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A SYSTEM OF OBSERVATIONS FOR FOUR-DIMENSIONAL GEODESY

ABSTRACT

Four-dimensional geodesy is a convenient term for those new high-precision observation techniques which yield position and gravity and, within a short time span, their variations. This data has applications in many areas of earth physics.

The measurements are approaching an accuracy of one part in 10^8. A global network of observing stations is required to obtain full accuracy, and this is consistent with the geophysical need for a fundamental station on each continental plate. Continuous monitoring of position and time at this station should be supplemented by periodic observations at a number of subsidiary stations spread over the plate.

The siting and marking of the stations requires care to avoid local movements and to ensure that the instrumental positions can be initially defined and later redefined precisely after a lapse of decades, or even centuries. In practice it is not possible to site all fundamental observing instruments at one observatory and they need to be connected in time and position by surveys of ultra high precision.

Coordinating bodies are needed on a national and international level to ensure that the observing programs, the data storage, the analyses and the research in this area are interrelated for optimum benefit.

1. Four-Dimensional Geodesy

New techniques of measurement are providing geodetic results of such high accuracy that the changes, with time, in position, length and gravity need to be taken into account. Conversely the measurements yield valuable data in the form of rates of change of these elements with time. Time becomes an active element, so that it is appropriate to use the term four-dimensional geodesy (4-D geodesy) in these studies.

The precision of measurement is approaching 10 cm for position, 10 microgals for gravity and one part in 10^8 for intercontinental distances (FALLER ET AL 1972; SMITH ET AL 1972A; SAKUMA 1971; KELLERMAN 1972). Since these accuracies are of the same order of magnitude as the annual variation of position and gravity, it should be possible to detect changes within a time span of about three years and to define rates of change within ten years.

In order to make valid comparisons it is essential that all results be referred to the same reference system. Within a framework where all elements, even the so-called fundamental constants, may be changing, this is a requirement fraught with difficulties. The time span of observations is several decades, at least; the observing stations are spread over the whole globe; and the observations involve objects in earth-based and celestial coordinate systems.

This problem has been investigated by Mather who has proposed a special reference frame for long-term studies (MATHER 1972; 1973). His solution involves adopting a rigid body model for the earth and applying corrections to account for any variations from the model. Appropriate expressions are derived for transforming astronomical observations into the system. Since the emphasis is on determining movements of continental plates, a single station is chosen as reference, and movements in longitude are all referred to its longitude. Shifts in the position of the geocentre - the earth's centre of mass - are vital, and will require to be monitored by periodic high-precision measurements of gravity.

Within this framework the data should be expressed in a form made familiar by star catalogues. The data should be given for a particular epoch, say 1975.0, with the 'proper motion' of each element listed, in addition.

2. Applications

4-D geodesy brings a new emphasis on time and the need for a special reference frame. It also introduces a closer relationship between geodesy and other earth sciences. Data from geodesy is applicable to many of the problems currently being investigated in geophysics, geodynamics and oceanography (KAULA 1971; LAMBECK 1972).

Variations in the position of the earth's axis of rotation and in the rate of rotation will be measured by continuous observing programmes to yield results accurate to about 10 cm and 100 μs (MELCHIOR & YUMI 1972). Greater accuracy in polar motion and rotation will help resolve problems in the possible mechanisms of the variations, such as the relationship between earthquakes and the Chandler motion and between rotation, atmospheric circulation and the coupling between the core and the mantle (KAULA 1971; MELCHIOR & YUMI 1972; MANSINHA ET AL 1970). Detailed data on continental plate motion will show whether present motion is the same as the average over past millions of years; whether there are differential movements; whether plates are subject to flexure or vertical movements. The measurements will fill in details in the picture of global tectonics which has emerged over the past decade. This indicates that continental plates are moving apart, with related sea floor spreading from mid-ocean ridges, while elsewhere the plates are colliding with one plate being subduced or forced under the other (le PICHON 1968; HEIRTZLER ET AL 1968; DEWEY & HORSFIELD 1970; le PICHON ET AL 1973).

Satellite geodesy should improve the determination of the gravitational field in two ways: improved accuracy from laser ranging should yield more accurate values for the low order harmonics, and satellites carrying radar altimeters should provide a higher resolution. Anomalies in the low order harmonics show a correlation with tectonic features (HIDE & MALIN 1970), but until more laser range data is available for analysis, the accuracy will not be sufficient for the unambiguous definition of the anomalies (LAMBECK 1972).

