output with the techniques given in sections 3.5.2.1 to 3.5.2.3.

As soon as a distance measurement is started, with the photodiode in the optical coupler acting as reflector (signal strength "80"), the following frequencies are detected by the optical coupler in the following order: 3.75 kHz, 15 MHz, 375 kHz. Upon completion, the modulation signal returns to 375 Hz. Because of the short time span of a distance measurement, the tracking mode is more suitable for the detection of the higher frequencies.

In the tracking mode of the slope distance, which takes about 1.5 s per reading to complete, the frequencies follow in the same sequence 3.75 kHz, 15 MHz and 375 kHz. After a first measurement with these three frequencies, only the 15 MHz and the 375 kHz frequencies are repeated in turn and ad infinitum. It should be possible to measure the latter two frequencies with any methods given in sections 3.5.2.1 and 3.5.2.3.

3.5.2.7 Topcon DM-C2

The coupler output is discussed for the three "measuring" modes which correspond to the following switch settings:

* set/audio
* fine
* coarse

The two latter modes can be used in connection with coupler measurements, because the instrument is capable of measuring the distance to the photodiode of the coupler.

In the "set/audio" mode, the modulation frequency in the transmitted beam changes between the HF (15 MHz) and the LF (75 kHz) signal for indefinite periods. Both frequencies are available for approximately 1.2 s, with 0.2 s long blackouts in between.

Between the two "beep" tones of a "fine" mode cycle, four pulses of the LF are followed by four pulses of the HF. The fine mode takes 4.8 s to complete. Short blackouts occur between LF and/or HF pulses. On completion of a fine measurement, a new measurement is commenced automatically, which means that both frequencies are available indefinitely.

In the "coarse" mode, with a duration of approximately 1.6 s between the "beep" tones, one LF pulse is followed by one HF pulse, with a blackout in between.

The "fine" mode of distance measurement, in conjunction with the phase locked loop (PLL) technique, has been successfully used during some test measurements. All other methods as described in section 3.5.2.3 however should also be feasible.

3.6 Setability of PPM Dial

The first velocity correction in EDM accounts for the change of the value of the velocity of light with atmospheric temperature, pressure and humidity. Most short range distance meters have a facility to dial-in the appropriate first velocity correction in parts per million (PPM) based on measurements of ambient temperature and pressure (RÜEGER, 1980a). In most cases, the microprocessor of the distance meter will apply this correction by computation. Some instruments however employ a different technique: the modulation frequency is changed depending on the PPM knob setting. This has the advantage that the first velocity correction is correctly applied, even if the distance measured is longer than the maximum range of the distance display of the distance meter (overflow of the left most digit). The disadvantage is that the precision of any frequency monitoring is limited by the precision with which the PPM dial can be set to zero (or to any other position). The term *setability* will be used subsequently to describe the precision with which the PPM dial can be set to a given value.

Two types of the instruments tested are in this category. The setability has been tested by frequency measurements for repeated settings of the dial to the same position (zero ppm). The precisions of single dial settings as obtained from sets of 10 settings each are listed in Table 3.6.

Instrument	Setability (15 MHz)	Setability (ppm)	95% C.I. (ppm)
HP 3800B	±2.3 Hz...±4.8 Hz	±0.15...±0.32	±0.72
AGA Geodimeter 14	±1.9 Hz...±3.1 Hz	±0.13...±0.21	±0.47

Table 3.6: Setability of PPM dials

The 95 percent confidence interval for a frequency measurement from a single ppm dial setting is given for the worst samples only and is based on a two-tailed t-test with a degree of freedom of 9. To reduce the effect of the setability of the ppm dial on to frequency measurements, the frequency would have to be measured for repeated dial settings and the mean taken. This is of particular importance if the frequency is monitored over the years and small frequency changes (ageing) are to be investigated. The dial setting is likely to be disturbed over longer periods of time due to packing and unpacking for example and thus cannot be assumed to keep its setting over the years.

3.7 Direct versus Indirect Frequency Measurements

Comparative tests have been executed to establish the agreement between frequency measurement by direct and indirect techniques. The results are listed in Table 3.7. The HP 5313A Universal (reciprocal) Counter has been used for the direct measurements and the indirect measurements of unpulsed EDM instruments against the frequency standard of the Sydney County Council Measurement Laboratory, School of Electrical Engineering, University of New South Wales (Electronic Counter HP 5243 L). The reference frequencies for the indirect measuring methods of pulsed EDM instruments were obtained from the Adret Electronique Synthesizer Model 201, which used the standard frequency of the HP 5243 L counter. The direct and indirect frequencies were the same for all but the Topcon instruments. In this case, the 1.5 kHz frequency, measured directly, was multiplied by 50 to get a 75 kHz signal for the comparison with the indirect measurement. The sequence of measurements was always direct-indirect-direct-indirect...direct. To reduce the effect of residual warm-up drifts, the relative frequency differences Δf were computed from

$$\Delta f_i = \frac{\frac{1}{2}(f_{DIR(i-1)} + f_{DIR(i+1)}) - f_{INDIR(i)}}{f_{INDIR(i)}} \qquad (3.7.1)$$

For a total number m of direct and indirect measurements, n values of Δf were available, where:

$$n = 0.5\ (m-1) \qquad (3.7.2)$$

Finally, the mean relative frequency difference $\overline{\Delta f}$ was calculated as follows:

$$\overline{\Delta f} = \frac{\Sigma\ \Delta f_i}{n} \qquad (3.7.3)$$

All $\overline{\Delta f}$ were tested against zero using the two-tailed t-distribution at a 95% confidence level. The $\overline{\Delta f}$ marked with an asterix in Table 3.7 are significantly different from zero. During all measurements, the co-axial cable used for the direct measurement of frequency, remained attached to the test point (or the permanent frequency output socket). In addition, the instruments AGA Geodimeter 14, HP 3820A and Topcon DM-C2 were measured whilst the instrument case was removed.

It follows from the results given in Table 3.7, that frequencies measured by the two techniques differ by less than 0.1 ppm and by insignificant amounts in most cases. This is consistent with the findings of WITTE & SCHWARZ (1979) and SOBOTTA et al (1980).

The largest difference, being significant in a statistical sense, was established for the AGA Geodimeter 14. As the coupler measurements were executed with the co-axial cable attached and the instrument case removed, two additional effects as discussed in sections 3.2.9 and 3.2.10 must also be considered. A direct comparison of a direct measurement of the HF with the co-axial cable attached and the instrument case removed with a coupler measurement with the cable removed and the case attached reveals a relative frequency difference of 0.60 ppm, the indirect measurement given the lower frequency. This relationship must certainly be considered, if the modulation frequency of this instrument is to be measured in an absolute sense by direct frequency measurement to better than 1 ppm.

The second largest difference, again significantly different from zero in a statistical sense, was found for the Kern DM 501. The instrument case had not to be removed for either method of frequency measurement, as the test point is accessible from the outside (RÜEGER et al, 1975). The cable loading however has to be considered. If the cable effect (see section 3.2.10) is removed from the $\overline{\Delta}f$ value in Table 3.7, the relevant frequency difference between a direct measurement (with co-axial cable attached) and an indirect measurement (cable removed) is reduced to zero.

Instrument	Frequency	$\overline{\Delta f}$	$s_{\overline{\Delta f}}$	n	Indirect Technique
		ppm	±ppm		
AGA Geodimeter 14 (S/N 14075)	15 MHz	+0.101*	0.011	7	Optical Coupler
	75 kHz	+0.025	0.031	6	Optical Coupler
HP 3800B (S/N 1226A00368)	150 kHz	+0.002	0.005	4	Optical Coupler + PLL
	15 kHz	-0.006	0.005	4	Optical Coupler + PLL
HP 3805A (S/N 1440A01439)	75 kHz	-0.001	0.003	16	Optical Coupler + PLL
HP 3820A (S/N 1650A00131)	375 kHz	<0.3	-	1	Optical Coupler + Lissajous Patterns
Kern DM 501 (S/N 250942)	150 kHz	+0.065*	0.025	6	Optical Coupler
Topcon DM-C2 (S/N 911266)	75 kHz	-0.003	0.006	6	Optical Coupler + PLL

Table 3.7: Difference between direct and indirect frequency measurement of modulation frequencies of distance meters

4. FREQUENCY TESTS OF SHORT RANGE DISTANCE METERS

For the purpose of standardization of EDM instruments, a programme of the measurement of modulation frequencies has to take into account all relevant oscillator errors as discussed in sections 2.3.2 and 2.3.3. However, if standardization is restricted to an ultimate accuracy of ±0.1 ppm, a number of effects become negligible. The short-term stability (section 2.3.3.2) certainly falls into this category. The effects of line voltage changes should also be negligible in most cases (section 2.3.3.3). Most modern distance meters warn the operator when the supply voltage reaches a critically low value and some even shut down automatically if it drops below the critical level. Proper design of the power supply and regulating circuit of a distance meter insures that the shut down occurs before the frequency is affected. This was confirmed by frequency monitoring during field trials with AGA Geodimeter 14 and Hewlett-Packard HP 3800B distance meters. No further tests of the line voltage effect have been executed. Reports on this effect by other researchers have been summarized in section 2.3.3.3.

All other oscillator errors are now discussed in order of decreasing importance.

4.1 Frequency versus Temperature Characteristic

The frequency versus temperature characteristic is the first temperature related effect; the second temperature effect, namely the warm-up effect, will be treated separately in the next section. The temperature effects are most pronounced in short range distance meters, because they usually employ simple room temperature crystal oscillators (RTXO) or temperature controlled crystal oscillators (TCXO). Some typical specifications are listed in Table 2.4 (section 2.4).

4.1.1 Test Arrangements

All measurements for the evaluation of temperature characteristics were carried out in the SCC Measurement Laboratory, School of Electrical Engineering, University of New South Wales. This laboratory owns a temperature controlled air box large enough to allow a simultaneous test of two distance meters. In addition, use was made of the laboratory's frequency standard (Hewlett-Packard Electronic Counter HP 5243L), of another counter (HP 5300B/HP 5308A) and of a two-channel chart recorder (Moseley Model 7100B). The frequency standard is calibrated periodically against the national frequency standard to an accuracy of better than 0.02 ppm, by using television signals as a transfer standard for both time and frequency. The temperature controlled air box incorporates heating coils, two ventilators, a cooling pipe and control circuitry linked to a temperature sensor. The refrigeration unit, which supplies the cooling agent to the cooling pipe, is detached from the box, but controlled by the air box control electronics. The desired temperature can be set on the temperature controlled air box; after reaching the set temperature, it is maintained to within ±0.2°C.

All instruments but the HP 3820A were connected to a mains operated 12 V dc power supply, either directly (HP 3805A) or through a dc-to-dc converter (as supplied by the instrument's manufacturer: AGA Geodimeter 14, Topcon DM-C2) or through the battery pack of the distance meter (Kern DM 501, HP 3800B). For the electronic tacheometer HP 3820A, a connector fitting the battery compartment was built, and power supplied by a mains operated dc power supply at 4.0 V. All battery packs were installed inside the air box, next to the distance meters. The environmental correction dials of AGA Geodimeter 14 and HP 3800B distance meters were set to zero.

The co-axial cables for the frequency measurements were attached to permanent frequency output sockets, internal test points or the optical coupler on the distance meter side and to the two frequency counters on the other side. The standard frequency (from HP 5243L) was supplied to the second counter (HP 5300B/5308A), bypassing the internal timebase of the latter. Through two digital-to-analogue converters, the measured frequencies (or periods) were supplied to the chart recorder for online recording.

All instruments were tested in the temperature range from +5°C to 40°C, measuring a "warm temperature" and a "cold temperature cycle" on two different days. Typical measuring sequences were as follows:

warm cycle : 20-25-30-35-40-30-20 (°C)
cold cycle : 20-15-10- 5-12.5-20 (°C)

Instruments were kept in continuous operation for the full time of a cycle of approximately eight hours. The frequencies measured refer therefore to oscillator *frequencies after a complete warm-up* period. This will have to be considered when discussing the measured temperature characteristics.

The temperatures inside the air box were monitored with termistor thermometers. A minimum period of 50 minutes between reaching a set temperature and setting the next temperature was observed in all cases. The time lapse between setting a temperature on the air box and the air box actually reaching this temperature was longer when cooling down than when heating up, due to the slower response of the refrigerating unit.

4.1.2 Results of First Group of Instruments

The results of the frequency versus temperature curve determinations are discussed separately for two groups of instruments. The test of the first group of instruments, namely two distance meters each of the models Hewlett-Packard HP 3800B and HP 3805A, have already been reported elsewhere (RÜEGER, 1978). These early measurements will be summarized only; more details may be found in the publication listed above. Since 1977, the frequency characteristics of two of the four instruments have been re-measured. Some relevant technical data of all determinations are listed in Table 4.1.2.1. The results are depicted in Figure 4.1.2.

The curve "A" in Figure 4.1.2 exhibits by far the smallest frequency drift with temperature. The two curves "B" and "G" have been obtained with the same instrument; however, more than two years elapsed between the two determinations. The slopes of the curves are almost identical, the offsets are due to either ageing effects or the limited setability of the "ppm-dial" or both. The former effect will be discussed later. The setability has been given in section 3.6 as ± 0.3 ppm (max) for a single setting. Taking the offset of the two curves as 1.4 ppm (at 20°C) and the standard deviation of the offset due to the random setting errors of the ppm dial in both epochs as ± 0.42 ppm, it can be concluded that the actual offset is not solely due to setting errors. The offset is larger than three times the random setting error.

Curve	Instrument	Date of cycle		Measured frequency	Frequency (F) or period (P) average	Least count error (ppm)	Technique of measurement
		cold	warm				
A	HP 3800B, 1141A00110	7.1.77	17.1.77	15 MHz	F	0.07	direct, from permanent freq. output socket
B	HP 3800B, 1226A00368	12.1.77	11.1.77	15 MHz	F	0.07	direct, from permanent freq. output socket
C	HP 3805A, 1338A00123	14.1.77	13.1.77	15 MHz	F	0.07	direct, from permanent freq. output socket
D	HP 3805A, 1440A01439	14.1.77	13.1.77	15 MHz	F	0.07	direct, from permanent freq. output socket
E	HP 3805A, 1440A01439	31.3.77	30.3.77	75 kHz	F	1.33	direct, from permanent freq. output socket
F	HP 3805A, 1440A01439	28.8.79	27.8.79	75 kHz	P	0.01	direct, from permanent freq. output socket
G	HP 3800B, 1226A00368	{15.5.80 16.5.80}	19.5.80	15 MHz	F	0.07	direct, from permanent freq. output socket

Table 4.1.2.1: Details of measurements of frequency versus temperature characteristics.

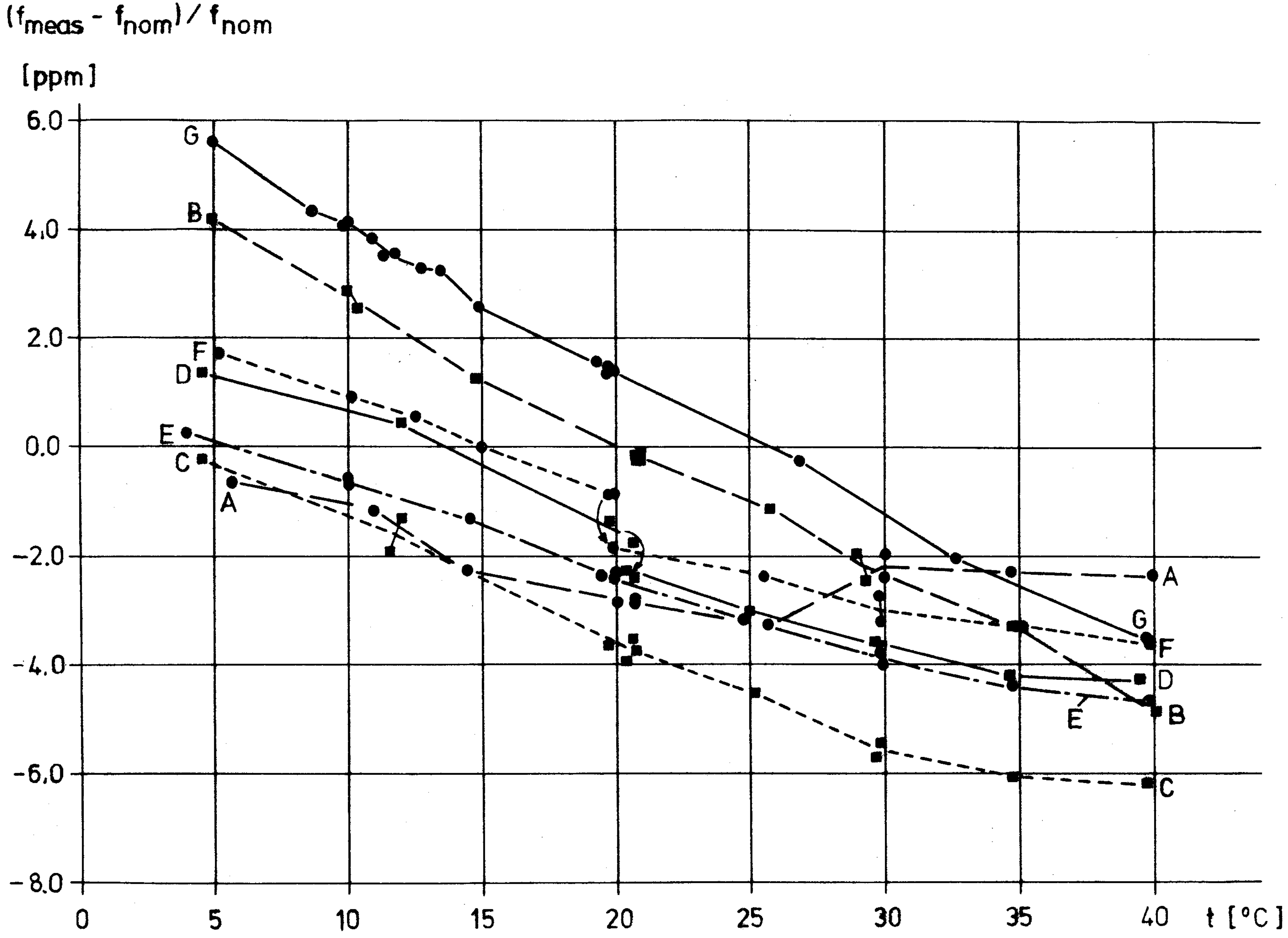

Fig. 4.1.2 Frequency versus temperature characteristics of four distance meters HP 3800B and HP 3805A. See Table 4.1.2.1 for details.

