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Geodetic Fixing of Tide Gauge Bench Marks

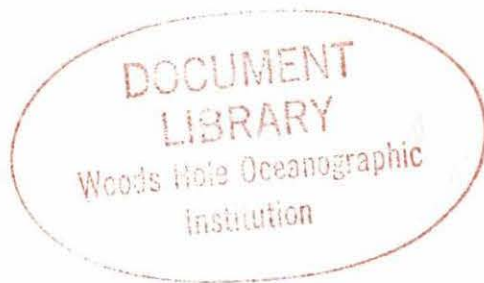
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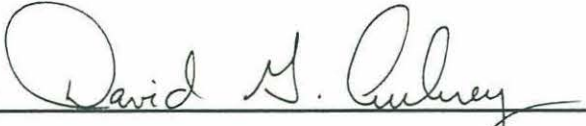
Technical Report

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GEODETIC FIXING OF TIDE GAUGE BENCH MARKS

A Report to

The Commission on Mean Sea Level and Tides
International Association for
Physical Sciences of the Ocean (IAPSO)

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FOREWORD

At the International Union of Geodesy and Geophysics (IUGG) General Assembly, August, 1987, in Vancouver, Canada, the International Association for Physical Sciences of the Ocean (IAPSO) established a Commission on Mean Sea Level and Tides (MSLT). David Pugh, United Kingdom, was appointed President of the new Commission, and in June 1988, he established an ad hoc geodetic committee to "study the geodetic fixing of tide gauge bench marks (TGBMs)."

In selecting members to serve on the committee, an attempt was made to include active researchers from each of the advanced geodetic technologies: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Positioning System (GPS), satellite altimetry, and gravimetry; and analysts working on problems related to global sea level: plate tectonics, glacial rebound, vertical datums, terrestrial reference frames. The number of members was limited in order to make it possible for the entire group to participate in informal working sessions that often required detailed discussions of complex technical questions. This, along with the limited funding available, did result in less international participation than we would have liked. A list of the members and their addresses is given in Annex A.

The committee met at the Woods Hole Oceanographic Institute (WHOI), Massachusetts, November 8 through 10, 1988. More than 16 hours of working sessions were held over two and a half days, but there was still time to enjoy the beautiful setting and the gracious hospitality of WHOI, that included tours of the Research Vessel KNORR and the campus and laboratories, a delicious dinner, and the use of a well-equipped meeting facility, supported by an efficient professional staff. The Committee would like to thank Dr. David Aubrey, the Coastal Research Center and the entire WHOI staff for hosting the meeting, and for sharing the meeting and publication costs.

The travel and subsistence costs of the members of the committee were paid from funds allotted by IAPSO and by the National Oceanic and Atmospheric Administration (NOAA). We thank Ms. Fatimah Taylor, NOAA Office of Foreign Affairs, for her handling of the many arrangements, before and during the meeting, that made it possible for the participants to attend the meeting and work so productively.

EXECUTIVE SUMMARY

This executive summary is organized in three sections. The first section states the terms of reference established for the geodetic committee by the President of the Commission on Mean Sea Level and Tides [Pugh, private communication, 1988]. The second section lists the 5 primary technical conclusions reached by the committee. The third section is a brief overview of the geodetic technologies and the roles of each in the strategy developed by the committee. Also included in the third section are specific recommendations for actions to be taken by the President of the Commission on Mean Sea Level and Tides to enlist the support from the international geodetic and oceanographic communities required to realize an absolute global sea level monitoring system.

More detailed discussions of the geodetic techniques, references, and supporting documentation are presented in the main body of the report.

Terms of Reference

The terms of reference established for the geodetic committee were:

1. To identify the oceanographic and geophysical requirements for fixing Tide Gauge Bench Marks (TGBM's) in an absolute terrestrial coordinate system.
2. To evaluate the technology available for fixing TGBM's.
3. To make recommendations to the MSLT Commission of a strategy for coordinated global fixing of TGBM's and for making the results centrally available.

Technical Conclusions

The primary technical conclusions reached by the geodetic committee are:

1. All gauges to be used to monitor sea level must have a local network of several (6 to 10) bench marks that are resurveyed by spirit leveling or Global Positioning System (GPS) at least once each year.

2. Tide gauges should be organized into regional networks and the relative positions of the gauges within each network should be determined by frequently, preferably at least once per year, GPS surveys designed to achieve sub-centimeter accuracy.
3. The regional sea level networks should be organized around the primary stations of the International Earth Rotation Service (IERS) Terrestrial Reference Frame. This is the only terrestrial reference frame of sufficient accuracy for monitoring global sea level change. (See Figure 5).
4. Absolute gravity measurements should be made at all of the IERS primary stations, near as many of the individual tide gauges as possible (with highest priority being given to island tide gauges), and in regions of glacial rebound and tectonic activity. The measurements should be repeated on appropriate time scales to detect secular changes in gravity of 1 to 3 μgals per year (equivalent to vertical crustal motion of 0.3 to 1 cm per year).
5. A center, preferably the PSMSL, should be designated to collect, archive, and distribute the geodetic information for each of the TGBM's, absolute gravity stations established for monitoring global sea level, and the tide gauge time series.