In relation to the earth's elasticity, the new observations will provide data on earth tides and the response of continental margins to tidal loading. It will be possible to determine the Love number k and to investigate its apparent variations in different regions of the globe (SMITH ET AL 1972B).

The launching of the GEOS C satellite in 1974 will provide measurements of the geoid surface over ocean areas, from which, in the first instance, the gravitational field can be determined to a higher resolution (APEL 1972). If the geoid is known independently, then geoid - sea level relationships, such as open ocean tides, sea surface slopes, and ocean circulation can be studied (APEL 1972).

3. Measurements

The measurements of 4-D geodesy include laser ranging to satellites (SMITH ET AL 1972A), laser ranging to the moon (BENDER ET AL 1973), very long baseline interferometry (VLBI) (SHAPIRO & KNIGHT 1970) and high precision gravimetry (SAKUMA 1971). Each method of observation has its limitations on accuracy. Laser ranging to both satellites and the moon is affected by the atmosphere and the inherent accuracy of the instruments but these are no longer limiting factors (FALLER ET AL 1972; SAASTAMOINEN 1973). In satellite ranging, uncertainties in the gravitational field, earth tides, radiation pressure and atmospheric drag, all of which cause perturbations of the orbit, are the factors which limit the accuracy (KAULA 1966). In lunar ranging it is again the perturbations of the satellite orbit - in this case the lunar librations - which are the limiting factors (WILLIAMS ET AL 1973; FALLER ET AL 1972).

Altimeter results from GEOS C are expected to be accurate to slightly better than one metre when observing in the high energy mode. Later altimeters, as in the SEASAT series of satellites of the EOPAP programme, should be accurate to 10 cm. The limitations are in the instrumentation, the directional guidance and the effects of ocean waves and other surface irregularities.

In VLBI the volume of data required and the high rate of acquisition have caused difficulties but these have been effectively overcome (SHAPIRO & KNIGHT 1970). The system is capable of giving the required precision but the atmospheric corrections place a limit on the accuracy. Because of the great length of the baselines, there is no similarity between the paths traversed through the atmosphere at the two ends (JONES 1969; SHAPIRO & KNIGHT 1970; KELLERMAN 1972).

Doppler measurements of satellites are generally considered to be of lower accuracy but the method has given results consistent to one metre, in the determination of polar motion (BEUGLASS & ANDERLE 1972). It has been stated that the instruments are capable of an accuracy of 5 cm (SMITH 1971). The remaining limitation on the accuracy is the uncertainty in the atmospheric correction. The advantages of the Doppler system are the ease of obtaining observations, the number of satellites available and the 24 hour capabilities, independent of weather.

4. The Ideal System

In order to obtain the full accuracy of the methods, satellite and lunar laser ranging require a global distribution of observing stations. This is consistent with the geophysical need for a fundamental station on each major continental plate. The problems are on the southern land masses: South America, Africa and Australia, and in Asia where until recently scientific cooperation was very difficult. A satisfactory distribution would be a very minimum of six stations, one each in North and South America, Europe, Southern Africa, Eastern Asia and Australia.

Each station would constitute the fundamental geodetic observatory for its region. Facilities would include the two laser ranging systems, antenna for interconnection of stations by VLBI, Doppler satellite instruments and a base for absolute gravity measurements. A continuous programme of observations would include laser satellite and lunar ranging and Doppler measurements. The VLBI and gravity measurements would be taken at regular intervals.

In addition to the fundamental station, each region would require a number of main stations set up for periodic observations according to a set programme. Here observations would be made using transportable equipment for satellite ranging, Doppler measurements, gravity and possibly interferometry using wide-band transmitters carried by satellite or on the moon. With a 1 000 km spacing, it would require about 15 stations for the Australian continent and its margins. For a 500 km spacing, the requirement would increase to 40 stations. In addition it would be desirable to add a coverage of stations on appropriately situated islands so as to cover oceanic regions.