The temperature characteristic "C" exhibits a horizontal tangent at the 40°C mark, indicating a turning point at that temperature. The curves "D", "E" and "F" refer to the same instrument and require some further analysis. The characteristic "E" is certainly the smoothest curve and does not show any jump at the 20°C mark, between the cold and the warm cycle. This curve has been derived from low frequency measurements (75 kHz) in the frequency measuring mode, as indicated in Table 4.1.2.1 and is affected by a least-count error of 1.3 ppm. This may explain the offset from curve "D" which has been measured only two and half months earlier. No setting error of the ppm-dial has to be considered here, because the dial position does not affect the modulation frequency in this type of instrument (HP 3805A). The LF measurements were necessitated because of a fault in the ON-OFF switch, which meant that the HF was not provided at the frequency test point during a self check cycle (see section 3.2.6). The measurements corresponding to curves "D" and "F" are separated by more than two and a half years. The curves display a jump of 0.8 ppm and 1.0 ppm respectively between the measurements at 20°C, of the cold and warm cycles. The least-count errors of the measurements were 7 parts in 10^8 and 7 parts in 10^9 for the "D" and "F" curves respectively. Hysteresis effects can be excluded as an error source in both cases, because the measurements at 20°C at the beginning and at the end of a temperature cycle coincide. This leaves retrace (section 2.3.3.5) as a possible explanation.

The frequency versus temperature characteristics in Figure 4.1.2 are in good agreement with the predicted characteristic of AT-cuts in Figure 2.2.3.1 (section 2.2.3.1). The only curve to deviate from the third-order polynomial behaviour (Eq. (2.2.3.1.1)) is "A", where one would expect a frequency rise from 30°C to 40°C.

Approximation of the curves in Figure 4.1.2 by lines of best fit (linear regression) leads to the expressions for the frequency error $\Delta f/f$ in the temperature range +5°C to +40°C given in Table 4.1.2.2. It is evident that the linear trend of frequency with temperature remains constant over the years, for a particular instrument.

Data set	Linear trend: (ppm) $\Delta f/f$ =	Date
A	- 0.038 (T + 36.5°C)	Jan. 1977
B	- 0.252 (T - 20.7°C)	Jan. 1977
G	- 0.261 (T - 25.5°C)	May 1980
D	- 0.177 (T - 10.7°C)	Jan. 1977
E	- 0.165 (T - 5.7°C)	Mar. 1977
F	- 0.167 (T - 14.1°C)	Aug. 1979
C	- 0.184 (T - 1.5°C)	Jan. 1977

Table 4.1.2.2: Linear trend of frequency error with temperature of two HP 3800B and two HP 3805A distance meters. (For data sets, refer to Table 4.1.2.1).

4.1.3 Results of Second Group of Instruments

The measurements of this second group of instruments, purchased since 1978, have not been published previously. The details of the measurements are listed in Table 4.1.3.1. The optical coupler has been employed in a number of cases, on one occasion in connection with the phase locked loop technique. The resulting frequency versus temperature characteristics are depicted in Figure 4.1.3.

One instrument, namely the Topcon DM-C2, exhibits the very small frequency drift with temperature shown in curve H.

The instruments AGA Geodimeter 14 (curves I, J) and Hewlett-Packard HP 3820A (curve K) display a slightly larger drift rate. The curved line between 25°C and 35°C of curve K follows a minimum and maximum of the curve between the measured points, as derived from the plots of the chart recorder. The maximum was obtained between 30°C and 35°C whilst increasing the temperature as well as between 40°C and 30°C whilst decreasing the temperature. Similarly, the minimum was measured twice, between 25°C and 30°C and between 30°C and 20°C. The curves I, J and K were measured whilst the instrument cases were removed. It is possible that different curves would have resulted if the instrument cases had been closed.

Curve	Instrument	Date of cycle		Measured frequency	Frequency (F) or period average (P)	Least count error (ppm)	Technique of measurement
		cold	warm				
H	Topcon DM-C2, 911266	12.5.80 14.5.80	13.5.80	75 kHz	F	0.01	indirect, optical coupler PLL, "FINE" mode
I	AGA Geodimeter 14	28.8.79	27.8.79	15 MHz	F	0.01	direct, from test point open case
J	14075	30.8.79	29.8.79	15 MHz	F	0.01	direct, from test point open case
K	HP 3820A, 1650A00131	27.8.80	26.8.80	375 Hz	P	0.04	direct, from test point open case
L	Kern DM 501		19.5.80	15 MHz	F	0.07	indirect, optical coupler
M	250942	16.5.80		15 MHz	F	0.07	indirect, optical coupler
N		15.5.80		15 MHz	F	0.07	indirect, optical coupler
O			29.8.79	150 kHz	P	0.02	direct, closed case
P		30.8.79		150 kHz	P	0.02	direct, closed case

Table 4.1.3.1: Details of measurements of frequency versus temperature characteristics.

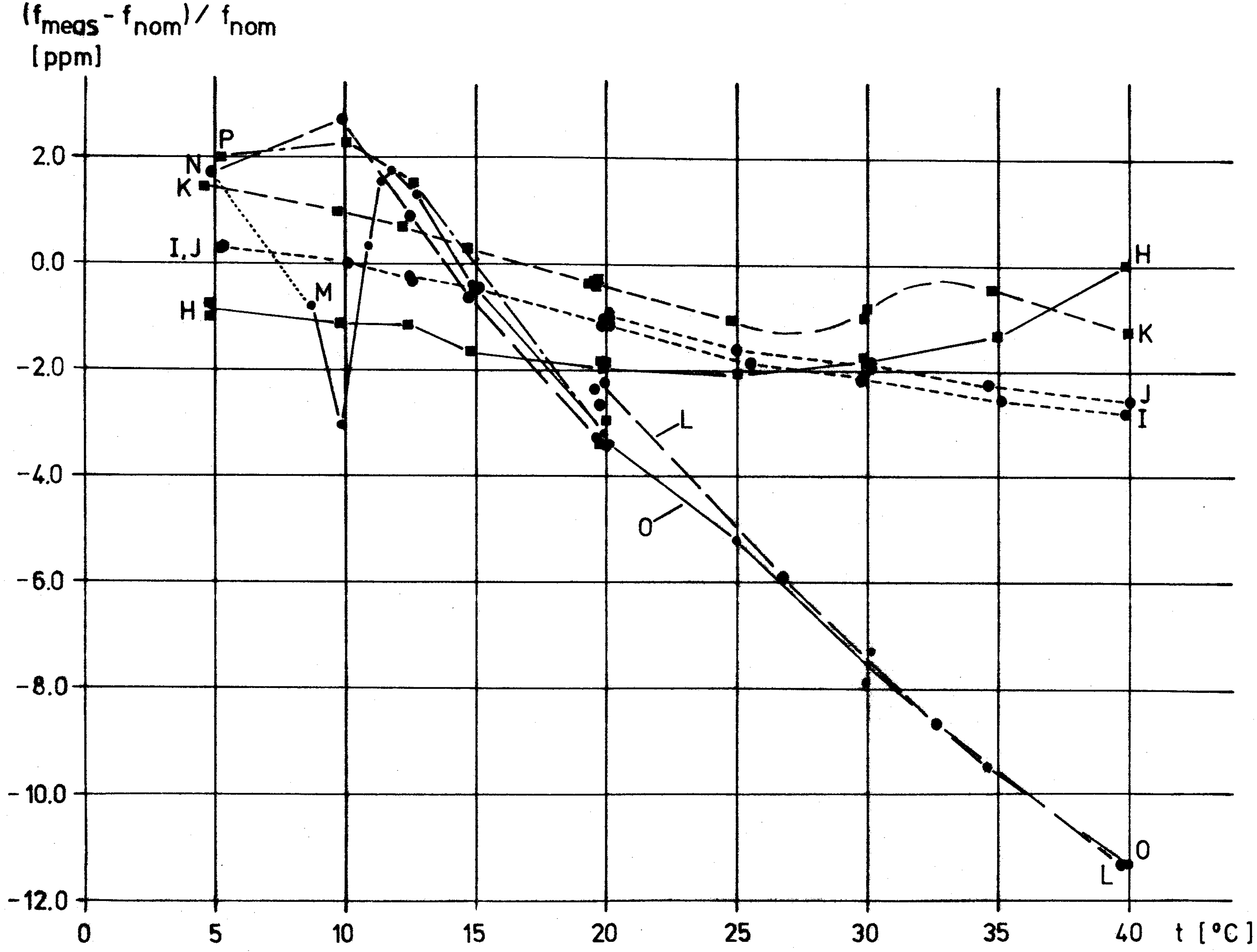

Fig. 4.1.3 Frequency versus temperature characteristics of distance meters AGA 14, HP 3820A, Kern DM 501 and Topcon DM-C2. For details see Table 4.1.3.1.

The temperature characteristic of the Kern DM 501 (curves L to P) is of particular interest. On one hand it shows a large linear trend between 20°C and 40°C; on the other hand, two turning points are evident between 5°C and 12.5°C. During the measurements of curves L and N, the maxima and minima shown in Table 4.1.3.2 have been extracted from the plots of the chart recorder.

Date	Temperature run from	Temperature run to	Minimum	Maximum
30.8.79	+ 5°C	+ 12.5°C	- 2.4 ppm	+ 3.8 ppm
30.8.79	+ 11.5°C	+ 4.8°C		+ 3.6 ppm
30.8.79	+ 9.3°C	+ 5.0°C	- 2.5 ppm	+ 3.6 ppm
15.5.80	+ 10.0°C	+ 5.0°C	- 3.5 ppm	+ 2.9 ppm
15.5.80	+ 5.0°C	+ 12.5°C	- 3.3 ppm	

Table 4.1.3.2: Maxima and minima of the frequency versus temperature characteristic of a DM 501 between + 5°C and + 12.5°C.

The frequency variation in the temperature range from 5°C to 12.5°C is therefore in excess of 6 ppm. In a third test, the temperature steps were reduced to 1°C between 9°C and 12°C, with a supplementary measurement at 11.5°C (curve M). A minimum was found at 10°C (- 3.1 ppm) and a maximum at 12°C (+ 1.8 ppm). Considering all three curves (L, M and N), it becomes evident that the frequency error at the 10°C mark can be anywhere between -3.1 ppm and + 2.7 ppm, depending on the temperature cycle to which the instrument has been exposed (hysteresis effect). Therefore, no frequency corrections for temperatures about 10°C should be extracted from the frequency versus temperature characteristic for the purpose of correcting field measurements.

Like the curves D and F in Figure 4.1.2, the curves L and O in Figure 4.1.3 exhibit different values at the 20°C mark. Again, the measurements at 20°C at the beginning and at the end of both tests agree well, which renders "in-cycle" hysteresis an unlikely cause. Retrace is also unlikely to be the reason, because the curves L and O coincide at temperatures higher than 25°C. The sole difference between the 1979 data set (curves O and P) and the 1980 data set (curves L, M and N) consists in the fact that the cold cycle was measured first in 1979 but second in 1980. This may be an indication of "between-cycle" hysteresis.

The linear trend of all curves in Figure 4.1.3 has been solved for by linear regression. In Table 4.1.3.3 the frequency error $\Delta f/f$ of curves H, I, J, K refers to the full temperature range from + 5°C to + 40°C. In the case of curves L to P it applies to the temperature range from + 12°C to + 40°C only.

Data set	Linear trend: (ppm) $\Delta f/f$ =	Date
H	- 0.001 (T + 1515.9°C)	May 1980
I, J	- 0.092 (T - 8.9°C)	Aug 1979
K	- 0.072 (T - 18.9°C)	Aug 1980
L, M, N	- 0.457 (T - 14.2°C)	May 1980
O, P	- 0.460 (T - 13.9°C)	Aug 1979

Table 4.1.3.3: Linear trend of frequency error with temperature of distance meters Topcon DM-C2 (H), AGA Geodimeter 14 (I,J), HP 3820A (K), and Kern DM 501 (L to P). (For details see Table 4.1.3.1).

The trends of the first three instruments are distinctly smaller than most trends found for the first group of instruments in section 4.1.2. The last instrument exhibits the largest trend of all instruments tested. The magnitude of the trends is consistent with values established elsewhere. JACOBS (1980) reported on a trend of - 0.40 ppm/^{o}C for a Kern DM 500. This is in line with trends found for a similar instrument (Kern DM 501) in curves L to P. BACKHAUS (1981) obtained a linear trend of - 0.14 ppm/^{o}C for a Hewlett-Packard HP 3820A, which compares favourably with the slope of curve K.

Again, good agreement is obtained between measured characteristics in Figure 4.1.3 and predicted ones in Figure 2.2.3.1. The actual and predicted curves deviate at the 10^{o}C and 40^{o}C mark of the characteristics M, N, P and K respectively.

4.1.4 Problems Encountered

During the measurement of the frequency versus temperature characteristics, numerous problems were encountered. During the earlier tests, the temperature controlled air box of the Sydney County Council Laboratory (School of Electrical Engineering, University of New South Wales) caused some problems due to separate controls for heating and cooling sections. Furthermore, the heating elements caused considerable electromagnetic interference By 1979, the temperature control for cooling and heating was integrated and more stable, and the interference by the heating section eliminated. The motor driving one of the two fans which circulate the air inside the box, burned out on two occasions, causing delays in the measurements. The electromagnetic interference caused by on/off currents of the refrigerating unit was affecting all tests; the effect was however easily monitored on the chart recorder.

Due to the length of the tests of 8 to 10 hours per day, all instruments had to be supplied from mains operated dc power supplies. In the case of HP 3800B and Kern DM 501 distance meters, the 12 V dc source had to be connected to the battery packs. It was found that the HP 3800B distance meters cannot be operated with a flat internal battery, even if 12 V dc is supplied to the battery pack. This contradicts the information given in the instrument's manual. It is however consistent with the design of the unit, according to the manufacturer. To enable continuous operation over long time periods, the internal battery must be charged prior to the test and supported by an external 12 V dc power source during the test, or, the internal battery must be disconnected (which requires opening of the battery pack), and the 12 V dc power supply connected to the battery pack. The former solution has been employed during the tests.

The same problem was also experienced with the battery pack of the Kern DM 501 instrument. In this case, the manufacturer was able to trace the error to a resistor of incorrect resistance and supplied a replacement with correct specifications. Subsequently, the distance meter was operational with attached 12 V dc supply, even if the internal batteries were flat, and thus complying with the handbook information.

On one occasion, the optical coupler technique failed at + 5°C, because of condensation on the optics of coupler and EDM instrument. With the laboratory atmosphere having shown a temperature of 21°C and a relative humidity of 55 percent, it can be easily demonstrated that the humidity in the box reached 100 percent. At low temperatures, the temperature controlled air box should therefore incorporate a humidity control, to allow trouble free optical coupler measurements.

Some other problems experienced were a faulty cable between the DM 501 battery pack and the theodolite/distance meter, poor connections at frequency test points, triggering problems, a fault in the "self-check" knob of one of the two HP 3805A distance meters and losing the HF frequency during tests of the AGA Geodimeter 14. In the last case, which was due to spurious reflection inside the air box (causing completion of a distance measuring cycle), the problem was easily solved by starting a new measurement. For this purpose, the temperature controlled air box had to be opened, which meant that 50 minutes had to elapse again before the next temperature could be set.

4.2 Warm-up Effect

As discussed in section 2.3.3.4, the warm-up effect is a second form of frequency drift with temperature, caused by the rise of temperature inside instrument and oscillator during operation. The warm-up effect is maximal, if the instrument is kept in continuous operation for longer periods of time. It can be reduced by switching off the distance meter in between distance measurements (cycled operation).