Overview, with Recommendations

Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) have reached a capability to determine the relative positions (cartesian coordinates X, Y, Z) of points distributed globally with an accuracy of a few centimeters and temporal resolutions of several days for VLBI and a few months for SLR. These methods are already being used by the International Earth Rotation Service (IERS) to monitor variations in the Earth's rotation, and to establish and maintain a global Terrestrial Reference Frame. Both VLBI and SLR measurements have detected the relative velocities of the plates that form the crust of the Earth, verifying plate tectonic theory, and confirming that the plates are currently moving at rates roughly equal to (but in some cases,

perhaps, geophysically significantly different from) the historical rates determined by geological techniques.

The current capabilities of VLBI and SLR are marginally adequate to position a limited number of sea level monitoring stations, near the frequently operated primary observatories. But improvements by factors of 5-10 in both accuracy and temporal resolution are needed to make it practical to determine vertical rates of motion of a global network of TGBMs with sub-millimeter per year accuracy. Based on the historical progress, and assuming that key organizations such as the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) continue to support and develop these technologies, the required improvements in accuracy and temporal resolutions should be achieved during the 1990-1995 time frame.

RECOMMENDATION: The President of the MSLT Commission should forward copies of this report with cover letters to key organizations (e.g., NASA, NOAA, European Space Agency) spelling out the importance of the continued refinement of the accuracies and temporal resolutions of VLBI and SLR, and request their continued support of and participation in the IERS.

RECOMMENDATION: The President of the MSLT Commission should forward copies of this report with cover letters to the President of the International Association of Geodesy (IAG) and the Chairman of the IERS Directing Board noting the importance of extending and improving the IERS Terrestrial Reference Frame (ITRF), to reach as quickly as possible the accuracies and temporal resolutions required for monitoring of global absolute sea level.

Early observations using only the partially completed constellation of satellites have demonstrated the capability of the Global Positioning System (GPS) to determine the relative positions (cartesian coordinates X, Y, Z) of points separated by a few hundred kilometers with an accuracy of a few centimeters in observing periods of 5 to 6 hours. When the constellation is completed and the system is fully operational (now scheduled for late 1990), it will be possible to observe 24 hours per day, which will substantially improve the accuracy and efficiency of GPS surveys. Simulations suggest it should be possible to attain 1 to 3 mm accuracy in 24 hours of observation over distances of several hundred kilometers.

The international geodetic community already has begun regular operation of a civilian tracking network to determine accurate satellite ephemerides, under the auspices of the IAG Subcommittee on GPS. In a pilot campaign conducted from October 30 to November 19, 1988, some 17 nations operated more than 30 tracking stations to test the operation of a global network. Approximately one third of the GPS receivers were collocated at VLBI or SLR stations, directly linking the GPS orbits to the ITRF.

RECOMMENDATION: The President of the MSLT Commission should inform the President of the IAG, the Chairman of the IERS Directing Board, and the President of the IAG Subcommittee on GPS that GPS is expected to play a critical role in positioning and monitoring TGBMs relative to the IERS, and request that every possible effort be made to integrate the GPS orbit tracking network into the IERS system.

The change in gravity with height at the surface of the Earth is approximately 3 μ gals per centimeter. Recent field experience, most notably a series of measurements made by NOAA using the JILA#4 absolute meter, indicates that it is now possible to move an absolute gravity meter from site to site, at a rate of about one site per week, and to determine the absolute gravity with a repeatability of 1-3 μ gals. Intercomparisons of 3 JILA meters agree at the 3-5 μ gal level. At carefully selected sites where no shallow subsurface mass changes occur (such as those associated with changes in ground water level or active volcanism), time series of gravity measurements should prove a highly sensitive method for monitoring vertical motions.

Neo-tectonics cause changes in the position of the crust relative to the oceans. This Earth signal may be misinterpreted as a local sea level change. For instance, redistribution of mass in the mantle of the Earth associated with glacial rebound causes maximum rates of uplift of more than one centimeter per year in regions of Canada and Scandinavia, subsidence of a few millimeters per year in regions just beyond the maximum extent of the ice (e.g., the Atlantic coastline of the United States), and lesser rates of vertical motions over the entire globe. Inaccuracies in modeling these vertical land motions contaminate the tide gauge records and introduce systematic errors in estimates of change in global sea level.