5. Location of Stations

Apart from normal siting requirements the fundamental stations should be chosen for stability in position over a long term, extending over several decades and possibly centuries. On a regional scale, they should avoid coastal areas where tidal loading may be difficult to model, and zones of known instability due to crustal collision, faulting, earthquake or volcanic activity. On a local scale, site investigation will be needed to avoid local faulting, subsidence or known local earthquake zones.

The objective is to be able to relate, to mm accuracy, positions of all observations taken over the full time span, and to ensure that movements are representative of the whole region. A system of reference marks will be necessary. The marks will probably be in three sets, each set comprising four marks or more. One set will be the stable monuments, set in bedrock and not easily accessible. The next set will be the working monuments, conveniently situated for connecting to the instruments by precise survey. The third set will be the recovery marks placed, for safety, at some distance from disturbing influences on the observing site. The marks will all be interconnected by precise survey. Since there are four marks in each set it will be easy to detect the disturbance of one or two marks.

The same considerations hold for main stations, though they need not be applied so strictly. They may be situated especially for observing a disturbing factor such as fault movement or coastal tide loading.

Because of the accuracy requirement, the definition of the "instrument centre" to which measurements refer, requires careful consideration. The centre may be defined implicitly in the calibration process, or it may depend on the physical form of the equipment. The design of the instrument should provide a clear and direct definition of the centre for the connection to the working monuments by precise survey.

6. The System in Practice

The situation in practice will fall short of the ideal. It may not be possible to set up all observing systems in each of the six continental regions. The instruments are unlikely to be sited together in one geodetic observatory. It may not be possible to arrange a full coverage of main stations over each continent and oceanic region.

As a result one of the problems arising will be the determination of relative positions of different observing systems, so as to compare results. This will be, in effect, tying together the elements of the geodetic observatory. Conventional ground surveys, if carried out to the highest precision, will be sufficiently accurate for plan position over distances up to about 100 km. Care will be necessary in transforming the measurements into the appropriate reference system. Transfer of heights by precise levelling involves an extra difficulty because the datum for those heights is the geoid. The difference in geoid ellipsoid separation can only be carried to the required accuracy for short distances, well under 100 km.

From these considerations it is clear that in most cases the methods of 4-D geodesy will be required to determine the relative positions. It will also be necessary to interrelate the stations in terms of their gravity values, and, during observing periods, their time systems. These determinations should provide no difficulties.

7. The System in Australia

In Australia there are some activities relating to 4-D geodesy. The Division of National Mapping is setting up a lunar laser ranger near Canberra, as part of its Time Service. Initially the results are not expected to be in the 10 cm accuracy class. There is considerable activity in VLBI by the Space Research Group of the Weapons Research Establishment and others, but not directed towards geodetic results. A joint project has been proposed, involving groups in the U.S.A. and the School of Surveying, University of New South Wales (UNSW), to be sponsored by SAO and the Australian Research Grants Committee. If supported, this project will make use of the Tidbinbilla antenna to measure three base-lines of a trans-Pacific network. In gravimetry, the CSIRO's National Standards Laboratory is active in absolute gravity measurement, and the Bureau of Mineral Resources, which already has gravity stations of the National ISOGAL network distributed through Australia, has no formal plans to measure time variations in the gravity field. There is at present no prospect of setting up a satellite laser ranging instrument. This leaves a serious gap in the world-wide network, and in the types of measurement to be undertaken in Australia. In particular it leaves Australia with no participation in international studies, which are currently being planned, of the ocean surface using satellite altimeters.

A further element is necessary in 4-D geodesy: research and development. Much essential development is being undertaken by the National Mapping Division in setting up its lunar laser system. The UNSW School of Surveying has commenced a programme of research on a small scale but this has so far not been directly related to observing systems. In Australia the difficulty in this and other aspects of 4-D geodesy is that while the activities of the National Mapping Division include the applied aspects of geodesy, there is no body to take responsibility and provide funds for scientific geodesy. It will be unfortunate if, as a result, there is limited Australian participation in this new phase of geodesy.

8. Coordination of Activities

The activities under discussion cover a wide geographical range and a diversity of measuring techniques. They share common aims, so it is obvious that coordinating bodies are necessary on national and international levels. It is envisaged that these bodies would have an advisory role. Each national committee would keep in touch with the activities of 4-D geodesy, making assessments to ensure that the coverage was comprehensive and encouraging new projects where necessary. The committee might need to take a hand in the 'housekeeping' functions such as the provision and survey of adequate reference marks, facilities for retaining records of data and distributing data. The national committees would be the channels of communication with the international committee. This committee would have an analogous function in relation to the programmes in the various member nations.