4.2.1 Continuous Operation

To measure the warm-up effect for continuous operation, the distance meter is kept in constant ambient temperature for 4 to 6 hours, before it is switched on and the frequency recorded until it becomes stable. Tests by SCHWARZ (1981) indicate that the magnitude of the warm-up effect varies with temperature, depending on the frequency versus temperature characteristic of the instrument. If the warm-up effect is measured at a temperature of zero frequency drift with temperature (turning point), it is likely to be small. If it is measured at a temperature of maximum drift it is large. In a temperature range corresponding to a linear frequency versus temperature behaviour, the warm-up effect is likely to be independent of temperature.

Because of the variability of the effect with temperature, it was decided to restrict its measurement to ambient temperatures of approximately 20°C. This gives sufficient information on the magnitude, particularly, as most frequency versus temperature characteristics analyzed in section 4.1 are quite linear in the 5°C to 40° interval. Instead of calibrating the warm-up effect over the temperature range, it is suggested that, whenever necessary, the effect should be eliminated through warm-up of the instrument prior to critical distance measurements. The test results below indicate the warm-up times required to bring frequencies onto the level of the frequency versus temperature determined in section 4.1. These curves relate to continuous operation, as indicated before.

One warm-up curve at approximately 20°C is depicted in Figure 4.2.1 for each of the eight instruments evaluated. The particulars of these curves are listed in Table 4.2.1.1. This table gives also an indication of the warm-up times required to obtain frequencies within a range of 1.0 ppm or 0.5 ppm of the final frequency after warm-up. The 1.0 ppm times are below 10 minutes, except for the two Hewlett-Packard HP 3805A distance meters. A derivation of mathematical expressions for the computational compensation of the warm-up effect as suggested by JACOBS (1980) and BACKHAUS (1981), is therefore not warranted. Even the 0.5 ppm times are not excessive for all but the HP 3805A distance meters.

Curve	Instrument type	Instrument number	Date	Warm-up time required ± 1.0 ppm	Warm-up time required ± 0.5 ppm	Instrument case
A	Kern DM 501	250942	16. 5.80	5 min	9 min	closed
B	HP 3800B	1226A00368	16. 5.80	9 min	16 min	closed
C	Topcon DM-C2	911266	14. 5.80	9 min	21 min	closed
D	HP 3820A	1650A00131	26. 8.80	0 min	0 min	open
E	HP 3800B	1141A00110	18. 1.77	0 min	10 min	closed
F	HP 3805A	1338A00123	14. 1.77	35 min	50 min	closed
G	HP 3805A	1440A01439	14. 1.77	16 min	28 min	closed
H	AGA Geodimeter 14	14075	19.10.81	7 min	16 min	closed

Table 4.2.1.1: Particulars of warm-up characteristics as depicted in Figure 4.2.1.

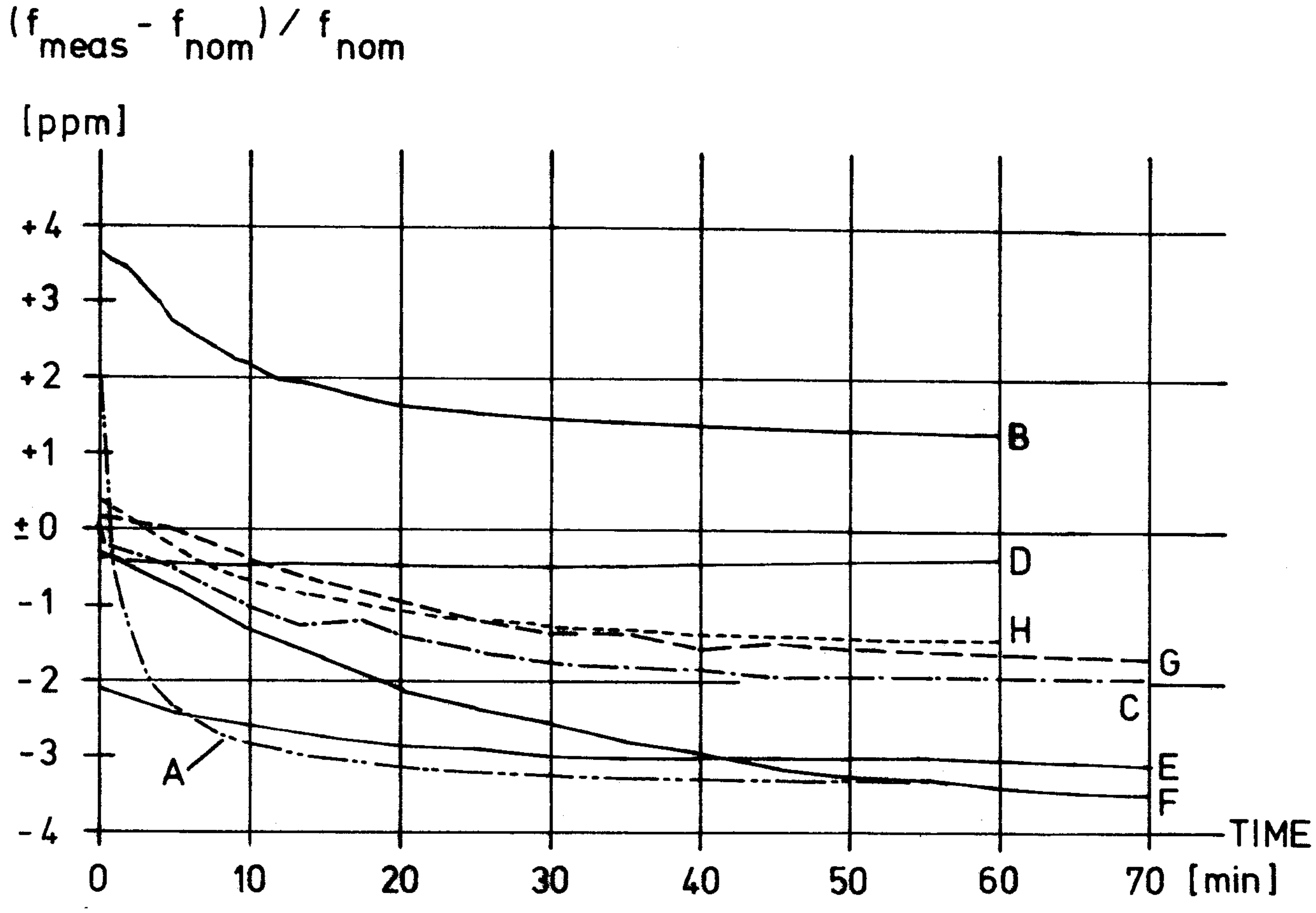

Fig. 4.2.1 Warm-up characteristics of eight different short range distance meters at 20°C. The frequency errors are plotted as measured, Important are the changes of the frequency errors. (Refer to Table 4.2.1.1 for details.)

Using the measured frequency drifts due to the warm-up effect, in combination with the linear trend of the frequency versus temperature characteristics allows a prediction of the oscillator temperature relative to the ambient temperature. In most cases, the drift rates listed in sections 4.1.2 and 4.1.3 were applicable. In cases marked with asterisks in Table 4.2.1.2, a new drift rate for the interval 5^{o} to $25^{o}C$ was computed because of a different drift rate at higher temperatures. The AGA Geodimeter 14 warm-up drift (marked with two asterisks) is not taken from Figure 4.2.1 (closed case) but from open case warm-up data (29/30 August 1979) in order to match the open case drift rate.

Most instruments with a large drift rate in the frequency versus temperature characteristic exhibit also a large warm-up effect. The exceptions are the Topcon instrument, which shows a relatively large warm-up effect but almost zero drift rate, and the HP 3820A with no warm-up effect but a distinct, although small rate. In the latter case, the non-existance of a warm-up drift may be explained by the

Instrument	Number	Total warm-up drift (ppm)	Drift rate (ppm/^{o}C)	Oscillator temperature above ambient
Kern DM 501	250942	- 5.24	- 0.458	$11^{o}C$
HP 3800B	1226A00368	- 2.37	- 0.256	$9^{o}C$
Topcon DM-C2	911266	- 2.01	- 0.80*	$25^{o}C$
HP 3820A	1650A00131	± 0.00	- 0.125*	$0^{o}C$
HP 3800B	1141A00110	- 1.00	- 0.130*	$8^{o}C$
HP 3805A	1338A00123	- 3.47	- 0.184	$19^{o}C$
HP 3805A	1440A01439	- 1.97	- 0.170	$12^{o}C$
AGA 14	14075	- 0.33**	- 0.092	$4^{o}C$

Table 4.2.1.2: Prediction of oscillator temperature relative to ambient temperature.

fact that the measurements were executed with an open instrument.

This necessarily rough analysis indicates that the oscillator temperatures are usually about 10°C above the ambient air temperatures. The exceptions are the Topcon DM-C2 and one of the two HP 3805A's, which are subject to oscillator temperatures of 25°C and 18°C respectively higher than ambient.

Separate tests with an open AGA Geodimeter 14 revealed an oscillator warm-up of 1.5°C and 12.0°C in the first 60 minutes of operation in ventilated (3.5 m/s) and still air respectively. The corresponding frequency drops were measured as - 0.4 ppm for ventilated air and as - 1.8 ppm for still air. The former value is in agreement with the value listed in Table 4.2.1.2 and the latter with the total warm-up drift depicted by curve 'H' in Figure 4.2.1 (closed instrument). The impact of higher oscillator temperatures due to warm-up will be discussed in section 4.2.3.

4.2.2 Cycled Operation

In practice, EDM instruments are usually not operated in their cold state nor in their warm state (after a full warm-up cycle). Rather, the instrument is kept in operation until about two measurements to one target are completed. The instrument is then turned off until measurements to another target commence. This procedure is recommended by all manufacturers in order to conserve battery power. In this standard procedure of electronic distance measurement, the warm-up effect will depend on the time required for the measurement to one target (ON-period) and on the elapsed time between measurements (OFF-period).

To investigate the reduction of the warm-up effect due to cycled operation, some realistic assumption had to be made with regard to the time requirement for distance measurements to one target. For distance meters HP 3800B, 70 seconds were timed for switching on, electronic pointing, distance measurement in all four frequencies and switching off. For instruments HP 3805A, 30 seconds were measured for switching on, electronic pointing, two full measurements (including a readjustment of the balance knob in between) and switching off. Different lengths for the off-periods were selected (multiples of measuring time) and the instruments operated over one hour with alternating between on- and off-cycles.

A summary of the results is given in Table 4.2.2.
More details on the tests may be found in RÜEGER (1978). The drifts for continuous operation were obtained as a mean of several tests; they therefore do not coincide with the values listed in Table 4.2.1.2.

In relative terms, the warm-up effect is reduced to less than 50 percent (of the value for continuous operation) if the off-cycle is double the length of an on-cycle. A reduction to 20 percent is achieved for off-cycles in excess of five times the length of the on-cycles. In absolut terms, the warm-up effect is reduced to less than 0.5 ppm as soon as the ON/OFF time ratio becomes smaller than 1:5. It follows that the warm-up effect during normal operation of EDM instruments is likely to be insignificant. Also, the warm-up effect should not be corrected for by computation based on an equation obtained from warm-up in continuous operation, as long as the instrument's oscillator is not truly at ambient (air) temperature. This will rarely be the case in cycled operation.

Based on Tables 4.2.2 and 4.2.1.2, it is again suggested that the warm-up effect is either ignored or compensated for by warm-up of the instrument for a time period specified in Table 4.2.1.1.

4.2.3 Warm-up Effect and Temperature Characteristic

Because the frequency versus temperature characteristics of Figures 4.1.2 and 4.1.3 have been measured with fully warmed-up EDM instruments, the implications of the warm-up effect on the interpretation of the frequency characteristics must be fully understood.

The difference between oscillator temperature and ambient (air) temperature (as listed in Table 4.2.1.2) is important, because the temperature parameters in the frequency versus temperature characteristics of Figures 4.1.2 and 4.1.3 refer to ambient rather than oscillator temperature. The ambient temperature dependence is valid when extracting frequency corrections from the characteristics for field measurements with warmed-up instruments, because only ambient air temperatures are available as entry. However, as soon as the characteristics are to be compared with the manufacturer's accuracy specifications, the oscillator temperature offset given in the last column of Table 4.2.1.2 should be added to temperatures on the temperature axis. This is because manufacturers are likely to specify the accuracy for distance measurements executed immediately on switch-on and not after a full warm-up cycle.

Instrument	Number	Date	Ratio ON/OFF	Time ON	Time OFF	Frequency drift 0-60 min cycled	Frequency drift 0-60 min continuous	Ratio cycled/cont
		1977		s	s	ppm	ppm	percent
HP 3800B	1141A00110	10.2.	1:2	70	140	- 0.53	- 1.10	48
		11.2.	1:4	70	280	- 0.13		12
		10.2.	1:6	70	420	- 0.20		18
HP 3800B	1226A00368	10.2.	1:2	70	140	- 0.93	- 2.57	36
		10.2.	1:3	70	210	- 0.60		23
		11.2.	1:5	70	350	- 0.40		16
HP 3805A	1338A00123	1.3.	1:2	30	60	- 1.13	- 3.04	37
		3.3.	1:4	30	120	- 0.67		22
		4.3.	1:8	30	240	- 0.33		11
HP 3805A	1440A01439	1.3.	1:2	30	60	- 0.80	- 2.00	40
		3.3.	1:4	30	120	- 0.53		27
		4.3.	1:6	30	180	- 0.27		13

Table 4.2.2: Reduction of warm-up effect during cycled operations of four distance meters.

An example may illustrate the case. The temperature stability of the oscillator of the Kern DM 501 is specified by the manufacturer as ± 5 ppm between 0°C and 40°C (Table 2.4). Because of the oscillator operating at a temperature of 10°C above ambient after warm-up, the temperature characteristic (curves L to P in Figure 4.1.2.2) should be considered in the temperature range from 5°C to 30°C only. The peak-to-peak drift in this range amounts to 10 ppm which is consistent with the manufacturer's specification.

It has been explained in section 2.5 that oscillators are generally adjusted at room temperature (20°C to 25°C) after about two minutes operation with the oscillator still being approximately at ambient (air) temperature. Because of the frequency characteristics being established after warm-up, the zero crossing of the curves in Figures 4.1.2 and 4.1.3 cannot be expected at the 20°C to 25°C mark, but rather at a temperature which is lower than the 20°C to 25°C range by the amount given in the last column of Table 4.2.1.2. This is confirmed in the case of most curves, despite the fact that ageing and setability of the ppm-dial cause the curves to shift up or down and thus also affect the point of the zero crossing. The ageing effect is therefore unlikely to be of great magnitude.

4.3 Frequency versus ppm-dial Setting

In some EDM instruments the ppm-dial "pulls" the oscillator frequency by an amount equivalent to the set dial position. In these cases, the frequency versus ppm-dial setting curve has to be part of a complete standardization, unless the dial is always set to zero during distance measurements. Of the eight instruments investigated, three were of this type, namely two HP 3800B and one AGA Geodimeter 14 distance meters.

4.3.1 AGA Geodimeter 14

In Figure 4.3.1, three curves are depicted which relate the relative frequency error (in ppm) to the setting on the ppm-dial. The dial was set only once per data point, which means that each data point is subject to a random setting error of ± 0.2 ppm (section 3.6). For all curves, the frequency error was assumed to be zero for a dial setting of 0 ppm, to allow an easier comparison of the three curves. Curve A was measured on 22 January 1981, curves B and C on 12 May 1980.