RECOMMENDATION: The President of the MSLT Commission should contact key organizations (NOAA, Geophysical Survey of Canada, etc.) to call their attention to the contribution absolute gravity measurements could make to monitoring global sea level change, and request that they work

cooperatively with other nations to develop absolute gravity networks, to remeasure the gravity at regular intervals, and to provide the gravity time series to researchers for analysis and interpretation.

No central facility currently exists to collect, archive, and distribute the geodetic information for each of the TGBMs and the absolute gravity stations. The Permanent Service for Mean Sea Level, (PSMSL), United Kingdom, handles the tide gauge data, and works to improve the global collection of data by providing expert advice and training on the operation of tide gauge stations.

RECOMMENDATION: The President of the MSLT Commission should contact the PSMSL and request that they take on the additional duties of collecting, archiving, and distributing the geodetic data (time series of TGBMs coordinates and absolute gravity values) on behalf of the international community. Alternative organizations that might be willing to take on the task would include NOAA and NASA, where much of the geodetic data will be reduced and analyzed, as part of on-going programs in global and climate change. If the PSMSL declines the task, these alternative organizations should be approached.

INTRODUCTION

This report is an assemblage of brief technical reviews by individual experts of the status of currently available geodetic technologies that could be brought to bear on the specific problem of “fixing TGBMs in an absolute terrestrial co-ordinate system”; a discussion of how these different techniques might be combined to best exploit the strengths of each (*i.e.*, a strategy); and specific recommended actions to be taken by the President of the IAPSO Commission on Mean Sea Level and Tides (MSLT) to gain the international support and participation required to implement the program. The report does not address such issues as the number and distribution of tide gauge stations that will be needed to sample the oceans adequately to detect a global change in their volume, water level measurement techniques, or the roles of satellite and in situ observations in monitoring changes in sea level. While certain members of the Committee do have experience and recognized expertise in these subjects, the purpose of the Woods Hole meeting was to focus sharply on the geodetic issues.

For those readers unfamiliar with the primary issues in monitoring global sea level and how improved geodetic control may contribute, we present the following brief overview. Tide gauges

have been operated in many harbors around the world, primarily for maritime purposes, for intervals of decades to centuries. These records have been studied by many researchers over the years to determine the long term (eustatic) change in sea level and neo-tectonic trends, including glacio-isostasy. There is widespread agreement that the records indicate a rise in global sea level of 10 to 30 centimeters during the past century, but there are large differences in the rates indicated by different tide gauges, or even groups of tide gauges spanning regions as large as the Atlantic coast of North America. These differences are thought largely to be caused by vertical motions of the land, associated with a variety of phenomena, including glacial rebound, tectonophysics, subsurface fluid withdrawal, and sediment consolidation. Measurements of the vertical crustal motions in a global geocentric reference frame will improve:

1. Estimates of the past and current rates of change in global sea level, which will help in determining the cause of the change, and in investigating the possibility that the rate of change is increasing because of a global warming as pollution intensifies the greenhouse effect.
2. Estimates of the variations in geostrophic flow through straits and between islands in regions where contemporary vertical crustal motions are significant.
3. The calibration of satellite altimeters and the reduction of the radial orbit errors.
4. Understanding of earth crustal processes and responses to stresses set up by relative plate motions and other tectonics.

While the focus of this report is on the benefits to oceanography and climate change studies to be derived from geodetic positioning of tide gauges, we should point out that the science of geodesy will, in turn, benefit from the global tide gauge network.

Fundamental to positioning is the concept of height or elevation above some gravity equipotential reference surface. The definition of this reference surface varies from country to country and agency to agency with no universal method adopted for use with the exception that the reference surface should be near mean sea level. However, mean sea level does not provide us with an equipotential surface because dynamic ocean processes result in features, such as the Gulf Stream, that cause the surface to depart from the geoid even over long time scales.

Consequently, most countries have vertical reference systems which are incompatible for international vertical datum purposes.

In order to achieve a global vertical reference surface that is associated with a mean sea surface, it is necessary to use tide gauge stations situated in a global network. Such stations should be tied into a global geocentric coordinate system. Having the location of the station would enable the determination of the gravity potential at each tide gauge site. Appropriate averaging could yield a gravity potential that could form the basis for a global vertical reference system. In addition, variations of local mean sea level from the global average could be studied and used to determine local vertical datum connections. In addition to the 4 benefits listed above, then, we can state a fifth benefit to be derived from the geodetic positioning of tide gauges:

5. The establishment of a world vertical datum, by providing a means to accurately connect national and continental vertical datums.

GEODETIC TECHNIQUES

This section of the report consists of short reviews of the current status of the advanced geodetic techniques recommended for use in fixing TGBMs.