The existing coordinating bodies in Australia are probably similar to those elsewhere. The Academy of Science has a National Committee on Geodesy and Geophysics (ANCOGG) which has a small Sub-Committee on Geodesy. This sub-committee is too limited as the scope of activities required in 4-D geodesy go far beyond its scope. On the other hand, ANCOGG has interests in a great range of fields besides those involved in 4-D geodesy, and even so does not encompass the whole of 4-D geodesy. There is a clear case for the establishment of an ad hoc body to carry out the functions of coordination in four-dimensional geodesy.

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10. Discussion

MELCHIOR: I am still not clear on the problem of Doppler accuracy. We get a precision of 80 cm from the Navy Navigation Satellite. If we had satellites at a greater distance, say 3000 km with 3 frequencies, you could have a higher precision with Doppler.

ANGUS-LEPPAN: Yes. I have carefully not mentioned future possibilities. Particularly with Doppler there are possible new developments just over the horizon.

MELCHIOR: When you are proposing some programs, don't you think there are existing in the Geodynamics Project some working groups who *should* deal with the problem and have probably not done so?

WALCOTT: There are the necessary organizations at the international level but not at the national level.

BOULANGER: Yes.

MELCHIOR: I am a member of working group six in the Geodynamics Commission; this working group deals with problems of the rotation of the Earth, changes in gravity, tides, etc, and they have until now, not made anything very clear.

BOULANGER: We have several regions in the Soviet Union where velocities of vertical crustal movements reach 120 mm yr^{-1}. It is not possible to use such precise measurements without fixing the time of measurements. It is quite easy to see in this problem of measurements for four-dimensional geodesy as spoken of four years ago by Kukkämäkki, Levallois and Marussi. A special study group should be formed to look into this matter; perhaps firstly the question of international programs. In geodesy it is very important and it must be an inter-union organization.

MELCHIOR: The Geodynamics Project is precisely such an inter-union project and with some working groups; and some of those groups are working.

DOOLEY: In the context of measuring changes in gravity, I would like to mention that the (Australian) Bureau of Mineral Resources, in conjunction with the Division of National

Mapping, is setting up two networks in New Guinea for measuring crustal movements in two regions of rapid movement and we plan to make gravity measurements across these zones. Secondly, with the help of Boulanger's group, we have a very accurate net of gravity measurements covering the whole of Australia. It is planned that in ten to twenty years from now, this net will be re-measured with a view to detecting changes in gravity in this way. You also state that your system should have at least one station on every continental plate. I would suggest that you need at least two fundamental stations to each plate, as it requires three parameters to define the relative motion of two plates. It is not possible to get relative rotation from one station.

ANGUS-LEPPAN: The proposal is to have one station at which you take regular observations and a number of other stations where you have a program of periodic observations.

DOOLEY: It will depend on whether you measure relative azimuth at these stations. If you measure only distance, and you are on the one plate, the distances should stay the same. You should measure at least three distances between two plates.

ANGUS-LEPPAN: The proposal was in terms of fixing position each time with respect to the basic frame, rather than distance.

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FUTURE APPLICATIONS OF LASER RANGING SYSTEMS

1. Text

The NASA Earth and Ocean Physics Applications Program (EOPAP) will make extensive use of the advanced laser tracking capabilities which are now being developed. The Earth Dynamics portion of the program will involve laser tracking of satellites in order to make very accurate measurements of the Earth's crustal and rotational motions. Tectonic plate motions of the order of a centimetre per year; and polar motion anomalies of the order of a couple of centimeters in half a day will be monitored to provide basic information about earthquake processes and their possible correlation with the motion of the Earth's rotational pole. The Ocean Dynamics missions of EOPAP will also depend on the power of the laser approach to give the accurate orbital positions needed for the interpretation of the