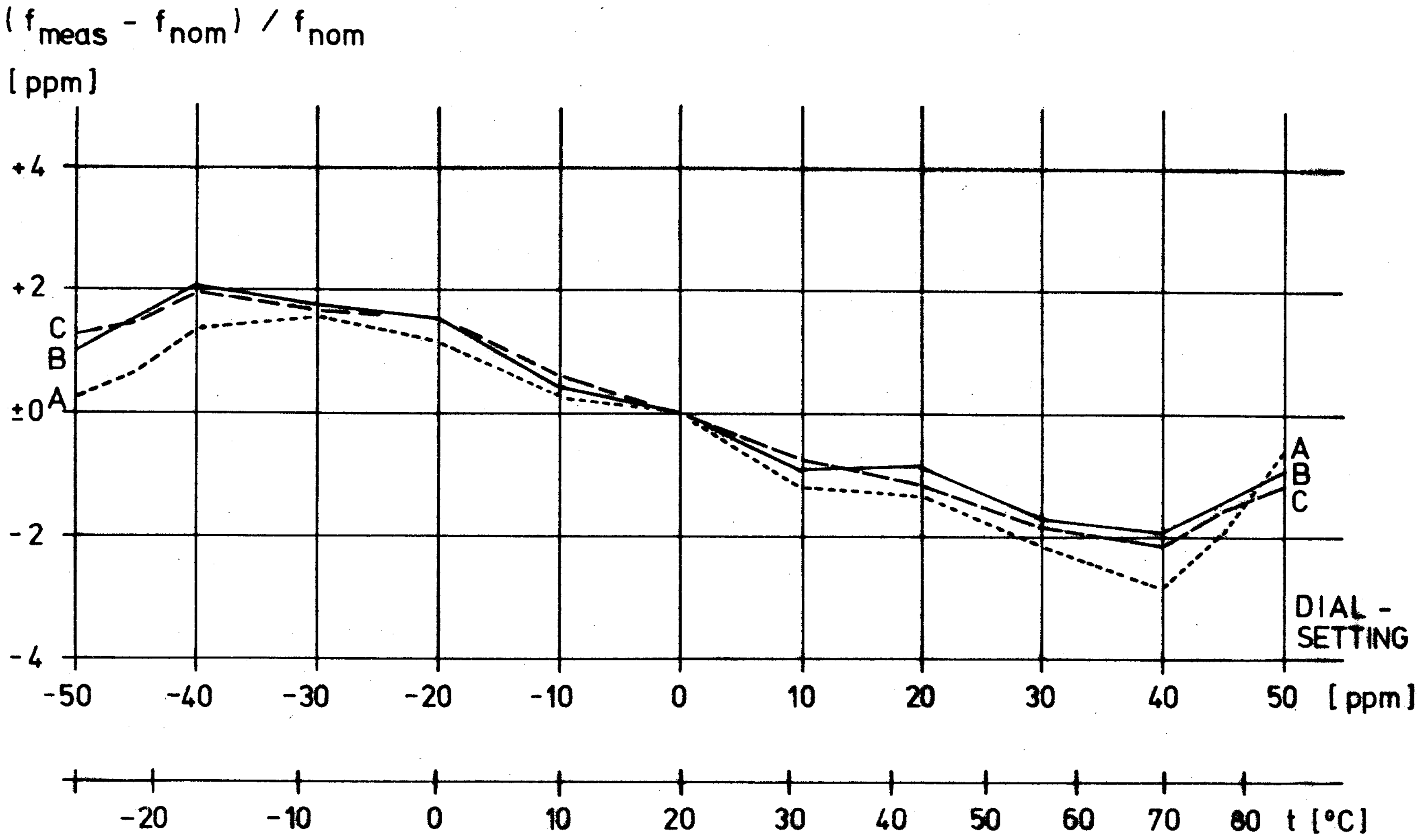

Fig. 4.3.1 PPM dial error versus PPM dial setting of AGA Geodimeter 14

All measurements were executed at room temperature after a complete warm-up of the distance meter. On a second abcissa the temperature is given, which corresponds to a particular ppm-setting, assuming a sea level pressure of 1013.25 mb. This information makes it possible to relate the dial error to the frequency versus temperature characteristic of this instrument in Figure 4.1.3.

The frequency error introduced by the dial in the interval - 20 ppm to + 20 ppm changes at a rate of - 0.064 ppm per dial unit (ppm). Translated into temperature units, this amounts to a slope of - 0.060 ppm/^{o}C in the temperature range between 0^{o}C and 40^{o}C; sea level pressure is assumed. In the frequency versus temperature characteristic, which has been measured with a zero ppm-dial setting, the drift rate is - 0.092 ppm/^{o}C (Table 4.2.1.2). If the ppm-dial had been used during the measurement of the frequency characteristic, a drift rate of - 0.152 ppm/^{o}C would have resulted. The accuracy of the AGA Geodimeter 14 is specified by the manufacturer as ± 3 ppm (0^{o} - 40^{o}C, using "accuracy knob"). Multiplying the above drift rates by 40 (^{o}C), it becomes evident that the instrument tested is within specifications as long as only the oscillator characteristic is considered. The combined oscillator - ppm-dial drift exceeds the specification by a marginal amount. It is therefore advisable to set the dial always to 0 ppm if ultimate accuracy is required.

4.3.2 Hewlett-Packard HP 3800B

The frequency error versus dial setting curves of two HP 3800B distance meters are depicted in Figure 4.3.2. Again, each data point is based on one dial setting only and thus subject to the random setting error of approximately ± 0.3 ppm (section 3.6). All measurements were reduced to give zero error at a dial setting of 0.0 ppm. The details of the measurements are shown in Table 4.3.1.

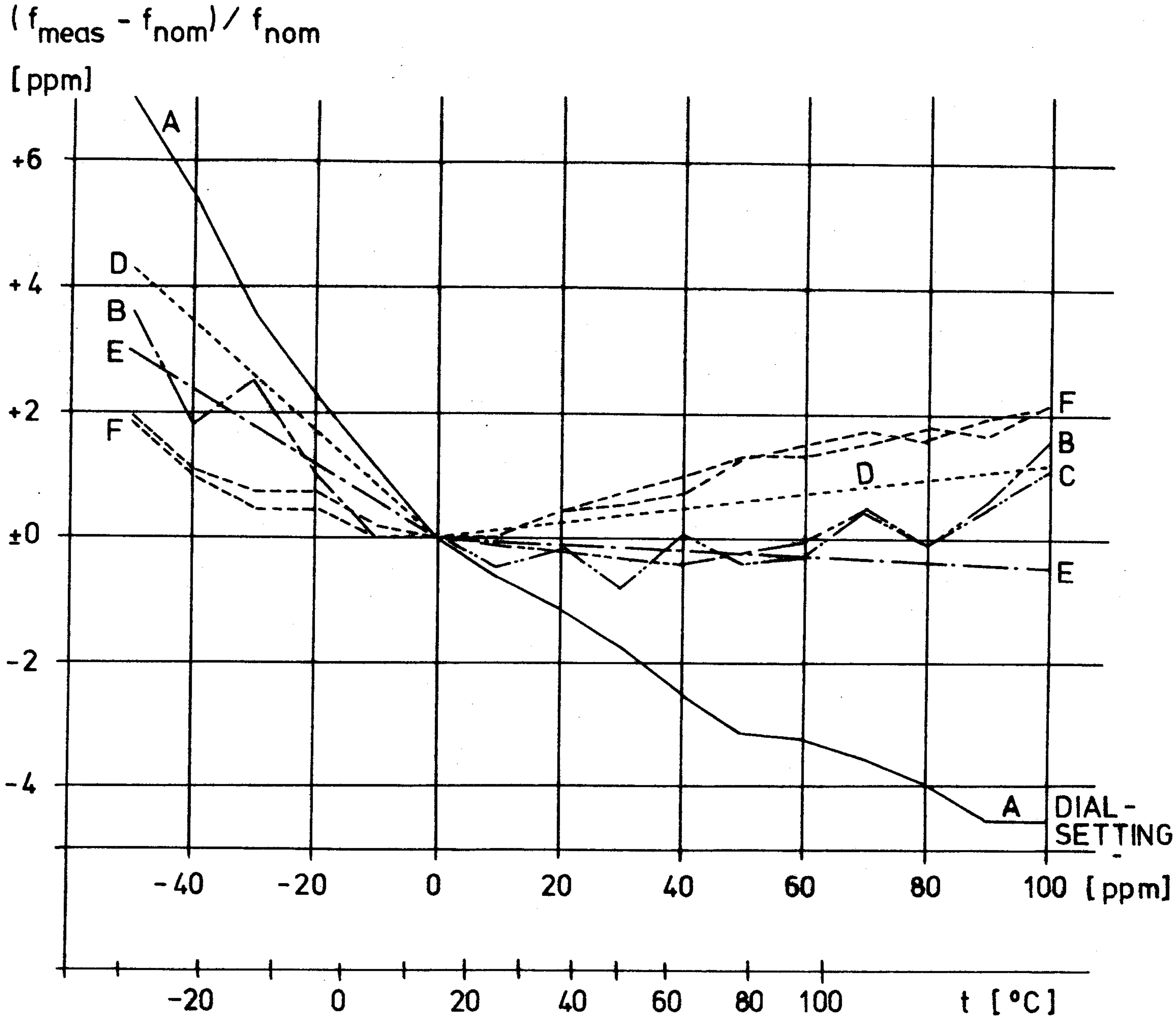

Fig. 4.3.2 PPM dial error versus PPM dial setting of two Hewlett-Packard HP 3800B distance meters. For details see Table 4.3.2.

Curve	Instrument	Date	Remarks
B	1141A00110	20. 3.81	
C		28. 3.81	
D		6.10.76	
A	1226A00368	28. 3.81	faulty ppm-dial
E		21. 9.76	
F		28.10.81	after repair of ppm-dial

Table 4.3.1: Details of frequency error versus ppm-dial setting tests executed with two Hewlett-Packard HP 3800B distance meters.

In Figure 4.3.2, the temperatures which, in combination with the seal level pressure, would require a certain ppm-dial setting are plotted on a second abscissa. This allows an easy evaluation of the dial error in relation to the frequency versus temperature characteristics of Figure 4.1.2. Only curve A exhibits a significant trend of - 0.065 ppm/^{o}C in the temperature range from 5^{o} to 40^{o}C. With an oscillator drift of the same instrument and in the same temperature interval of - 0.256 ppm/^{o}C, the combined oscillator and dial drift yields - 0.321 ppm/^{o}C. The scale accuracy of the distance meter is specified by the manufacturer as ± 10 ppm between - 10^{o}C (+ 15^{o}F) and 40^{o}C (105^{o}F) (GORT, 1971). Multiplying the above drift rate of - 0.321 ppm/^{o}C by 50^{o}C indicates that the worse of the two instruments is still within specification, even if the ppm-dial error is included.

An analysis of Figure 4.3.2 reveals that the curves B, C, D agree very well, although one curve was measured five years earlier than the other two. The curves A and E of the second instrument disagree quite considerably. The 1976 curve E is in line with the curves of the other instrument. The 1981 curve A exhibits a much larger error, although it is still within specifications. The deterioration of the performance of the dial and its circuitry may be attributed to parameter changes of components in the circuitry or to a fault which developed in the five years between the measurements. The latter assumption is supported by the fact that the frequency of the instrument was found to be "stuck" at + 50 ppm at the beginning of the 1981 trials, for dial settings between - 50 ppm and + 50 ppm. The normal frequency change with dial setting was restored only after the dial was turned to a position above + 50 ppm. The curve A in Figure 4.3.2 was measured immediately after this incident.

To avoid any erroneous distance measurements with the HP 3800B No 1226A00368 in future, it is advisable to turn the dial fully anticlockwise and fully clockwise before setting the dial to the desired position or to zero. (Subsequent repair of the battery pack of this instrument eliminated the problem).

4.4 Ageing

As defined earlier in sections 2.2.3.2 and 2.3.3.1, ageing describes the long-term drift of an oscillator's frequency over the years. To get a reliable information on the ageing, the repeated measurements (in yearly or half-yearly intervals) should be executed in exactly the same manner and under the same conditions. A suitable arrangement would be:

(1) Measurement in air-conditioned laboratory at 20°C.

(2) EDM instrument (switched off) stored in laboratory for 24 hours prior to test.

(3) Power supplied by mains operated dc power supply.

(4) Frequency measured after warm-up from 55 to 65 minutes after switch-on. Mean frequency in this interval adopted.

(5) The instrument operated in ventilated ambient conditions during the 65 minutes of operation and the temperature measured in the same position relative to instrument and fan all the time.

(6) Frequency measurement by indirect technique using an optical coupler.

(7) With instruments where the frequency is subject to the ppm-dial setting (e.g. AGA Geodimeter 14, HP 3800B), the ppm-dial should be turned fully clockwise and anticlockwise before taking frequency measurements for at least ten separate settings to zero ppm.

The first requirement makes it possible to execute all measurements at the same temperature. No reduction to a reference temperature (20°C) is necessary, which eliminates possible uncertainties in the drift rates as determined from frequency versus temperature characteristics.

The second criterion insures that the instrument has adapted to the ambient conditions of the laboratory. Failing to observe this rule may lead to erroneous measurement, because the instrument is still partly subject to previous temperature exposure (incl. previous operating periods).

Observing rule three ascertains that always the same voltage is used, at least where no battery pack is necessary between power supply and EDM instruments. (In the case of HP 3800B distance meters, the battery must be charged prior to the test.)

If the fourth rule is followed, ample time (55 minutes) is available to set-up and check the indirect frequency measurement equipment. Also, the timing is less critical, as the frequency is measured at a section of the warm-up characteristic exhibiting a small frequency versus time gradient. (Upon turn-on, this gradient may be very pronounced, thus requiring very accurate timing).

Criterion five is to make sure that a good heat dissipation between instrument case and ambient is achieved. Possible changes between still air and draft conditions in the laboratory are thus rendered ineffective. Furthermore ventilated air compares better with field conditions (wind) than still air. Small frequency changes between still air and ventilated air conditions are suspected. In the case of an opened AGA Geodimeter, the frequency after warm-up at 20^{o}C differed by 1.40 ppm between still air and ventilated air (3.6 m/s) operation. Further investigations are required to determine the effect for closed case operation of this and other instruments.

The sixth requirement is not an absolute one. If adhered to, the frequency measurement conditions are comparable to distance measurements in the field, where no cables are attached (in the case of HP 3800B distance meters, no distance measurement is possible as long as frequency measuring cables are attached) and the instrument case is in place. If direct frequency measurement techniques are employed, corrections may be required to make the frequencies measured comparable to distance measurements in the field.

The last requirement is necesarry to decrease the effect of the setability of the ppm-dial to insignificant levels. Also, it gives an assurance that the dial was in fact at zero ppm during the test, even if the dial should exhibit a fault as discussed in section 4.3.2.

The above procedure provides ideal conditions for the establishment of ageing patterns if repeated over the years. In addition, it yields a very important element of the standardization of an instrument, namely the offset of the measured frequency from the nominal value at 20°C ambient temperature.

Due to the continuing improvement of measuring techniques in the context of this investigation, the data available for the establishment of ageing patterns are less homogeneous than one would like. The analysis of the ageing behaviour is largely based on frequency measurements executed for other purposes such as the frequency versus temperature characteristic and warm-up effect determinations. For two out of eight instruments, no results are presented because repair work was executed between dates of frequency measurements. (One distance meter had to be repaired five times in five years!).

In Table 4.4.1, the data of three instruments are listed. The three instruments have in common that the environmental correction dial (ppm-dial) pulls the oscillator frequency. The measurements are therefore subject to the random setability error of the dial, unless the frequency listed refers to the mean of 10 dial settings. The precision of a single dial setting is ± 0.2 ppm and ± 0.3 ppm for the Geodimeter 14 and the HP 3800B distance meters respectively (section 3.6). All AGA Geodimeter 14 data were reduced to the condition of indirect frequency measurement at 20°C ambient temperature. The Hewlett-Packard HP 3800B data required corrections for temperature only and refer to direct frequency measurement with closed case. (These instruments are equipped with a permanent frequency output socket). It should be noted that the Geodimeter 14 oscillator was adjusted between the measurements of 22.1.1981 and 23.1.1981. With the third instrument of Table 4.4.1, an additional test was executed in October 1981. This test revealed a fault in the mechanism of the ppm-dial

Instrument	Date	Ambient temp.	Elapsed time	No. of dial settings	Measured frequency	Correction to +20.0°	Correction to Cable off	Correction to Case on	Correction to Ind. meas.	Corrected frequency	Freq. error	Details
		°C	min		Hz	Hz	Hz	Hz	Hz	Hz	ppm	
AGA Geodimeter 14	29. 8.79	20.0	62	1	14985513.5	-	-2.97	-6.22	-1.51	14985502.8	-1.68	direct, open case
No 14075	30. 8.79	20.0	52	1	514.6	-	-2.97	-6.22	-1.51	503.9	-1.61	direct, open case
	22. 1.81	26.0	180	10	473.5	+8.27	-	-	-	481.8	-3.08	indirect
	23. 1.81	22.0	90	3	497.0	+2.76	-2.97	-6.22	-1.51	489.1	-2.60	direct, open case
	30. 3.81	23.2	61	10	471.4	+4.41	-	-	-	475.8	-3.48	indirect
	19.10.81	20.3	63	10	480.6	±0.00	-	-	-	480.6	-3.16	indirect
HP 3800B	7. 1.77	20.8	120	1	14985412.0	+1.6	-	-	-	14985413.6	-2.70	direct, closed case
No 1141A00110	17. 1.77	20.7	60	1	411.3	+1.4	-	-	-	412.7	-2.76	" " "
+HP 3801B	8. 9.77	19.7	130	1	431.0	-0.6	-	-	-	430.4	-1.57	" " "
No 1149A01330	9. 9.77	19.4	90	1	433.4	-1.2	-	-	-	432.2	-1.45	" " "
	28. 3.81	23.6	87	10	429.4	+7.0	-	-	-	436.4	-1.17	" " "
	30. 3.81	23.7	148	10	431.6	+7.2	-	-	-	438.8	-1.01	" " "
	1. 4.81	23.5	122	10	431.1	+6.8	-	-	-	437.9	-1.07	" " "
	28.10.81	22.7	63	10	434.6	+5.3	-	-	-	439.9	-0.94	" " "
HP 3800B	11. 1.71	21.0	65	1	14985451.7	+3.8	-	-	-	14985455.5	+0.10	direct, closed case
No 1226A00368	12. 1.77	21.0	70	1	459.3	+3.8	-	-	-	463.1	+0.61	" " "
+HP 3801B	15. 5.80	20.0	63	1	475.0	-	-	-	-	475.0	+1.40	" " "
No 1227A02954	16. 5.80	20.0	53	1	474.5	-	-	-	-	474.5	+1.37	" " "
	19. 5.80	20.0	50	1	477.5	-	-	-	-	477.5	+1.57	" " "
	28. 3.81	23.5	64	11	503.2	+13.4	-	-	-	516.6	+4.18	" " "
	28.10.81	22.7	62	10	418.5	+10.4	-	-	-	428.9	-1.68	" " "

Table 4.4.1: Frequency measurement for the determination of the ageing pattern

Instrument	Date	Ambient temp.	Elapsed time	Measured frequency	Correction to 20.0°C	Correction to Cable off	Correction to Ind. meas.	Corrected frequency	Freq. error	Details
		°C	min	Hz	Hz	Hz	Hz	Hz	ppm	
HP 3820A	26. 8.80	20.1	50	14987089.1	-	-	-	14987089.1	-0.39	direct, open case, f = 375 Hz
No 1650A00131	27. 8.80	20.0	59	090.0	-	-	-	090.0	-0.33	" " "
	29. 1.81	20.5	60	091.2	-	-	-	091.2	-0.25	" " "
	30. 3.81	23.5	60	087.0	+6.6	-	-	093.6	-0.09	" " "
Kern DM 501	29. 8.79	20.0	62	14985349.4	-	+1.0	-1.0	14985349.4	-3.38	direct, f = 150 kHz
No 250942	30. 8.79	20.0	52	350.1	-	+1.0	-1.0	350.1	-3.33	" "
	15. 5.80	20.0	63	348.0	-	-	-	348.0	-3.47	indirect, f = 15 MHz
	16. 5.80	20.0	53	350.5	-	-	-	350.5	-3.30	" "
	19. 5.80	20.0	50	365.0	-	-	-	365.0	-2.34	" "
	21. 1.81	28.0	75	284.0	+54.9	-	-	338.9	-4.08	" "
	28. 3.81	23.7	63	304.8	+25.4	-	-	330.2	-4.66	" "
Topcon DM-C2	12. 5.80	19.9	50	14985405.0	-	-	-	14985405.0	-2.14	indirect, f = 75 kHz
No 911266	13. 5.80	20.0	50	407.0	-	-	-	407.0	-2.00	" "
	14. 5.80	20.0	67	408.0	-	-	-	408.0	-1.94	" "
	28. 1.81	20.5	85	405.9	-	-	0.0	405.9	-2.08	direct, f = 1.5 kHz
	30. 3.81	23.5	60	403.3	+4.2	-	0.0	407.5	-1.97	" "

Table 4.4.2: Frequency measurements for the determination of the ageing pattern.