VERY LONG BASELINE INTERFEROMETRY (VLBI)

In geodetic VLBI, networks of radio telescopes located thousands of kilometers apart simultaneously track extragalactic radio sources. Each station records the microwave signals received in digital form on magnetic tape, along with precise time from Hydrogen Maser frequency standards. Typically, 10 to 20 sources are tracked for periods of 3 to 6 minutes several times each during a 24-hour observing session. The data tapes are sent to a correlator center where the signals are processed to determine the differences in arrival times (delays) and the changes in the delays with time (delay rates) between each pair of stations. The delays and delay rates are then analyzed by least squares techniques to estimate a variety of parameters including such nuisance parameters as the offsets and differences in rates between station clocks and atmospheric refraction corrections, important global parameters such as the coordinates of the radio sources define the celestial reference frame, and time varying parameters that describe the temporal variations in the orientation of the Earth. The observations can also be used to determine the

relative positions of the observatories and to detect changes in those positions with time, *i.e.*, to establish and maintain a terrestrial reference frame. VLBI is not sensitive to the locations of the stations relative to the center of mass of the Earth, and the geocentric coordinates of at least one station in the network must be known from another source, such as from satellite laser ranging observations. [Carter and Robertson, 1986; Carter *et al.*, 1984; Carter *et al.*, 1985].

There are two ongoing major international geodetic VLBI programs: the NASA Crustal Dynamics Project (CDP), which includes collaborating researchers and observatories in several nations [Coates *et al.*, 1985]; and the International Radio Interferometric Surveying (IRIS) network, organized by the IRIS Subcommittee of the IAG [Carter *et al.*, 1988]. The CDP sponsored the development of the MARK III instrumentation, and pioneered the application of VLBI to geodynamics. The emphasis in the CDP effort is on research and development, while that of IRIS is on long term application of the technology operationally, to monitor earth orientation, plate motions and distortions, and variation in absolute global sea level [Carter *et al.*, 1986; Carter *et al.*, 1988]. The observing campaigns organized by the two programs often use many of the same observatories, and the data are exchanged routinely. As a result, the CDP and IRIS networks are accurately interconnected and essentially form one integrated terrestrial reference frame. Figure 1 shows the locations of operating and planned geodetic VLBI observatories.

Analysis of the repeatability of VLBI measurements and intercomparison of VLBI and SLR measurements show conclusively that 24-hour observing sessions between observatories separated by 4000 to 7000 kilometers routinely yield baseline vectors accurate to a few centimeters [Herring 1986; Herring *et al.*, 1986]. Tom Herring [private communication, 1988] has found that means of groups of 18 to 24 measurements collected over periods of 3 to 4 months with the Westford (Massachusetts) - Wettzell (Bavaria) interferometry have a repeatability in the length of the baseline of approximately 2 millimeters, after removal of a linear rate representing the relative plate motions. Accounting for the geometry, this corresponds to a repeatability in the vertical of approximately 4 millimeters.

The CDP has set a goal of improving the accuracy of VLBI by an order of magnitude during the next decade. This will be done incrementally by making improvements to several components of the MARK III system. A number of improvements will be completed within the next 2-3 years and by the early 1990's the accuracy of a 24-hour measurement should be better than 1 centimeter. The repeatability will be significantly better, probably reaching the 1 to 2 mm level.