EOPAP OBJECTIVES

- DEVELOPMENT AND VALIDATION OF METHODS LEADING TO EARTHQUAKE-HAZARD ASSESSMENT AND ALLEVIATION MODELS TO PREDICT PROBABLE TIME, LOCATION AND INTENSITY OF EARTHQUAKES.
- DEVELOPMENT AND VALIDATION OF MEANS FOR PREDICTING THE GENERAL OCEAN CIRCULATION, SURFACE CURRENTS, AND THEIR TRANSPORT OF MASS, HEAT, AND NUTRIENTS.
- DEVELOPMENT AND VALIDATION OF METHODS FOR SYNOPTIC MONITORING AND PREDICTING OF TRANSIENT SURFACE PHENOMENA, INCLUDING THE MAGNITUDES AND GEOGRAPHICAL DISTRIBUTIONS OF SEA STATE, STORM SURGES, SWELL, SURFACE WINDS, ETC., WITH EMPHASIS ON IDENTIFYING EXISTING AND POTENTIAL HAZARDS.
- REFINEMENT OF THE GLOBAL GEOID, EXTENSION OF GEODETIC CONTROL TO INACCESSIBLE AREAS INCLUDING THE OCEAN FLOORS, AND IMPROVEMENT OF KNOWLEDGE OF THE GEOMAGNETIC FIELD FOR MAPPING AND GEOPHYSICAL APPLICATIONS, TO SATISFY STATED USER REQUIREMENTS.

Figure 1

MEASUREMENT REQUIREMENTS SUMMARY

MEASUREMENT	ACCURACY
• CRUSTAL MOTION	1 cm / year
• POLAR MOTION, EARTH ROTATION	2 cm / 0.5 day
• SATELLITE ORBITS	10 cm
• GRAVITY FIELD / GEOID	10 cm
• SEA SURFACE TOPOGRAPHY	10 cm

Figure 2

altimeter data (see figures 1 & 2; NASA 1972).

The evolution of laser tracking system accuracies is indicated in figure 3. The EOPAP flight missions which will take advantage of these capabilities are listed in figure 4 (NASA 1972; VONBUN 1972). Laser tracking will be used to determine the altitude of the GEOS-C spacecraft as its altimeter measures sea surface topography in the western north Atlantic next year. Lasers having a 10 cm range accuracy located at Wallops Island, Bermuda, Cape Kennedy and Goddard will track this satellite and provide the kind of accurate geometrical position reference needed both to calibrate the altimeter and to determine topographical features of the ocean after the instrument has been validated. Results of an analysis of the accuracies attainable with laser tracking data from Goddard, Cape Kennedy and Bermuda are indicated in figures 5 and 6 (BERBERT 1973).

LAGEOS, a dense, spherical, retroreflector studded satellite, to be launched into an orbit of high altitude and inclination in 1976, will be a key element of the EOPAP endeavour. LAGEOS will be the

LASER TRACKING SYSTEM ACCURACIES

1970	50 cm
1973	10 cm
1975	5 cm

Figure 3

NASA EARTH AND OCEAN PHYSICS APPLICATIONS PROGRAM (EOPAP)
MISSIONS EMPLOYING LASER RANGING

GEOS-C	1974
LAGEOS	1976
SEASAT I	1978
GEOPAUSE	1979
SEASAT II	1982

Figure 4

first flight mission devoted exclusively to laser ranging applications. The satellite and its orbit will be designed especially to minimize errors associated with retroreflection from the satellite's corner cube array, and uncertainties in orbital perturbations due to gravitational and radiation pressure effects. A network of lasers having 5 cm range tracking accuracy will be deployed to provide the data needed for determining accurate LAGEOS orbits, and to monitor the motions of the ensemble of large tectonic plates which form the Earth's cover. Polar motion and variations in the