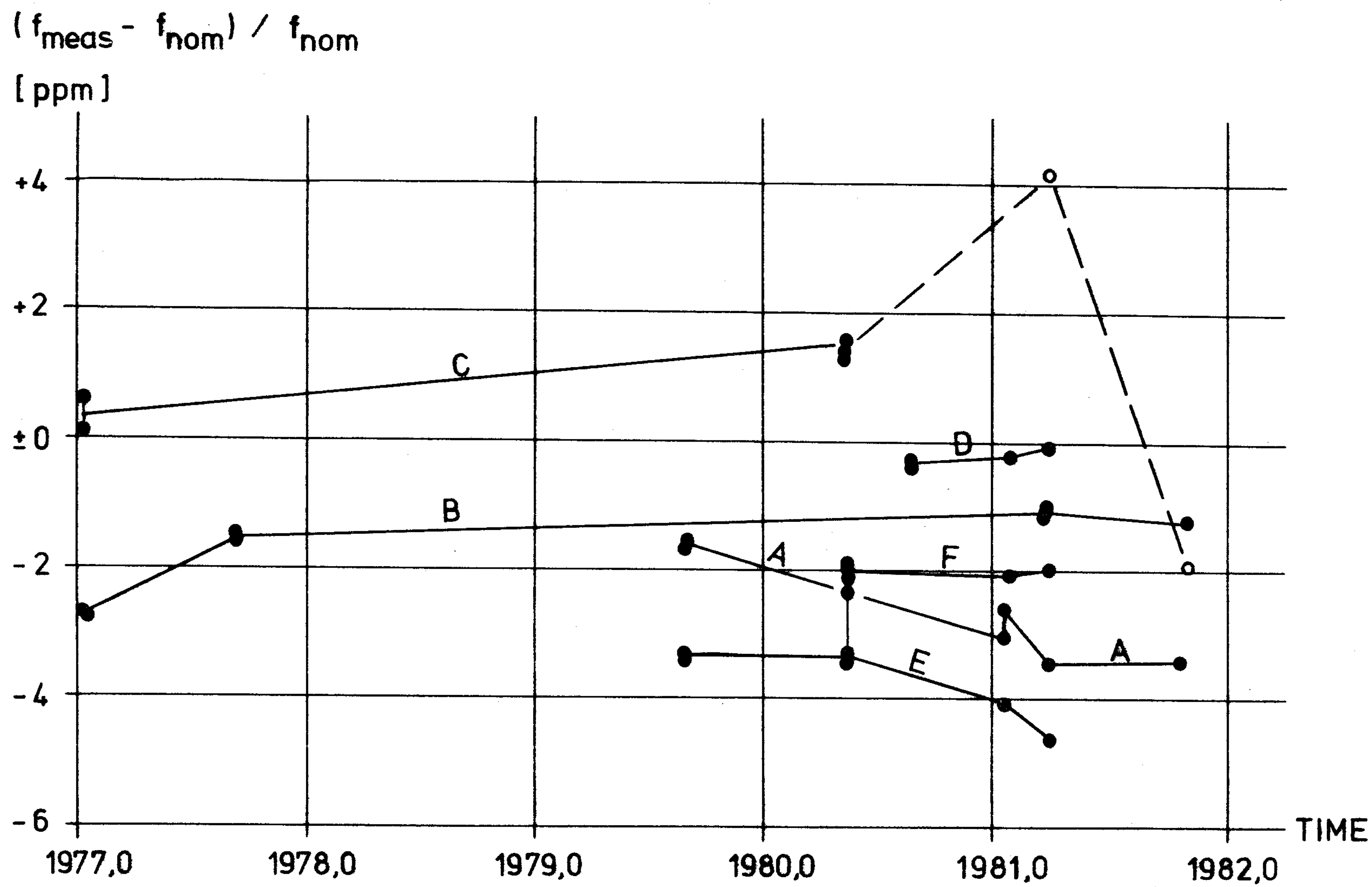

Fig. 4.4 Ageing patterns of six short range distance meters: A = AGA Geodimeter 14, B = HP 3800B (No 1141A00110), C = HP 3800B (No 1226A00368), D = HP 3820A, E = Kern DM 501, F = Topcon DM-C2.

as the nominal frequency was obtained at - 10 ppm and at - 70 ppm dial setting depending on the dial being brought in from the clockwise or anticlockwise stop. The last data set given in Table 4.4.1 (date: 28.3.81) must also be considered suspect, as some problems with the dial were already experienced at that time. (The instrument has been repaired since.)

The data of three other instruments are listed in Table 4.4.2. The modulation frequency of these instruments is not affected by the ppm-dial setting.

All data are plotted against time in Figure 4.4. The second last measurement in curve C is suspect for reasons given before and will not be considered further. The vertical step at 1981.06 in curve A is caused by the readjustment of the oscillator. The offset of two measurements at 1977.03 in curve C are caused by a resetting of the ppm-dial (to zero). In curve E, one of three measurements at 1980.37 differs considerably from the remaining two. The reason is not known.

In Table 4.4.3, the ageing rates, as calculated from the data given in Tables 4.4.1 and 4.4.2, are listed. They have been computed by linear regression and exclude the last measurement in curve C and one outlier in curve E.

Curve	Instrument	Number	Ageing rate
A	AGA Geodimeter 14	14075	-0.82 ppm/y
B	HP 3800B	1141A00110	+0.29 ppm/y
C	HP 3800B	1226A00368	(+0.33 ppm/y)
D	HP 3820A	1650A00131	+0.40 ppm/y
E	Kern DM 501	250942	-0.71 ppm/y
F	Topcon DM-C2	911266	+0.01 ppm/y

Table 4.4.3: Ageing rates of short range distance meters.

When discussing the results given in Table 4.4.3, one should keep in mind that they are based on relatively few measurements and that the results given for the HP 3800B instruments are further affected by the setability of the ppm-dial. The uncertainty of the ageing rates of these instruments due to the random setability error of the dial amounts to ± 0.15 ppm/year approximately. All ageing rates conform with the expected values of 3 ppm/y and 1 ppm/y for RTXO's and TCXO's respectively (see section 2.3.3.1). Of the instruments listed in Table 4.4.3, only the AGA Geodimeter 14 is known to be equipped with a TCXO (see Table 2.4).

The statement made in section 2.2.3.2, namely that oscillators age either upwards or downwards, is confirmed in Figure 4.4. It has also been mentioned in the same section that metal enclosed oscillators age downwards and glass enclosed oscillators upwards. On this basis one may conclude that the instruments AGA Geodimeter 14 and Kern DM 501 are equipped with metal enclosed oscillators, and the three Hewlett-Packard instruments with glass enclosed oscillators. In the case of the AGA instrument, this conclusion has been confirmed by inspection of the circuitry. No attempt has been made to confirm the above suppositions for the other instruments, as this would have required dismantling of the instruments concerned.

No reports on ageing rates of oscillators of short range distance meters have been found in literature, as far as RTXO and TCXO equipped instruments are concerned. The most comprehensive results have been published by MEIER-HIRMER (1978b, 1980). Ageing rates of - 0.4, - 0.8, + 0.9, 0.0 and + 1.1 ppm/year for two Tellurometers MRA4, one Tellurometer CA 1000, one Geodimeter 8 and one Tellurometer MA 100 respectively were stated. Only the ageing rate of the CA 1000 of + 0.9 ppm/year is of interest here, because it refers to an RTXO (see Table 2.4). All other instruments in question employ OCXO's. HODGES (1974) measured an ageing rate of + 0.6 ppm/year for an AGA Geodimeter 6. Long-term frequency investigations with an AGA Geodimeter 8 were also reported by RICHTER (1978), but are too inconsistent to allow a derivation of a linear trend. Some rather general remarks on the frequency behaviour with time were made by WERMANN (1979).

It may be concluded that the ageing rates of short range distance meters (as investigated here) as well as of long range distance meters (reported elsewhere) are small and almost always smaller than 1 ppm per year. Ageing is therefore significantly less critical than the frequency versus temperature and the warm-up behaviour. Following the rules given at the beginning of this section, the ageing pattern can be easily monitored.

4.5 Retrace and Hysteresis

Following the definitions given in section 2.3.3.5 for the two effects, the magnitude of retrace and hysteresis may be extracted from the measurements executed for the determination of the frequency characteristics (Sections 4.1.2 and 4.1.3). Retrace is taken as the difference of the first measurements at 20°C on two consecutive days. Hysteresis is taken as the difference of two frequency measurements at the same temperature on the same day, the first being after a temperature increase, the second after a temperature decrease (or vice-versa). Hysteresis data are usually available for measurements at 20°C and 30°C and sometimes also at 10°C. The maximum values as determined from the curves (or group of curves) of Figures 4.1.2 and 4.1.3 are listed in Table 4.5.

Curve(s)	Instrument	Number	Maximum hysteresis	Maximum retrace
			ppm	ppm
A	HP 3800B	1141A00110	0.4	0.2
B	HP 3800B	1226A00368	0.4	0.2
			0.2	0.2
C	HP 3805A	1338A00123	0.7	0.3
D	HP 3805A	1440A01439	0.2	0.7
E			0.2	0.2
F			0.5	0.9
H	Topcon DM-C2	911266	0.1	0.2
I,J	AGA Geodimeter 14	14075	0.2	0.2
K	HP 3820A	1650A00131	0.2	0.2
L,M,N	Kern DM 501	250942	0.7	1.1
O,P			0.6	0.2

Table 4.5: Maximum values of hysteresis and retrace measured during the determination of the frequency versus temperature characteristics.

The retrace determination for the instruments AGA Geodimeter 14 and HP 3800B may be affected by the limited precision with which the ppm-dial can be set to zero in case of the dial being reset prior to a new temperature cycle. To overcome this problem, the ppm dials were kept in position during the two or more days of measurement by adhesive tapes.

The evaluation of hysteresis is naturally affected by the time elapsed at a specific temperature prior to the frequency reading. This time period was always in excess of 50 minutes. Particularly affected is the hysteresis derived between the first and second frequency measurement at 20°C. The first reading is executed after 50 minutes operating time, the second after eight hours. Any residual warm-up effects between 50 minutes and eight hours will be interpreted as an *apparent hysteresis* effect. The values for the hysteresis in Table 4.5 are therefore rather conservative estimates.

Two instruments exhibit particularly large hysteresis effects. The first instrument (HP 3805A No 1338A00123) requires also a very long warm-up period of 50 minutes to stabilize within 0.5 ppm of the final frequency (see Table 4.2.1.1). The second instrument (Kern DM 501) needs only a short warm-up period but exhibits the by far steepest frequency versus temperature characteristic (- 0.46 ppm/°C).

At least one data set per instruments shows retrace effects of less than (or equal to) 0.3 ppm. Repeated measurements are available for two instruments and indicate a large variability of the magnitude of the retrace effect. No reason has been found why a small retrace is found on one occasion and a large one on other occasions. As retrace and hysteresis effects severely limit the accuracy of frequency calibrations (standardization) of distance meters, further investigations would be beneficial.

In literature, only one publication gives some information on retrace and hysteresis effects of short range distance meters. From the warm-up curves at different ambient temperatures, published by SCHWARZ (1981) for an unspecified distance meter, frequency differences of 0.9, - 0.8 and - 0.4 ppm respectively between measurements after increase and decrease in temperature and after 40 minutes of operation are evident at ambient temperatures of + 20°C, + 10°C and - 10°C. The instrument was kept for 6 hours at a newly set temperature prior to switching on and monitoring the warm-up effect.

The frequency differences listed above are therefore a combination of the retrace and hysteresis effect. The values reported by SCHWARZ are similar to the results in Table 4.5 and refer to an instrument with a frequency versus temperature drift rate of approximately - 0.27 ppm/^{o}C (0^{o} to 40^{o}C).

4.6 Electromagnetic Interference (EMI)

4.6.1 Interference by a Small Transceiver

In field operations with short range distance meters, walkie-talkies (transceivers) are commonly used to maintain communications with the reflector party. It was therefore warranted to investigate the effect of one type of transceiver on the modulation frequency of distance meters. A National Panasonic RJ-380/S citizen band transceiver, transmitting with 0.5 W at 27.24 MHz was used for the tests.

When locating the tip of the telescopic antenna of the transceiver (in transmitting mode with speech modulation) about 0.1 m off the EDM instruments AGA Geodimeter 14, HP 3820A, Kern DM 501 and Topcon DM-C2, no change of the modulation frequency was noticed. Also, no effect was recorded when testing the distance meter section of the two distance meters HP 3800B. However, when placing the antenna over the battery pack (HP 3801B No 1149A001330) of one of the two instruments (HP 3800B No 1141A00110) the modulation frequency changed dramatically as soon as the antenna was closer than 0.2 m. The resulting frequency reduction amounted to 270 ppm and 2700 ppm for antenna positions above the battery pack of 0.1 m and 0.05 m respectively. Although it is unlikely that the antenna will be so close to the battery pack during normal field operation - the battery is usually on the ground and the transceiver in the hands of standing instrument operator - the necessary care should be taken. Interestingly, the second instrument of the same type (HP 3800B No 1226A00368 with HP 3801B No 1227A02954) was not subject to this radiated interference (Section 2.3.3.6).

NASH (1978) investigated the effects of transceivers on distance measurements rather than modulation frequencies of distance meters. The tests of two distance meters in connection with a Sharp CBT66 AM transceiver (1.0 W at 27.24 MHz) are comparable to the tests discussed above. The distances measured with both instruments - a Hewlett-Packard HP 3800B and an AGA Geodimeter 12 - were unaffected by radio transmission without speech modulation in the sense that neither the mean of the displayed distance (300 m) nor its variance changed. No tests were executed for speech modulated transmissions with these instruments. It is interesting to note that the HP 3800B was affected by the transmission of a STC 73.88 MHz transceiver. The average distance measured decreased by 7 mm over 300 m or 23 ppm. The sign of the distance change is in agreement with the frequency change found above, the magnitude however not. As NASH (1978) gave few details of his tests, no further comparisons can be made. However, further tests would be warranted as transceivers may affect distance measurements without affecting modulation frequencies of EDM instruments.

4.6.2 Interference on Frequency Measurements by an Electric Motor

Interference by the electric motor of the compressor of the refrigerating unit was experienced during the measurements of the frequency versus temperature characteristics using the temperature controlled air bath. (Other motors of the air box, such as the fan motors and the electric pump keeping the cooling agent in circulation did not interfere, because they were operating continuously.) It has been stated before that abrupt changes of large currents (ON/OFF of motor) generate impulse noise, which may be transferred to the instruments and cables involved in the frequency measurement by radiated or conducted interference. (Section 2.3.3.6.) Conducted interference could not be excluded, because the power supplies of the EDM instruments and the frequency counters were connected to the same mains outlet as the refrigerating unit. The temperature controlled air box provides electromagnetic shielding on 5 sides, but not on the top face which incorporates a large glass window. Radiated interference must therefore also be considered.