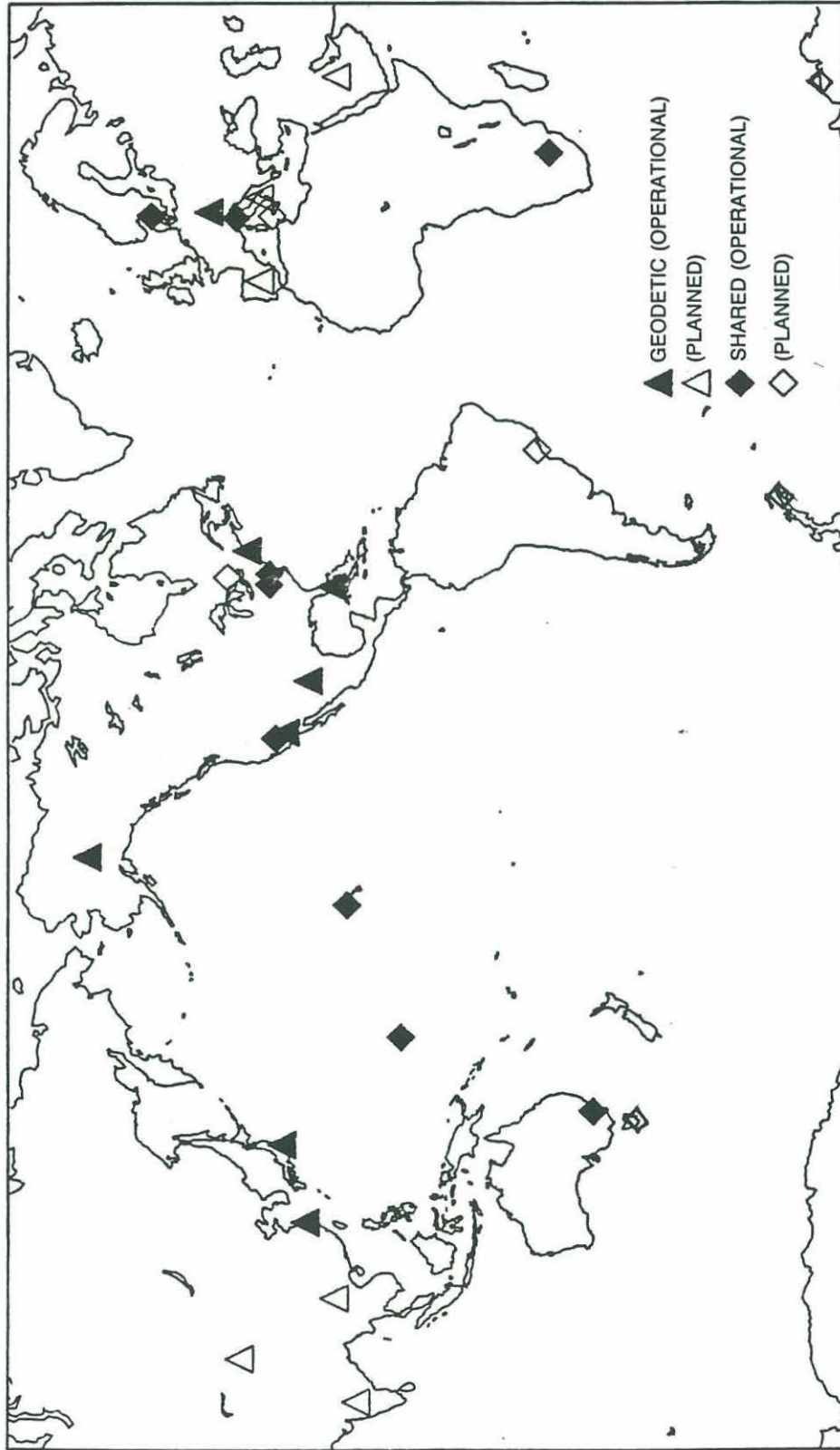


Figure 1. This map shows the locations of permanent VLBI observatories in operation as of January 1, 1989 (solid markers) and planned to become operational during the 1990-1995 timeframe (open markers).

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SATELLITE LASER RANGING (SLR)

Satellite laser ranging (SLR) is characterized by the illumination of a target satellite by a short duration pulse of laser emitted light. The measurement of time required for the pulse to travel the round trip from the ground-based instrument to the target satellite and back to the point of

origin is related to the "range." Range measurements are now made routinely to the Laser Geodynamics Satellite (LAGEOS) with a precision of less than one centimeter and a substantially smaller precision when several measurements are compressed into a "normal point." Furthermore, experiments have been performed to demonstrate that these measurements are essentially unbiased or have biases less than the instrument precision. Descriptions of laser ranging instrumentation are given by Degnan [1985] and Shelus [1985].

The SLR measurement is influenced by the motion of the target satellite as well as the motion of the ground-based instrument. As a consequence, a set of range measurements collected over an appropriate interval of time contains information from which satellite force parameters and the coordinates of the laser station can be estimated. Of particular interest to the measurement of absolute sea level is the inherent ability of SLR measurements to determine the coordinates of ground-based laser tracking instruments in a coordinate system with an origin that is theoretically coincident with the Earth center of mass. In practice, the origin is believed to be determined to within a few centimeters of the center of mass.

Since the launch of LAGEOS in 1976, a sizable data base of range measurements has been accumulated from almost 100 globally distributed sites, located on most tectonic plates. However, no measurements have been collected with this technique from the Antarctic Plate and few measurements have been obtained on the African Plate. Although nearly 100 SLR sites have been occupied, a set of about 25 high precision stations provide the bulk of the data used in analyses. These stations form a set of permanent "base stations" which are complemented by sites occupied by mobile SLR systems. In early 1989, seven mobile SLR systems were in operation (4 U.S., 1 German, 1 Dutch, and 1 Japanese). In the early 1990s, several new mobile systems are expected to be added to this inventory. Table 1 lists the fixed SLR sites that contributed ranging data during 1988, with estimates of their range precision.

The mobile laser stations have occupied sites for typical periods of two to three months. This occupation time is determined, in part, by the site weather conditions. Additional factors that relate to the occupation time concern the adequacy of the data set to average remaining model errors.

The coordinates of the set of base stations and mobile stations have been determined in the geocentric coordinate system to a few centimeters. This statement is justified through comparisons

Table 1.