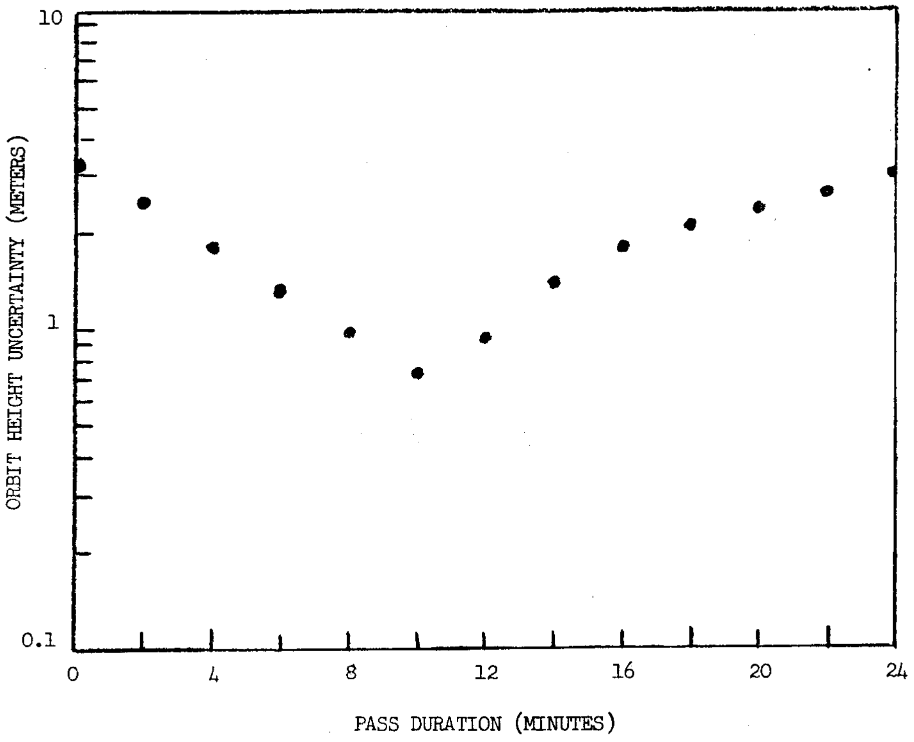

Figure 5. GEOS-C Height Uncertainty Corresponding to Laser Tracking from Goddard, Cape Kennedy, and Bermuda for a Typical SE - NW Arc
Detailed assumptions are listed in figure 6, and discussed in (BERBERT 1973)

Laser Observations (1 per 10 seconds)		
Range Bias	ΔR	20 cm
Range Noise	σR	20 cm
Azimuth Noise	σA	30 arc sec
Elevation Noise	σE	30 arc sec
Time Bias at Reference Site (Goddard)	Δt	0 μsec
Time Bias at Other Sites	Δt	50 μsec
Gravity Field		
Spherical Harmonic Coefficients		0.25 (APL 3.5 - SAO M1)
GM		1×10^{-6}
Survey		
Reference Site		(0, 0, 0) metres
Other Sites		
Cape Kennedy		(1.0,0.5,0.7) metres
Bermuda		(1.0,0.9,0.8) metres

Figure 6. A Priori Error Estimates for Orbit Height Recoveries

Earth's rotational rate will also be determined by this LAGEOS system consisting of the dedicated satellite and the associated laser network (figure 7).

The San Andreas Fault Experiment (SAFE), aimed at detecting and measuring motions some 100 km from the fault line, will also take advantage of the LAGEOS capabilities to achieve more accurate results. Sites already occupied at Quincy and San Diego will be supplemented by additional stations at other