During the tests, the compressor of the refrigerating unit was positioned about 1.5 m to 2.5 m from the air box and thus the distance meters. The power consumption of the motor concerned is 560 W; the unit draws therefore 2.3 A at 240 V.

The result of an analysis as extracted from the frequency versus temperature measurements is given in Tables 4.6.2.1 and 4.6.2.2. On some occasions, the erroneous frequency measurements were booked. In these cases a "nil" remark is given in the "uncertainty" column.

Instrument	Number	Date	Max. freq. error	Ambiguity	Case	Freq. measurement	Count
HP 3800B	1141A00110	7. 1.77	5 ppm	6.7 ppm	closed	direct (HF)	1 s
(HP 3801B)	(1149A01330)	17.11.77	6 ppm	6.7 ppm	closed	direct (HF)	1 s
HP 3800B	1226A00368	11.11.77	5 ppm	6.7 ppm	closed	direct (HF)	1 s
(HP 3801B)	(1227A02954)	12.11.77	5 ppm	6.7 ppm	closed	direct (HF)	1 s
		15. 5.80	NIL	NIL	closed	direct (HF)	1 s
		16. 5.80	NIL	NIL	closed	direct (HF)	1 s
		19. 5.80	NIL	NIL	closed	direct (HF)	1 s
HP 3805A	1338A00123	13. 1.77	800 ppm	1334 ppm	closed	direct (LF)	1 s
		14. 1.77	534 ppm	1334 ppm	closed	direct (LF)	1 s
HP 3805A	1440A01439	13. 1.77	69 ppm	133 ppm	closed	direct (LF)	10 s
		30. 3.77	16 ppm	133 ppm	closed	direct (LF)	10 s
		31. 3.77	41 ppm	133 ppm	closed	direct (LF)	10 s
		4. 4.77	9 ppm	133 ppm	closed	direct (LF)	10 s
		5. 4.77	35 ppm	133 ppm	closed	direct (LF)	10 s
		27. 8.79	36 ppm	NIL	closed	direct (period,LF)	13 s
		28. 8.79	35 ppm	NIL	closed	direct (period,LF)	13 s
HP 3820A	1650A00131	26. 8.80	160000 ppm	NIL	open	direct (period)	7 s
		27. 8.80	48700 ppm	NIL	open	direct (period)	7 s

Table 4.6.2.1: The effect of the impulse noise of an electric motor on the frequency measuring set-up.

Instrument	Number	Date	Max. freq. error	Ambiguity	Case	Freq. measurement	Count
AGA Geodimeter 14	14075	29.8.79	NIL	NIL	open	direct (HF)	10 s
		30.8.79	NIL	NIL	open	direct (HF)	10 s
		28.8.79	NIL	NIL	open	direct (HF)	10 s
		27.8.79	2 ppm	NIL	open	direct (HF)	10 s
Kern DM 501	250942	29.8.79	1 ppm	NIL	closed	direct (LF) (period)	7 s
		30.8.79	2 ppm	NIL	closed	direct (LF) (period)	7 s
		15.5.80	3 ppm	6.7 ppm	closed	indirect (HF)	1 s
		16.5.80	0.2 ppm	6.7 ppm	closed	indirect (HF)	1 s
		19.5.80	0.1 ppm	6.7 ppm	closed	indirect (HF)	1 s
Topcon DM-C2	911266	12.5.80	NIL	NIL	closed	indirect (LF)	10 s
		13.5.80	NIL	NIL	closed	indirect (LF)	10 s
		14.5.80	NIL	NIL	closed	indirect (LF)	10 s

Table 4.6.2.2: The effect of the impulse noise of an electric motor on the frequency measuring set-up.

In other cases, the erroneous measurements were extracted from the frequency versus time plot of the strip chart recorder, which meant that any frequency errors in excess of the full scale frequency range remained undetected. The corresponding ambiguity is listed (in ppm) in the tables.

The frequency error induced by the impulse noise of the electric motor is small for the first two instruments (HP 3800B) in Table 4.6.2.1, namely 5-6 ppm. In one measurement epoch (May 1980), no interference has been recorded. This could be due to the distance meter not being supplied from the same mains power point as the refrigerator of the air box. If this were the case, it would imply that the interference is of the conducted rather than the radiated type. It should be noted that the 12 V dc supply was connected to the battery pack and not the instrument directly.

The next two instruments (HP 3805A) in the same table exhibit much larger effects. Both instruments were supplied directly from a mains operated power supply. The instrument No 1338A00123 shows a much larger effect (800 ppm) than the second instrument. This has to be expected as the counting interval was 1 s only against the 10 s count of the second instrument. The second instrument exhibits errors of up to 69 ppm. The interference effects exceed the distance measurement precision by a factor 10 for a 10 second frequency count and by a factor 100 for a one second frequency count.

By far the largest interference effects were recorded with the HP 3820A, namely up to 16 percent of the measured frequency. The distance meter was supplied directly from a mains operated dc power supply during the tests.

The group of instruments listed in Table 4.6.2.2 is less subject to the impulse noise of the electric motor. The AGA Geodimeter 14 displayed an effect of 2 ppm on one single occasion only, despite the removed instrument case. The power supply was connected through the factory supplied dc-dc converter. The Kern DM 501 had the dc power supply attached to the battery pack. The maximum error for a 7 second count was 2 ppm. For 1 s frequency counts, a maximum value of 3 ppm was recorded. It is unlikely that the ambiguity of 6.7 ppm has any significance because it would require that the interference effect was around 7 ppm on all occasions. The interference effect can therefore be assumed to be smaller than the specified precision of the distance meter. The last instrument of Table 4.6.2.2, namely the Topcon DM-C2, shows no interference effect whatsoever. Again, the 12 V dc supply was attached to a factory supplied dc-dc converter.

Concluding, it has to be stated that a link between the electric motor and the distance meters was present during all tests. The largest effects were recorded for instruments which had neither a battery pack nor a dc-dc converter between mains operated power supply and distance meter. To establish if the effects are also present under battery operation of the distance meters, further tests would be beneficial. Should such further tests not show interference effects, it would prove also the assumption that the interference is of the conducted rather than radiated type. Interference effects on the frequency measurement cables and the counters can be excluded, as they would have been present in all tests.

4.7 Miscellaneous Effects

To conclude the long list of effects on modulation frequencies of short range distance meters, two phenomena shall be reported. Both were experienced on one occasion only and both are connected to an abrupt change of ambient temperature. One could talk therefore about temperature shock effects.

The first effect was noticed in a cold temperature cycle with the instrument HP 3800B No 1226A00368 (Figure 4.7.1). After a temperature stabilization at + 10°C and after eight minutes from setting a new temperature of + 20°C, the frequency jumped by 0.95 ppm to a higher frequency level. The frequency drifted then in the usual manner for 15 minutes at the 0.95 ppm offset before descending again to the normal level. Because of the duration of the effect and the magnitude of three times the setability of the ppm-dial (0.3 ppm), this effect puts some limitations on the accuracy of the instrument's standardization.

A frequency instability of lesser magnitude and shorter duration was recorded with the AGA Geodimeter 14 (Figure 4.7.2). After a stabilization at + 5°C and subsequent setting of a new temperature of 12.5°C for the air bath, the frequency jumped upwards by 0.22 ppm and then downwards by 0.41 ppm, before joining the usual drift pattern. The duration of the instability was about 1.5 minutes.

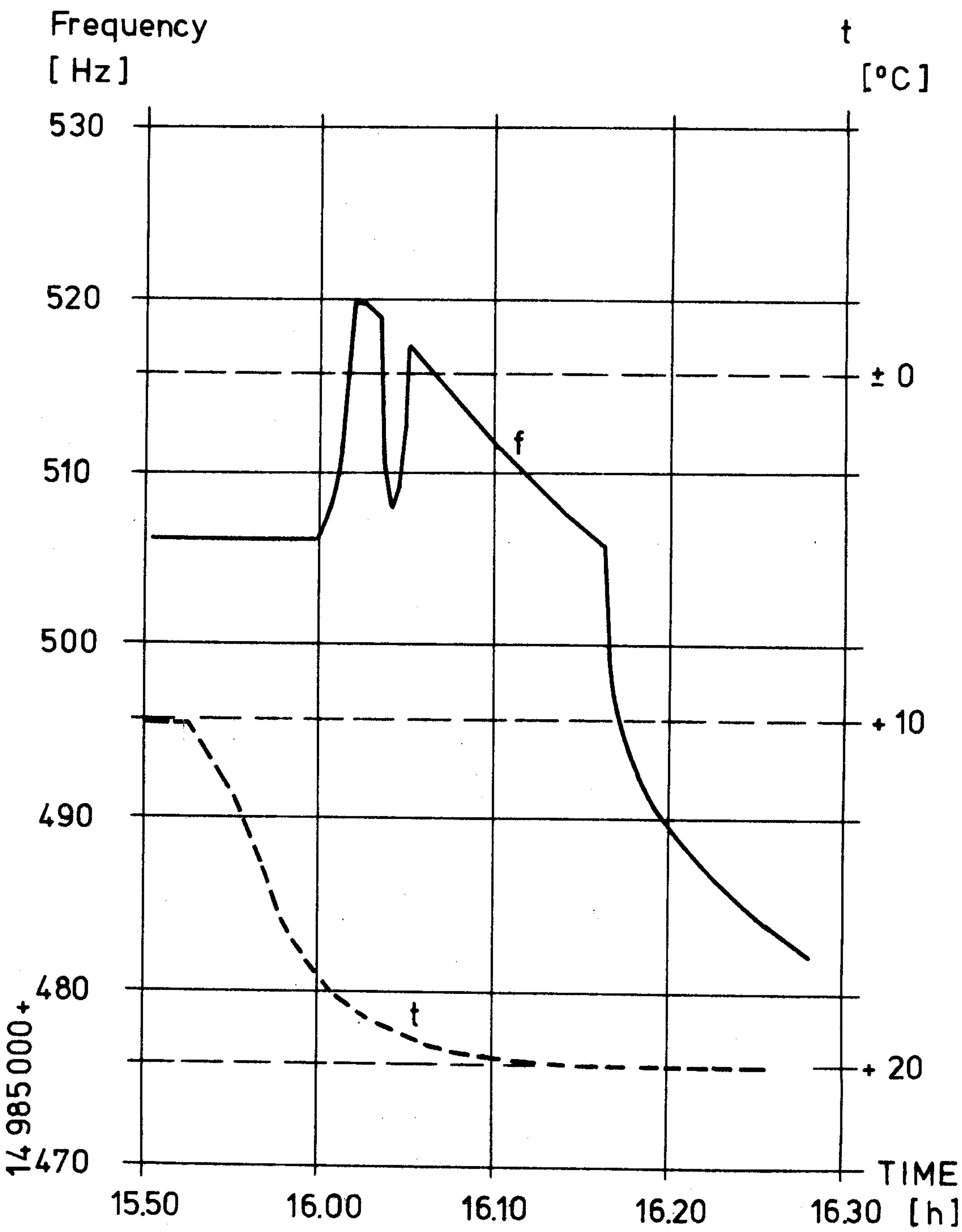

Fig. 4.7.1 Temperature shock effect recorded with the HP 3800B (No 1226A00368) distance meter on 12.1.1977 using one second frequency counts, (One part per million is equivalent to 15 Hz.)

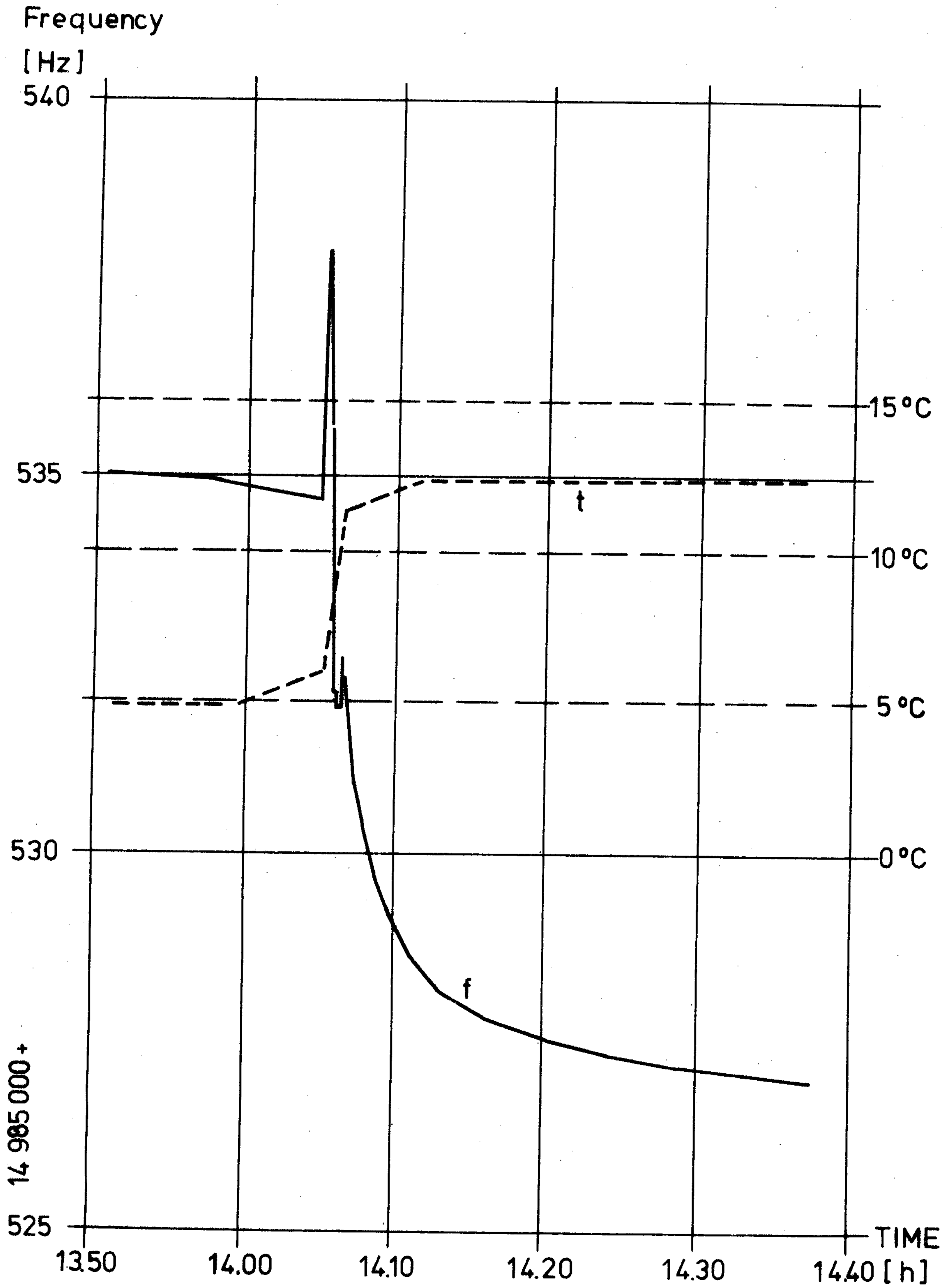

Fig. 4.7.2 Frequency instability recorded with an AGA Geodimeter 14 on 28.8.1979 using ten second frequency counts. (One part per million corresponds to 15 Hz.)

Both instabilities may be attributed to temperature gradient and/or stress relaxation effects as discussed in sections 2.2.3.2 and 2.2.3.3. Practical distance measurements are unlikely to be affected by these instabilities, or if they are, not significantly.

5. STANDARDIZATION OF EDM INSTRUMENTS BY FREQUENCY MEASUREMENTS

5.1 Aim and Philosophy

5.1.1 Aim

The process of standardization has been defined in section 1 as the measurement of the length of the distance meter's unit length in terms of the international standard of length. The most important aspect of standardization is therefore the establishment of a scale factor which converts distances displayed on the EDM instrument into truly metric distances. In the case of frequency measurement, the standardization relates to the international standard of time rather than length. This is of little consequence, as the velocity of light is known to a sufficient accuracy to allow a conversion into metric units (RÜEGER, 1980b). More important is the fact that the modulation frequency is not the only source of scale errors in EDM instruments; a number of other instrumental errors are also known to produce scale errors. This aspect will be discussed later. It should therefore be kept in mind that *frequency measurement alone is unlikely to provide a complete standardization of a distance meter.* Normally however, frequency errors are the largest contributor to scale errors and, thus, standardization.

Secondly, standardization provides the necessary information to decide whether or not an instrument fulfils the distance dependent part of the accuracy specification.

Thirdly, standardization can lead to an improvement in the accuracy of the instrument. Should this be required then frequency measurements executed in laboratory conditions should allow subsequent field measurements to be corrected to such a level as would be achieved by frequency monitoring in the field.

5.1.2 Philosophy

The overriding criterion in standardization - as in all measuring processes - is the accuracy requirement. The depth and accuracy of any standardization measurements has to be decided on the basis of this criterion, because excessive measurement programmes are unnecessary and costly.