SLR 1988 SITES

Station Location	Precision Estimate (CM)
1181 Potsdam, DDR	13.1
1884 Riga, USSR	13.1
1953 Santiago, Cuba	14.1
* 7035 Otay, CA	1.4
7080 McDonald, TX	3.6
7090 Yaragadee, Australia	1.0
* 7091 Haystack, MA	1.3
7097 Easter Is.	3.0
7105 Goddard SFC, MD	1.0
7109 Quincy, CA	0.9
7110 Monument Peak, CA	1.1
* 7112 Platteville, CO	5.5
7122 Mazatlan, MX	0.9
7123 Huahine, French Poly.	2.5
7210 Haleakala, HI	2.9
* 7288 Mojave, CA	1.4
* 7295 Richmond, FL	5.4
7530 Bargiyyora, Israel	8.7
* 7545 Cagliari,	5.2
* 7546 Medicina, Italy	6.0
7810 Zimmerwald, Switzer.	7.6
7811 Borowiec, Poland	12.9
7831 Helwan, Egypt	3.4
* 8833 Kootwijk, Neth.	5.1
7834 Wettzell, FRG	5.1
7835 Grasse, France	2.4
7837 Shanghai, PRC	6.9
7838 Simosato, Japan	3.7
7839 Graz, Austria	2.1
7840 Royal Greenwich Obs., UK	4.4
7843 Orroral, Australia	1.7
* 7853 Owens Valley, CA	5.6
* 7882 Cabo San Lucas, MX	1.2
7907 Arequipa, Peru	13.4
7939 Matera, Italy	12.4

* denotes 3-month occupation with a transportable laser ranging system

Easter Island and Huahine alternate for 6 months with the same transportable system.

of relative positioning, particularly baselines, with other techniques of comparable precision, such as VLBI. Furthermore, tests of internal consistency support the assertion that coordinate accuracy of a few centimeters has been attained, including the height of the station from the geocenter or a reference ellipsoid. Results of coordinates and baselines derived from SLR are given, for example, by Smith *et al.*, [1985] and Tapley *et al.*, [1985].

Past and future oceanographic satellites with altimeters have been or will be tracked by SLR systems. As a consequence, the orbits of these satellites are determined in a geocentric coordinate system defined by the SLR and a direct relation of the altimetric measurement with this reference system can be obtained. Since the altimeter measurement enables a determination of the sea surface with respect to the orbit of the satellite, the sea surface is further determined in a geocentric reference system. The accuracy of this determination is dependent on the nature of modeling errors in the determination of the orbit.

As noted in the preceding, almost 100 SLR sites have been occupied since 1976. However, some sites are not near suitable tide gauges, thereby reducing their utility for sea level applications. Nevertheless, the remaining set of SLR sites does provide a number of sites that are not duplicated by other techniques, such as VLBI, that will be important to maintaining the ITRF. The combined set of SLR and VLBI sites provide a larger base from which tide gauge measurements can be linked into an absolute coordinate system.

Conceptually, the SLR systems can contribute to the determination of mean sea level in the following ways:

- o Center of mass reference system provides a suitable origin.
- o Station coordinate accuracy of a few centimeters in all three components, with expected improvements in the future.
- o Determination of sea surface topography from satellite altimeters in a geocentric system altimeter.
- o Unique sites not duplicated by other techniques, thereby expanding the set of available sites available for establishing sea level.

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GLOBAL POSITIONING SYSTEM (GPS)

The Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS) is a navigation system of satellites being developed by the U.S. Department of Defense, scheduled to be fully operational in the early 1990's. When complete, the constellation will comprise 21 - 24 satellites, deployed in 6 planes inclined at 55°, with the ascending nodes spaced at 60° intervals. A minimum of 4 satellites will be visible 24 hours per day from any point on Earth. The nearly circular orbits will have semi-major axes of approximately 26,500 kilometers, yielding a period of about 12 sidereal hours.

At the time of the Woods Hole meeting, 7 usable Block I (developmental) satellites were available, providing 2-4 satellites simultaneously visible from two sites only a few (3-5) hours each day. The accuracy estimates presented below are based on experience with Block I satellites, and will certainly improve significantly when the full constellation of Block II satellites becomes operational. Table 2 lists the projected schedule for launching the Block II satellites [Mader *et al.*, 1988].

The International Association of Geodesy (IAG) Subcommittee on GPS has begun the development of a global network of stations to track the GPS satellites regularly to collect the data

Table 2.

GPS Launch Dates (Block II Satellites)

The following launch schedule has been amended after conversations with Lt. Dan Stockton of the GPS Joint Program Office (JPO) Space Segment. The first Block II launch is now scheduled for December 30, 1988. Specific Dates for the next three (3) launches are shown below. Obviously, they may be subject to change.