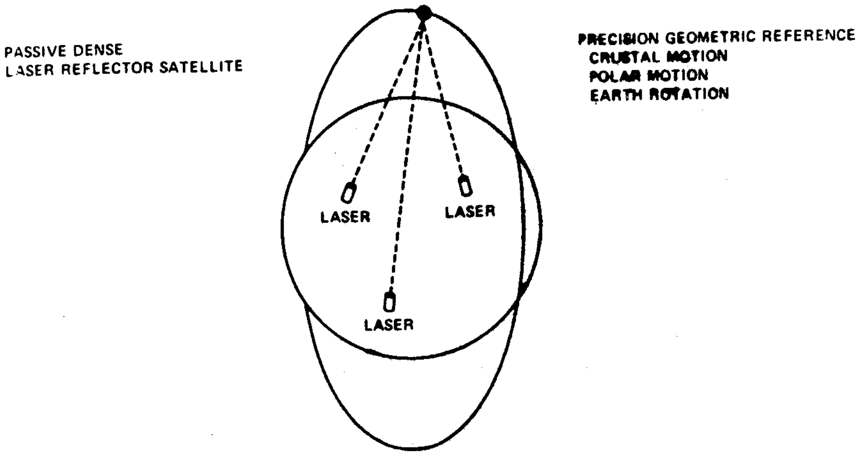

Figure 7. LAGEOS

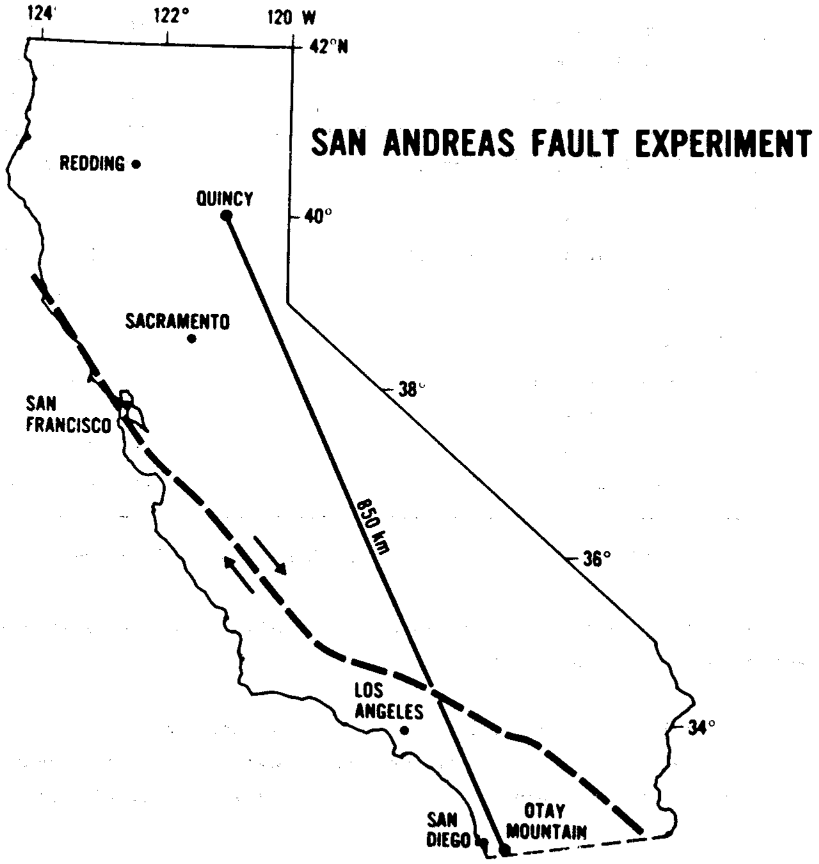

Figure 8.

locations in western North America (figure 8).

A longer look into the future outlined in the general EOPAP plan reveals the SEASAT-A, GEOPAUSE and SEASAT-B spacecraft envisioned for launching in 1978, 1979, and 1982 respectively. It is anticipated that SEASAT-A will be tracked by lasers deployed both globally and in local regions in the manner planned for GEOS-C. The improved capabilities developed for the LAGEOS program will also be used to good advantage in support of SEASAT.

GEOPAUSE, in a circular, polar orbit at a distance of about 30,000 km will also be tracked by the advanced ground laser complex (SIRY 1971). Thought is being given, too, to the possibility of operating a laser system in the GEOPAUSE satellite and using it to track retroreflectors on the ground. Uncertainties associated with orbital perturbations due to the geopotential will be negligibly small for this high orbit. The satellite will be above the horizon for four or more lasers simultaneously in many parts of its orbit; hence the prospect of eliminating tracking system biases on a continuing basis is opened up. Observation of polar motion and variations in the Earth's rotation rate in time intervals of less than half a day will also be possible. It will be practical in addition, to monitor crustal motion both in the small, in terms of effects occurring near fault zones, and in the large, in terms of the gross motions of the tectonic plates relative to one another.

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3. Discussion

HOLDAHL: In the diagram showing locations where you would send your portable lasers, the array seems quite dense (Ed: See diagram in paper by SIRY in this volume). Do you think the methods you described can compete with conventional geodetic methods at distances less than 300 km?

SIRY: Rule of thumb has it that conventional geodetic methods have a resolution of 1 part in 10^6. So once you go beyond 100 km, you are not operating at the 10 cm level. That's the rationale for using these techniques at the 300 km level.

HOLDAHL: What is the minimum spacing at which the observing stations should be placed? [†]

SIRY: Let's put it this way; beyond 100 km you would have difficulties in doing work to 10 cm accuracy with conventional techniques. You can improve on this by a factor of 2 to 5 by using satellite techniques.