The first two aims of standardization as listed in the previous section should be achieved with all distance meters. To assume that an instrument fulfils its stated accuracy specification at the time of purchase and for indefinite periods thereafter would be a wrong and possibly dangerous assumption. Although all manufacturers test their instruments before shipping, they expect the purchaser to check and thus standardize the instrument periodically (e.g. ZEISKE, 1980) in order to keep the instrument within specifications.

If, in addition, an improvement to the specified accuracy (distance dependent term) is sought, it is strongly recommended to do all frequency tests and all subsequent field measurements, where this improved accuracy is required, after a complete warm-up of the instrument. The option of calibrating the warm-up effect and correcting for it on the basis of the time elapsed since switch-on (JACOBS, 1980) cannot be supported. Firstly, the warm-up characteristics are dependent on ambient temperature (KAHMEN & ZETSCHE, 1974; WITTE & SCHWARZ, 1980; KOCH, 1981; SCHWARZ, 1981) and are thus time consuming and costly to establish.

Secondly, if EDM instruments are turned off after one or more measurements, they start to cool down, but will not cool down completely before the next set of distance measurements commences. The starting frequency thus becomes an unknown quantity for subsequent measurements and any adopted warm-up characteristic incorrect. An insight into this problem is given by Table 4.2.2 (See also RÜEGER (1978)).

Thirdly, the frequency versus temperature characteristic is established faster with a warmed-up instrument, because no time has to be allowed for cooling down between frequency measurements at different temperatures. Using this technique (FRERKING, 1978), it takes about 90 minutes for the initial warm-up and then 60-90 minutes for a data point at a specific temperature. The alternative technique as suggested by SCHWARZ (1981) requires about 7 hours per data point, namely 6 hours for cooling down and settling to a new temperature and 40 minutes for the frequency run at a specific temperature.

Fourthly, using a warmed-up instrument eliminates the problem of accurately timing the time-lapse since switch-on of the instrument. Because of the large frequency-versus-time gradients immediately upon turn-on, the timing is quite critical.

It becomes evident that the ultimate accuracy through standardization can only be achieved if standardization and field observations are executed with a warmed-up instrument.

5.2 Laboratory Tests Required

5.2.1 Ageing

The ageing pattern should be monitored according to the instructions given in section 4.4 at 6 monthly or 12 monthly intervals. It provides the scale correction at 20°C for distance measurements by interpolation from the frequency-versus-time plot. Additional measurements should be executed before and after repairs of a distance meter and after in-house frequency adjustments, in order to monitor any discontinuities of the curve.

5.2.2 Frequency versus Temperature Characteristic

A successful test arrangement for the establishment of this characteristic has been described in section 4.1.1. The temperature controlled air bath may be substituted by an incubator-refrigerator unit, in which case the latter has to be equipped with a small fan to circulate the air. The temperature range to be tested has to be selected on the basis of the temperature range likely to be experienced during distance measurements in the field. The measured frequencies are plotted against temperature. From this graph, the scale correction due to ambient temperature not being 20°C - the scale correction from ageing refers to 20°C - is derived from the frequency error at a specific temperature against the frequency error at 20°C.

As the frequency-versus-temperature characteristic is unlikely to change over the years, the necessary scale correction may be brought into a mathematical form on the basis of Eq. (2.2.3.1.1). An equivalent expression has been used by SCHWARZ (1981):

$$\kappa_M = A_0 + A_1 t + A_2 t^2 + A_3 t^3 \qquad (5.2.2)$$

where κ_M is the scale correction due to ambient temperature (in ppm), t is the ambient temperature (in °C) and A_0 to A_3 are coefficients to be determined by a least-squares adjustment. Considering Figures 4.1.2 and 4.1.3, it seems possible to restrict the above equation often to the first two terms, thus leading to a simple linear regression solution.

Finally, the scale corrections according to section 5.2.1 and Eq. (5.2.2) may be combined with the first velocity correction of the distance meter in order to get a single equation for all distance and temperature dependent corrections (JACOBS, 1980; BACKHAUS, 1981).

The recommended measurements for the frequency-versus-temperature characteristic provide some supplementary information which are of benefit. Firstly, the warm-up curve at 20°C is obtained automatically. These data may be used whenever distance measurements, which have not been obtained after a full warm-up cycle, are to be corrected. Secondly, information on the magnitude of the retrace effect (see section 4.5) is gained, if two or more days are required to establish the frequency-versus-temperature characteristic. Thirdly, the hysteresis effects (see section 4.5) can be evaluated on the basis of data points obtained after temperature increases and decreases. The latter two aspects are important for the evaluation of the accuracy of a standardization.

In cases where the ultimate accuracy in the determination of the frequency-versus-temperature characteristic is not required, a reduced programme may be adopted. JACOBS (1980) used frequency measurements at three temperatures in the 0° to 30°C interval, namely at 2, 13 and 28°C and a linear regression fit. Considering that most characteristics determined in the context of this investigation are in fact quite linear, JACOBS' approach seems quite feasible and may not even require a temperature controlled air bath or temperature controlled incubator-refrigerator unit. A room with central heating on a cold winter day (heating:on/off; windows:open/closed) may allow sufficient temperature variation as demonstrated elsewhere (RÜEGER, 1974) or, alternatively, a room equipped with a reverse-cycle air-conditioning unit.

5.2.3 Voltage Dependence

Whenever the ultimate accuracy in standardization is the aim, it is imperative to test the effect of voltage drops on frequency, on one occasion. The suggested test should be preceeded by the charging of the battery pack according to the manufacturer's instructions and the storage of the distance meter in an air-conditioned room for 24 hours prior to the test. The frequency should be monitored from the time the instrument is switched-on until the distance meter indicates a low battery voltage and further until the distance meter ceases to operate, if this second stage is permissible.

The frequency at the start of the low battery indication and just before black-out can then be compared to the frequency after warm-up (after 60 minutes operation), thus indicating the reliability of the frequency after a low battery voltage is displayed and also the proper (factory) setting of the low battery voltage indicator.
In addition, such a test will establish the capacity of the battery used.

5.2.4 Difference between Direct and Indirect Frequency Measurement

For the tests described in sections 5.2.1 to 5.2.3 either the direct or the indirect frequency measurement techniques may be used. As it is only the technique of indirect frequency measurement which establishes truly the frequency on which distance measurements are based, the difference of frequency between direct and indirect measurement should be established once, in the case where the former is used for the measurements outlined in sections 5.2.1 to 5.2.3. For the eight instruments tested here, the difference was equal or smaller than 0.1 ppm (Table 3.7) and therefore negligible in most cases.

5.3 Error Budget of Standardization

From the results of the tests described above, a scale correction can be derived and can be used to correct distances measured in the field. Measurement errors and a number of effects to which the frequency as such and its measurement are subject will limit the accuracy of such corrections. On the basis of the corrections being interpolated from graphs like Figures 4.1.2, 4.1.3 and 4.4, the error budget can be set-up according to Table 5.3.
A distinction is made between a best case and a worst case, on the basis of the best and worst instrument for each error source.
In Table 5.3.1 the setability of the ppm-dial refers to a single setting and affects the frequency-versus-time (ageing) plot.
This effect is only to be considered if the dial actually changes the modulation frequency as with the AGA Geodimeter 14 and the HP 3800B for example. The effect can be easily reduced by multiple frequency measurement with resetting of the dial (to zero) in between.
The standard deviation introduced for the retrace effect is equivalent to half of its total value as tabled in section 4.5.
The same approach has been used to derive a standard deviation for the hysteresis effect.

Error Source	Label	Best case (ppm)	Worst case (ppm)	Source
Resolution of freq. meas. (± 1 count error)	σ_F	± 0.01	± 0.07	Tables 4.1.2, 4.1.3
Setability of ppm-dial	σ_D	-	± 0.32	Section 3.6
Retrace	σ_R	± 0.10	± 0.55	Table 4.5
Hysteresis	σ_H	± 0.10	± 0.35	Table 4.5
Interpolation ageing	σ_A	± 0.02	± 0.15	Fig. 4.4
Interpolation freq. vs. temp. charact.	$\sigma_{F/T}$	± 0.05	± 0.45	Figs. 4.1.2, 4.1.3
Temperature measurement	σ_T	± 0.04	± 0.23	Table 4.2.1.4
Miscellaneous effects	σ_M	-	± 0.50	Section 4.7
Direct/indirect corr.	$\sigma_{D/I}$	-	± 0.03	Table 3.7
Combined effect	σ_{STAN}	± 0.16	± 1.04	

Table 5.3.1: Error budget of standardization

The errors given for the interpolation of the ageing and temperature characteristic curves are based on the assumption that the interpolation occurs along straight lines between data points. The approximation of a curved line by its chord produces errors, the maximum value of which can be estimated on the basis of some equations usually used for the setting out of circular curves. In the frequency versus temperature characteristics, data points have been established at 5°C intervals. Measuring, for example, the offset of the 35° point from the chord connecting the 30°C and the 40°C point, the offset at the 32.5° point from the chord 30° to 35° would be one fourth of the previously mentioned offset. The maximal interpolation errors have been derived from all curves in Figures 4.1.2, 4.1.3 and 4.4 and the relevant values are listed in Table 5.3 in form of a standard deviation. These interpolation errors could be significantly reduced by mathematical curve fitting.

The effect of the uncertainty of the temperatures measured during the evaluation of the frequency-versus-temperature characteristic has been estimated by multiplying the drift rates in Table 4.2.1.2 by ± 0.5°C. The contribution of the miscellaneous effects has been taken into account by taking half of the values reported in section 4.7.

The combined effect follows from the application of the propagation law of variances, introducing the first contribution twice. It is an indication of the accuracy of the scale correction which can be derived from standardization measurements in order to correct field data. The best case value of ± 0.16 ppm may be optimistic for a particular instrument, because an instrument may not perform best with respect to all contributing factors. On the other hand the worst case value of ± 1.04 ppm may be too pessimistic as a particular instrument is unlikely to be a poor performer in all aspects.

It should be noted that some atypically poor results have been omitted from the analysis, as for example the distinct difference between the curves M, N and P in Figure 4.1.3, where the frequency error at 10°C can be anywhere between + 2.5 and - 3.0 ppm, depending on the preceding temperature history. The standardization technique fails clearly at the 10°C mark in this case but at least pinpoints this considerable discontinuity.

In preparation for the investigation to be reported in the following section, the error budget is now derived for four specific instruments. In Table 5.3.2, the error components are denoted by the same symbols as in Table 5.3.1. The sources of the information are also the same as in the previous table. Question marks indicate that the data are not available, and asterisks that the value has been obtained from the other instrument of the same type.

As expected, the accuracy of standardizing corrections for specific instruments are smaller than ± 1 ppm, in fact half of the worst case value of Table 5.3.1.

Instrument/ error component	AGA Geodimeter 14 14075 (ppm)	HP 3800B 1141A00110 (ppm)	HP 3805A 1338A00123 (ppm)	HP 3805A 1440A01439 (ppm)
σ_F	± 0.01	± 0.07	± 0.07	± 0.07
σ_D	± 0.21	± 0.32	-	-
σ_R	± 0.1	± 0.1	± 0.15	± 0.45
σ_H	± 0.1	± 0.2	± 0.35	± 0.25
σ_A	± 0.15	?	?	?
$\sigma_{F/T}$	± 0.05	± 0.2	± 0.08	± 0.12
σ_T	± 0.05	± 0.06	± 0.09	± 0.08
σ_M	± 0.1	-	-	-
$\sigma_{D/I}$	± 0.01	± 0.00*	± 0.00*	± 0.00
σ_{STAN}	± 0.32	± 0.45	± 0.41	± 0.54

Table 5.3.2: Budget of standardization of four specific instruments.

6. VALIDITY OF STANDARDIZATION : FIELD TESTS

Standardization aims primarily at producing the corrections necessary to convert measured distances into truly metric distances. In addition, an improvement of the accuracy of the distance meter may be sought and/or achieved. It is therefore advisable to test the validity of the standardization correction on the basis of field tests. As only the frequency's contribution to standardization has been investigated, the scale correction as obtained from laboratory standardization will be compared with frequency measurements executed in the field.

6.1 Lay-out of Field Tests

Four instruments were tested on the UNSW EDM Research Baseline at Regents Park in Sydney. All 28 distance combinations were measured on one day per instrument on this eight pillar testline of 1 km length. For the analysis of the validity of the frequency standardization, 10 equally spaced frequency measurements will be considered. It took approximately 6 hours to measure all lines. The instruments were switched on about 50 minutes prior to the first distance and frequency measurement and kept operating until all lines were measured. The EDM instruments were shaded by an umbrella, which gave also shade to a suspended thermometer. (GULTON Tastotherm P60 thermistor thermometers were employed, together with probes GT60. The resolution of these units is 0.1°C.) The ppm-dials were set to zero and locked in this position by adhesive tape (AGA Geodimeter 14 and HP 3800B only). All distance meters except the HP 3800B were run off 12 V car batteries. In the case of the HP 3800B distance meter, the car battery supplemented the internal battery until the latter ran flat. Although the test was completed using the battery pack of the second instrument, the data gathered with the second battery could not be used for the present analysis due to the 7 ppm offset in frequency experienced. The second battery pack was later found to be faulty (See Figure 4.4).

A high stability time base RACAL 9420 (refer to Table 2.4) was used as field frequency standard (by courtesy of Mr. J.R. Pollard), powered by two 12 V car batteries in series. Either the Hewlett-Packard HP 5300B/HP 5310A/HP 5302A Measurement System or the Hewlett-Packard HP 5315A Universal Counter were employed for the frequency measurements. Both systems were powered by their internal batteries. Direct frequency measurement was used on all occasions, all instruments being equipped with permanent frequency output jacks.

6.2 Results of Field Tests

The results of the tests executed with one AGA Geodimeter 14, one Hewlett-Packard HP 3800B and two Hewlett-Packard HP 3805A are given in Tables 6.2.1 to 6.2.4. The correction to 20°C is derived from the frequency-versus-temperature characteristics in Figures 4.1.2 and 4.1.3 using linear interpolation between data points. The correction at 20°C is based on the ageing curves of Figure 4.4. For the AGA Geodimeter 14, an additional correction to direct frequency measurement is necessary, because the standardization refers to indirect measurement (Table 4.4.1). Both HP 3805A data sets include a warm-up correction to a reference level after 90 minutes of operation, to which the correction at 20°C refers. Because both HP 3805A distance meters underwent repairs prior to the field tests, the corrections "at 20°C" had to be derived from frequency measurements executed in October 1981, half a year after the field tests. (The importance of the recommendations in section 5.2.1 becomes therefore evident).

The *standardization correction* is the sum of all corrections mentioned above. The *measured* (frequency) *correction* follows from the equation

$$\text{meas. corr.} = \frac{f_{nom} - f_{meas}}{f_{nom}} \qquad (6.2.1)$$

where the nominal frequency is denoted by f_{nom} and the measured by f_{meas}. The *standardization error* may then be derived as "standardization correction" minus "measured correction".

The "bias" is the mean value of all ten standardization errors and reflects the accuracy of the standardization correction. The standard deviation of a single standardization error about the mean value (bias) is denoted by "st. dev." and indicates the accuracy of the "correction to 20°C" based on the frequency versus temperature characteristic.

For comparison of the field test results with the error budget of Table 5.3.2, the latter must be updated, because it accounts for the errors of the standardization correction only.

In the field, the ppm-dial had to be set to zero, the instrument switched on, the frequency and the temperature measured, thus leading to another contribution of the setability of the ppm-dial (σ_D), the retrace effect (σ_R), the resolution of the frequency measurement (σ_F) and the accuracy of the temperature measurement (σ_T). Because of the gradual increase of temperature at the beginning and decrease later, the hysteresis contribution (σ_H) should also be accounted for again. The error budget for the standardization error yields therefore

$$\sigma^2_{TOT} = \sigma^2_{STAN} + \sigma^2_F + \sigma^2_D + \sigma^2_R + \sigma^2_H + \sigma^2_T \qquad (6.2.2)$$

Taking ± 0.5°C as the accuracy of the temperature measurement in the field and considering the coefficients of Table 5.3.2, the results listed in Table 6.2.1 are obtained with respect to the four instruments in question.

Instrument	Number	σ_{TOT}
AGA Geodimeter 14	14075	± 0.41 ppm
HP 3800B	1141A00110	± 0.61 ppm
HP 3805A	1338A00123	± 0.57 ppm
HP 3805A	1440A01439	± 0.75 ppm

Table 6.2.1: Error budget for the standardization error.

The results of Table 6.2.2 for the AGA Geodimeter 14 are extremely pleasing. Both, the systematic (bias) and random component (st. dev.) of the standardization error are extremely small and well within the limits of the error budget. Furthermore, no correlation of the standardization error with temperature and/or time of operation is evident. It should be noted that the realization of such a small bias is purely accidental, as the setability of the ppm-dial (σ_D in Table 5.3.2) amounts to ± 0.21 ppm alone. Overall however, the AGA Geodimeter is likely to perform better because it is the only one of the four tested instruments to feature a TCXO.