WALCOTT: Isn't 1 part in 10^6 pessimistic? Aren't we up to 2 parts in 10^7?

ANGUS-LEPPAN: These are instrumental accuracies; but you are measuring through the atmosphere and I don't think the question of refraction has been solved to 1 part in 10^6.

[†] Post Symposium Comment by HOLDAHL: The rule of thumb mentioned should not be applied to detection of height changes. Error in height changes, when computed from levellings, is proportional to the square root of the distance between the observation point and the reference point. For distances less than 1000 km, precise levellings can detect height changes with an uncertainty less than 10 cm.

DISCUSSION ON SESSION "M" - METROLOGY (G.A. BELL AS CHAIRMAN)

ECKHARDT: Air Force Cambridge Research Laboratories (AFCRL) is presently supporting the development of a new, second generation laser-interferometer absolute gravity system which offers significant improvements over the original instrument constructed by Faller and Hammond with the support of AFCRL and the National Bureau of Standards. The method employed in both instruments is to drop one reflector of the two-beam Michelson interferometer and to determine the distance fallen in known time intervals by direct measurement in terms of interference fringes.

The original instrument which was designed to be transported and was successful in that it was taken to eight different sites and, after spending between one and two weeks total set-up, operate and take down time, absolute values with a precision of better than ±0.05 mGal were obtained at most sites. The apparatus was bulky and when packed for shipment had a total weight of about 2500 lb packed into about 20 shipping containers.

The aim of the new instrument is to decrease the time required to obtain an absolute value of gravity with a precision of at least as good as ±0.05 mGal to about 2 or 3 days and to cut the total weight to at most 800 lb. This is being accomplished by making some radical changes in the mechanical design and employing present day state-of-the-art electronics and computing equipment to give rapid computation of results.

The mechanical design has evolved with the express purpose of removing the necessity of having an ultra high vacuum. This removes the approximately 100 lb weight of the high vacuum pump and cuts the time by at least one full day besides greatly simplifying the problem of using trouble free materials in the vacuum chamber. Reliability will be increased because the tendency for clean surfaces to stick together will not exist in the moderate vacuum needed with the new design.

The main feature of the new design is that the freely falling reflector is enclosed in a small evacuated chamber which falls along with the reflector. These both fall in a larger vacuum chamber but since the air which comes in contact with the falling object is falling with the acceleration of gravity, air resistance cannot affect the measurement. The vacuum required in the outer chamber need be no better than 10^{-2} mm of Hg to prevent gaseous turbulence and to avoid air drag slowing its fall. The interior of the small chamber requires a vacuum of only 10^{-3} mm of Hg to place all possible air resistance effects beyond the level of consideration. While the mechanism required for separating the reflector from the small chamber during the fall is somewhat elaborate, it should be very reliable and be able to withstand many repetitions of operation.

The electronics system will make digital time measurements between a large number (50 to 500) of interference fringes and will thus make independent measurements of **g** and the gravity gradient as well as detect seismic motions occurring during the fall of the object. The digital data will be processed immediately by an on line process and control mini-computer. This will save all the time and trouble required with the original instrument to prepare data for computation and get co-ordinated with a computer facility at or near a field site.

The overall height of the instrument is about 1.5 m, while the use of aluminium in place of stainless steel and a lighter base permissible because of the new design, have also contributed to improvement in total weight. The progress of the state-of-the-art in electronics has resulted in electronic and computation systems that do much more than in the original instrument while its weight has been cut by a factor of two or three.

The future of absolute gravity instruments lies in two directions:

- portable instruments with precisions of between 0.01 mGal and 0.10 mGal; and
- fixed stations with precisions in the 0.001 mGal range.

The technology for producing such portable instruments is well in hand and if there were demand for a large enough quantity, they could become production items in the same sense that gravimeters have. The work of Sakuma at Bureau International des Poids et Mesures (BIPM) has shown that the technology for 0.001 mGal precision is available but the size and complexity of his instrument prove that it is not obtained without a great deal of extra effort and expense.

AUTHOR INDEX

Names in italics refer to participants
Entries in italics refer to contributions presented at this symposium

SUBJECT INDEX