Time (h)	Time of oper. (min.)	Temp. (^oC)	Corr. to 20^oC (ppm)	Corr. at 20^oC (ppm)	Indirect to direct corr. (ppm)	Stand. corr. (ppm)	Meas. corr. (ppm)	Stand. error (ppm)
09.32	54	15.0	-0.65	+3.45	-0.30	+2.50	+2.44	+0.06
10.12	94	17.6	-0.30			+2.85	+2.83	+0.02
10.52	134	17.8	-0.27			+2.88	+2.92	-0.04
11.37	179	16.6	-0.43			+2.72	+2.80	-0.08
12.21	223	17.8	-0.27			+2.88	+2.87	+0.01
12.43	245	18.0	-0.25			+2.90	+2.86	+0.04
13.45	307	17.8	-0.27			+2.88	+2.90	-0.02
14.30	352	19.4	-0.07			+3.08	+3.07	-0.09
15.09	391	19.0	-0.11			+3.04	+3.03	+0.01
15.30	432	18.9	-0.13			+3.02	+3.06	-0.04
							Bias =	-0.01
							St. Dev. =	±0.05

Table 6.2.2: Field test with AGA Geodimeter 14 No. 14075 on 15 August, 1981. Sunny weather, moderate to gusty winds.

The second instrument (HP 3800B, Table 6.2.3) produced the largest bias of + 0.77 ppm. The random component of the standardization error (± 0.19 ppm) is however well within the error budget of ± 0.61 ppm. A small trend of the standardization error with time and/or temperature is evident. On the basis of laboratory measurements, a residual warm-up effect can be excluded as a possible reason. An incomplete adaptation of the instrument to the relatively low temperatures in the field after transport, could account for this trend, leading to the instrument's temperature being above ambient. However, the most likely error source behind the large bias is the setability of the ppm-dial. Its contribution to the ageing curves should be minimal after a mean of ten settings has been used (Table 4.4.1). In the field, the dial was set only once, which can be done with a standard deviation of ± 0.32 ppm or with a maximum error of ± 0.96 ppm. The bias is within this maximum error.

The test with the instrument HP 3805A (No 1338A00123) lead to a bias of - 0.57 ppm and a random component of ± 0.28 ppm of the standardization error. (See Table 6.2.4.) Both values are (just) within the error budget. The standardization error exhibits a trend with the time of operation. A residual effect of warm-up can be excluded as the corresponding correction has been applied. Because this type of instrument responds very slowly to changes in ambient temperature, a lack of adaptation to the field conditions after transport could result in the instrument being at higher temperatures than ambient for the first few measurements leading to incorrect "corrections to 20°C". Alternatively, the drift may be explained on the basis of the very large hysteresis component (σ_H) and the temperatures increasing at first and decreasing at a later stage. Part of the bias may be caused by the fact that the "correction at 20°C" relies on one frequency measurement only, which was executed five months after the field test.

The fourth instrument, namely the HP 3805A distance meter (No. 1440A01439) (see Table 6.2.5) performed well in the test with a systematic and a random component of the standardization error of - 0.34 ppm and ± 0.17 ppm respectively. Both components are well within the error budget of ± 0.75 ppm. It seems that the largest error contributor, namely the retrace effect of ± 0.45 ppm, has been overestimated in the error budget. As with the two other

Time (h)	Time of oper. (min.)	Temp. (^oC)	Corr. to 20^oC (ppm)	Corr. at 20^oC (ppm)	Stand. corr. (ppm)	Meas. corr. (ppm)	Stand. error (ppm)
09.39	52	9.8	-1.80	+1.15	-0.65	-1.17	+0.42
10.05	68	10.6	-1.30		-0.15	-0.95	+0.70
10.29	102	11.7	-1.00		+0.15	-0.99	+0.84
10.45	118	11.6	-1.05		+0.10	-0.95	+0.85
11.18	151	11.2	-1.15		0.00	-0.76	+0.76
11.44	177	12.1	-0.90		+0.25	-0.70	+0.85
12.09	202	13.4	-0.45		+0.70	-0.41	+1.01
12.44	237	13.4	-0.45		+0.70	-0.47	+1.07
13.48	301	13.0	-0.60		+0.55	-0.17	+0.62
14.00	313	13.0	-0.60		+0.55	-0.17	+0.62
						Bias =	+0.77
						St. dev. =	±0.19

Table 6.2.3: Field test with HP 3800B No. 1141A00110 on 24 June, 1981. Weather sunny with strong winds throughout.

Time (h)	Time of oper. (min.)	Temp. (^{o}C)	Corr. to $20^{o}C$ (ppm)	Corr. at $20^{o}C$ (ppm)	Warm-up corr. (ppm)	Stand. corr. (ppm)	Meas. corr. (ppm)	Stand. error (ppm)
09.32	54	14.8	-1.25	+2.25	-0.36	+0.64	+1.70	-1.06
10.07	89	15.6	-1.06		-	+1.19	+2.00	-0.81
10.52	134	17.4	-0.63		-	+1.62	+2.20	-0.58
11.36	178	19.6	-0.10		-	+2.15	+2.66	-0.51
12.19	221	20.3	+0.05		-	+2.30	+3.11	-0.81
13.02	264	19.6	-0.10		-	+2.15	+2.88	-0.73
13.49	311	19.1	-0.22		-	+2.03	+2.38	-0.35
14.30	352	19.0	-0.25		-	+2.00	+2.32	-0.32
15.10	392	18.8	-0.30		-	+1.95	+2.19	-0.24
15.55	437	18.5	-0.37		-	+1.88	+2.13	-0.25
							Bias =	-0.57
							St. dev. =	±0.28

Table 6.2.4: Field test with HP 3805A No. 1338A00123 on 29 May 1981. Weather overcast with light wind. Occasional light rainfall.

Time (h)	Time of oper. (min.)	Temp. (°C)	Corr. to 20°C (ppm)	Corr. at 20°C (ppm)	Warm-up corr. (ppm)	Stand. corr. (ppm)	Meas. corr. (ppm)	Stand. error (ppm)
09.22	47	13.8	-1.20	+2.42	-0.23	+0.99	+1.11	-0.12
10.06	91	16.0	-0.80		-	+1.62	+1.79	-0.17
10.37	122	17.1	-0.58		-	+1.84	+2.09	-0.25
11.19	164	16.0	-0.80		-	+1.64	+2.00	-0.38
11.58	203	18.0	-0.40		-	+2.02	+2.28	-0.26
12.36	241	19.2	-0.15		-	+2.27	+2.53	-0.26
13.19	283	18.9	-0.22		-	+2.20	+2.50	-0.30
14.01	326	18.8	-0.23		-	+2.19	+2.60	-0.41
14.42	367	17.4	-0.50		-	+1.92	+2.54	-0.62
15.30	415	17.3	-0.53		-	+1.89	+2.50	-0.61
							Bias =	-0.34
							St. dev. =	±0.17

Table 6.2.5: Field test with HP 3805A No. 1440A01439 on 4 June, 1981. Sunny to overcast weather, light to strong wind.

HP instruments, a small trend of the standardization error with time of operation is present, possibly due to hysteresis or due to the slow response to ambient temperature changes with the instrument temperature having a time lag against ambient temperature. Part of the bias may be due to the "correction at 20°C" which again depends solely on one frequency measurement four months later.

In conclusion it can be stated that the standardization of the frequency component by laboratory techniques approximates the true correction to distance measurements in field with an accuracy of ± 0.5 ppm, in an average over the four instruments and using

$$\text{Accuracy} = \pm (0.25 \Sigma (\text{bias})) \qquad (6.2.3)$$

The precision of the standardization correction around a mean bias is, on the average, ± 0.20 ppm. It is important to note that this accuracy and this precision have been obtained with instruments after a full warm-up cycle, both in laboratory standardization measurements and in the field. Although some residual trends with time and, possibly temperature are not compensated by the standardization correction, they are sufficiently small to be ignored. Laboratory techniques are therefore a very efficient and accurate mean of standardization and are a valid substitute of frequency monitoring in the field.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The standardization of the oscillator component of scale errors in electronic distance meters requires a detailed knowledge of the error patterns of oscillators. Some error components have been considered in the past (ageing, voltage dependence), some others have been taken into account only recently (warm-up effect, frequency versus temperature characteristic). Little attention has been paid so far to effects like retrace and hysteresis although they ultimately limit the accuracy of standardization of the modulation frequencies of distance meters. The short-term stability (2 parts in 10^9) can be safely ignored in EDM application, the effects of shocks ($\leq$ 1 ppm) and nuclear radiation ($\leq$ 10 ppm) however cannot, at least in very special circumstances.

The measurement of the modulation frequencies of distance meters is a very efficient and simple mean of standardizing the oscillator component of their scale errors. The technique of direct frequency measurement requires only a frequency counter (and a calibration facility for it) as equipment. A permanent frequency output jack is of advantage, as it eliminates the need for a dismantling of the distance meter. Quite a number of manufacturers (or their suppliers) provide such jacks on request. More elegant and more consistent with the aim of standardization is the technique of indirect frequency measurement, where the modulation frequency is reconstructed from the transmitted infrared beam, leaving the distance meter untouched.

An optical coupler, which detects and demodulates the transmitted signal, has been built using commercially available components, at a cost of approximately 1000 dollars. If the transmitted beam is continuous, the frequency measurement is easily achieved with the aid of a frequency counter. In the case of pulsed transmissions, a phase locked loop technique (in connection with a synthesizer) has been employed, again using commercially available equipment. The measurement techniques have been fully evaluated and described for the distance meters AGA Geodimeter 14, Hewlett-Packard HP 3800B, HP 3805A, HP 3820A, Kern DM 501 and Topcon DM-C2, considering direct and indirect frequency measurement. Frequencies measured by the two techniques differ by up to 0.1 ppm only.

Eight distance meters of the types listed above were extensively tested over a five year period with respect to the following error components: Frequency versus temperature characteristic, warm-up effect, linearity of ppm-dial (3 instruments only), ageing, retrace, hysteresis and electromagnetic interference. The largest (linear) trend with temperature was found to be 0.46 ppm/^{o}C between 5^{o} and 40^{o}C. The largest warm-up effect experienced was - 5.2 ppm and the longest time required to bring the frequency to within 0.5 ppm of the end frequency was 50 minutes. Although short range distance meters are operational immediately upon switch-on, as claimed by manufacturers, warm-up effects may be quite significant and may require long periods of time to settle; in fact they may require longer periods than oven-controlled crystal oscillators. The non-linearity of the ppm-dials tested exceeded 4 ppm only in the case of a dial later found to be faulty. The ageing rates yielded values of less than 0.8 ppm/year and are smaller than expected. The retrace and hysteresis effects encountered had maximal values of 1.1 ppm and 0.7 ppm respectively and varied distinctly between instrument types and within the data available for one instrument. These effects follow a random pattern and therefore severely limit the accuracy of any standardization attempts.

Electromagnetic interference caused by a small citizen-band transceiver in transmitting mode was recorded for one instrument only after positioning the antenna less than 0.2 m above the battery pack (HP 3801B, error up to 2700 ppm). Electromagnetic interference due to on/off switching of an electric motor during laboratory measurements was evident during tests with all but one instrument. The magnitude of the frequency errors experienced vary greatly between instruments of the same type and between different instruments. The maximum error recorded was 160 000 ppm. Conducted interference through the mains supply (240 V) is suspected.

Based on the laboratory measurements, an error budget has been evaluated for the accuracy of standardization corrections for the frequency component of the scale error of EDM instruments equipped with RTXOs or TCXOs. The budget yields ± 0.16 ppm and ± 1.04 ppm for the best and worst cases respectively. With four out of the eight distance meters, field tests of approximately six hours duration were executed, each instrument on a different day. From the laboratory measurements, standardization corrections for

10 equally spaced measurements on any one day were computed and compared with another standardization correction, derived from the direct frequency measurement in the field. The average difference between the corrections yielded between 0.0 ppm and 0.77 ppm for the different instruments. This leads to the conclusion that standardization corrections derived from laboratory measurements are accurate to ± 0.5 ppm as long as fully warmed-up instruments are used in the laboratory and in the field. This corresponds to a scale accuracy which is usually obtained with oven-controlled crystal oscillators (OCXO) equipped EDM instruments only. The proposed standardization technique failed only for one instrument and for a very restricted temperature range (9°C to 11°C), where the frequency-versus-temperature characteristic exhibits a distinct discontinuity of 6 ppm.

The standardization process provides a valid check of an instrument's accuracy specification (scale component) - none of the instruments failed, mainly because the tests covered only the temperature range from 5° to 40°C -, a correction which brings displayed distances into line with the standard of length and an option for the improvement of the accuracy of RTXO- or TCXO-equipped instruments to the ± 0.5 ppm level of simple OCXOs.

Of all the possible sources of scale errors in EDM instruments, the oscillator is likely to be the most significant. Other sources may however be more significant in a small number of instruments, in which case a standardization of the oscillator component alone may not be sufficient. SCHWARZ (1981) reported on a non-oscillator scale error of 70 ppm. (The cause of this large scale error was not established (SCHWARZ, 1982); an erroneous wiring of the ppm-dial may be suspected.) A complete standardization will therefore have to include a number of distance measurements on an EDM testline of known length to establish, amongst other things, that the frequency standardization correction reduces scale errors to an insignificant amount. If this does not eventuate, other components of the standardization correction must be derived.

7.2 Recommendations

On the basis of the present investigations, a few recommendations can be made.

(1) The retrace effect, which describes the repeatability of the frequency after each switch-on has been found to be a significant and serious limitation whenever the ultimate accuracy in standardization is sought. Special tests are suggested to further investigate the effect.

(2) The execution of frequency standardization is strongly recommended for all EDM instruments with the aim of checking the compliance with accuracy specifications and of establishing a standardization correction for conversion of displayed distances into true metric units. The frequency-versus-temperature characteristic has to be established on one occasion only, the ageing pattern periodically at say yearly intervals. If no improvement in accuracy is sought, the frequency-versus-temperature characteristic may be established through measurement at three suitable temperatures only (e.g. $0^{o}C$, $20^{o}C$, $40^{o}C$).

(3) Governing bodies of the surveying profession should provide a service according to paragraph (2) for the benefit of the profession. Because of its universal application, the indirect method of frequency measurement is most appropriate for the purpose.

(4) Because of evidence of sources, other than oscillators, which produce scale errors, distance measurements on EDM testlines are indispensable.

(5) Most instruments tested were affected by the impulse noise of an electric motor in close vicinity through electromagnetic interference. Whether these effects can be cancelled by operation of the distance meters by battery, should be investigated. If not, the effect should be carefully considered in indoor and, possibly, outdoor applications of EDM.

(6) As it is rather simple to improve the accuracy of a short-range distance meter by standardization in general and by the evaluation of the frequency-versus-temperature characteristic in particular, manufacturers may consider introducing a new, possibly optional, feature of EDM

instruments. Firstly, the inclusion of programmable read-only memories (PROMs) in the microprocessor of EDM instruments for storage of the (temperature dependent) standardization correction ("look-up table"), in connection with a temperature sensing device near the oscillator, would allow real-time correction of the frequency drift with temperature. Secondly, the electronic (fine) tuning of the oscillator could be replaced by a microprocessor correction, thus improving the stability and repeatability of the oscillator. Such a correction would include the "scale correction at + 20°C" which compensates for frequency changes due to ageing. To enable the standardization of such instruments by the user, it is imperative that all stored data and the measured oscillator temperature be accessible through keyboard and display of the distance meter.

(7) The best results in frequency standardization are achieved with fully warmed-up instruments, which also eliminates the need for a warm-up standardization. This method is recommended whenever the ultimate accuracy is sought. The warm-up time required varies between 10 and 50 minutes for an accuracy of 0.5 ppm. For a complete warm-up, 60 to 90 minutes may be necessary.

(8) PPM-dials which tune the modulation frequency are a limitation in standardization in two ways, namely because of the limited setability and the non-linearity. The latter effect should be eliminated by keeping the dial on the neutral position, if an increase in accuracy is important. The former, although less critical, may be eliminated by permanent disabling of the dial, preferably by electronic means.

(9) Although it is relatively simple to standardize the oscillator component of the scale error of short-range distance meters to the ± 0.5 ppm level, the procedure is only useful, if, firstly, other components of the scale error are determined to the same level and, secondly, other instrument errors, such as additive constant, periodic errors and non-periodic errors are calibrated to a comparable accuracy.

(10) All instrument manufacturers should clearly state the temperature range to which the over-all accuracy specification of a distance meter refers, because the distance dependent part relates closely to the oscillator specification. Alternatively, the specifications of the oscillator may be listed separately.

(11) Preliminary investigations with an EDM instrument have shown that the modulation frequency can change between still air and ventilated air operation. Further tests are recommended to determine the magnitude of the effect and are likely to put a further limitation on the use of laboratory calibration data for the correction of field data.

(12) It is suggested to investigate further the effect of transceivers on EDM instruments in general and on their modulation frequencies in particular in order to correlate resulting distance and frequency errors.

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46.* Aust.J.Geod.Photo.Surv. No. 31, (December 1979) 177 pp.
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