Sat#	GPS#	Plane	Carrier	Launch	Sat#	GPS#	Plane	Carrier	Launch
1	13	D	MLV	Dec 30, 88	16	28	-	MLV	Apr 91
2	14	E	MLV	Feb 28, 89	17	29	-	MLV	Jun 91
3	16	F	MLV	Apr 27, 89	18	30	-	PAM-DII	Aug 91
4	17	D	MLV	Jun 22, 89					
5	18	D	MLV	Jul 89	19	31	-	MLV	Oct 91
6	19	F	MLV	Sep 89	20	32	-	MLV	Jan 92
					21	33	-	MLV	Apr 92
7	20	F	MLV	Oct 89	22	34	-	PAM-DII	Jul 92
8	21	B	MLV	Jan 90					
9	15	A	MLV	Mar 90	23	35	-	MLV	Oct 92
10	22	-	MLV	Jun 90	24	36	-	MLV	Jan 93
11	23	-	MLV	Aug 90	25	37	-	MLV	Apr 93
12	24	-	MLV	Sep 90	26	38	-	MLV	Jul 93
13	25	-	MLV	Nov 90	27	39	-	MLV	Jan 94
14	26	-	MLV	Jan 91	28	40	-	MLV	Jul 94
15	27	-	MLV	Mar 91					

* MLV = Medium Launch Vehicle (Delta Rocket)

needed to produce accurate ephemerides. Figure 2 shows the location of the stations currently operational. Most of the stations are collocated at VLBI observatories, and some are at or near SLR sites, thereby allowing the unification of the VLBI and GPS reference frames, and placing them both in the ITRF. (See the International Earth Rotation Service, this report).

The capability of the Global Positioning System (GPS) to provide accurate relative positioning has been widely proved and documented [Goad 1987].

The positioning accuracy depends on several items which contribute to the error budget, mainly:

- a. residual error in ionospheric propagation correction
- b. quality of the satellite ephemeris information
- c. residual error in tropospheric propagation correction
- d. multipath, phase center variations.

There is, therefore, a wide range in performance which can be expressed as accuracy of relative positions at one sigma level, as a contribution of a constant term A plus a term proportional to the interstation distance B.

In good conditions, A should not exceed 5 mm, while B depends mainly on items a and b, ranging from 2 ppm to 0.01 ppm. For a user's point of view, we shall consider three classes of typical GPS relative positioning:

- L1 BE: One-frequency receivers
 Use of Broadcast Ephemerides

- L1/L2 PE: Two-frequency receivers
 Use of Precise Ephemerides

- L1/L2 OD: Two-frequency receivers

 Orbit determination using fiducial stations

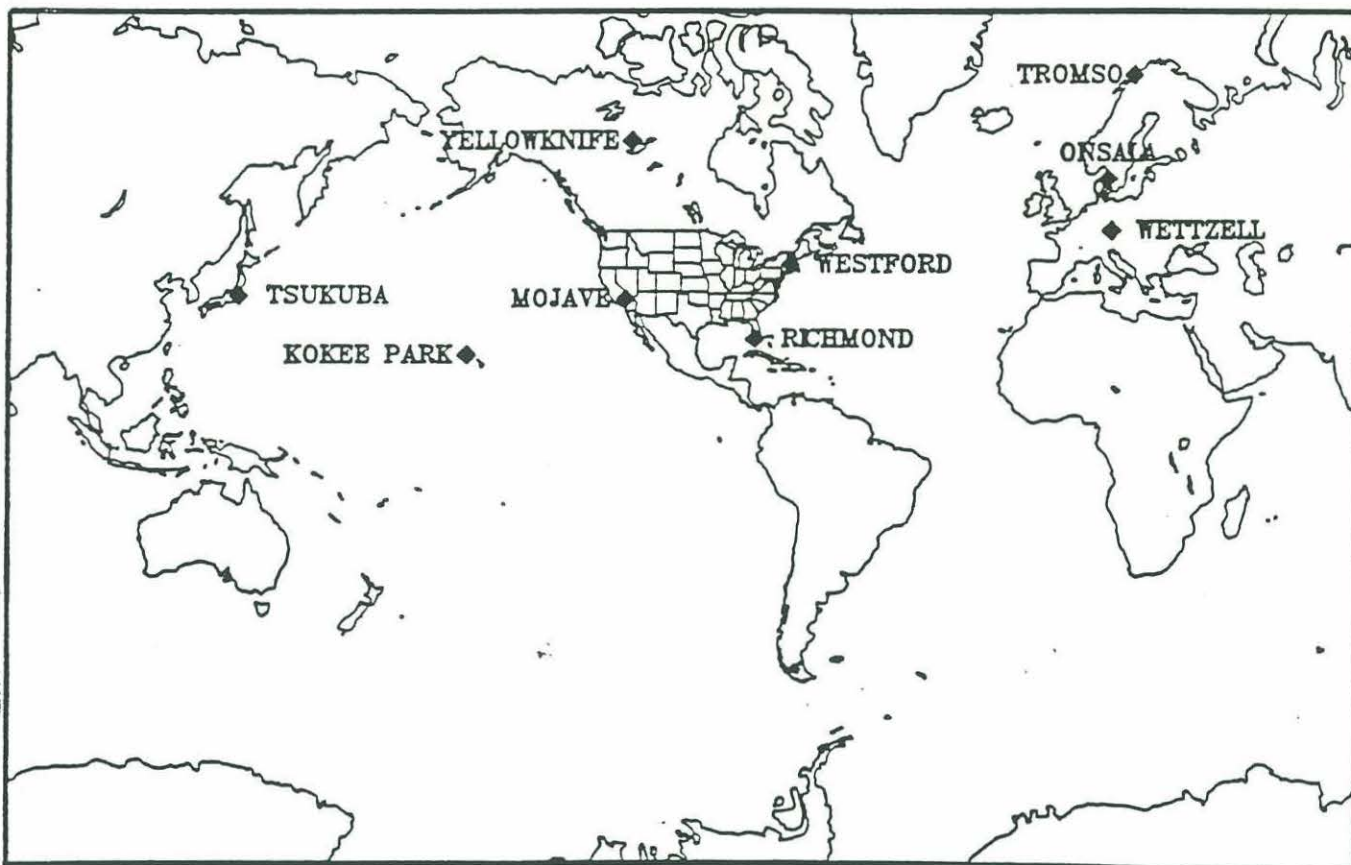


Figure 2. The map shows the locations of the stations currently participating in the Cooperative International GPS Network (CIGNET), which track the GPS satellites providing a fiducial data set that may be used for orbit computation and research. The data from all stations are sent to the National Geodetic Survey, Rockville, Maryland, where they are archived, reformatted, and compiled. The data are available upon request. Currently, all stations use TI-4100 receivers except Tsukaba which uses a Mini-Mac receiver.

so that the accuracy is typically:

	A (mm)	B (ppm)
L1 B	5	2.0
L1/L2 PE	3	0.1
L1/L2 OD	3	0.01

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OTHER RADIO SYSTEMS (DORIS, PRARE)

Other radioelectric satellite tracking systems are under development. Their common purpose is the precise orbit determination of satellites flying with ocean radar altimeters.

This is the case of the French DORIS system to be put on the TOPEX/POSEIDON satellite and the German PRARE system on the ESA ERS-1 satellite.

Both systems should be operational at the 1991 time frame. DORIS will also fly on the SPOT-2 satellite to be launched in mid-1989.

These systems, besides precise orbits, will also provide precise positions of ground stations, either permanently or by temporary tracking (few days).

A rough estimate of DORIS accuracy is 8 cm (1 sigma) in a geocentric reference system and $2 \text{ cm} \pm 0.1 \text{ ppm}$ for relative position of simultaneous tracking beacons spaced by 500 km or less. These values consider a 1000 km altitude satellite with orbital errors not exceeding 1 m. Such specifications are expected to be exceeded by the TOPEX/POSEIDON mission.

Table 3
Relative position accuracy (in cm)

System	Distance		
	10 km	100 km	1000 km
GPS L1 BE	2.1 cm	20	200
GPS L1/L2 PE	0.3	1.0	10
GPS L1/L2 OD	0.3	0.3	1.0
DORIS	2.0	2.2	10.2
PRARE	unknown	unknown	unknown

Table 3 gives a comparative status of relative accuracy achievable by the various systems.

SATELLITE ALTIMETRY

Satellite altimeter observations can be used in reverse ways for understanding of oceanic circulation.

Monitoring of geostrophic flows by pairs of sea level stations

Oceanic transports are usually derived from the density structure of the ocean obtained by measuring temperature and salinity from ships or moorings. These calculations are based on the hydrostatic and on the geostrophic balances. The hydrostatic balance states that the pressure changes with depth due to the weight of the above water column:

$$dp / dz = - \rho g \quad (1)$$

where p is the pressure, z is positive upward, ρ is the local density of the water, and g is the gravitational acceleration. The geostrophic balance holds for oceanic currents varying with length scales greater than 400 km and time scales longer than a day: the Coriolis force balances the transverse pressure gradient:

$$(1 / \rho_0) (dp / dx) = f_0 v \quad (2)$$

where ρ_o is the mean water density, f_o the average Coriolis parameter, and v the horizontal velocity perpendicular to the pressure gradient. Currents are obtained by eliminating the pressure between (1) and (2), which gives the thermal wind equation, and integrating this equation with depth from an arbitrary reference level z_o . However, the major uncertainty within this approach is the need for a reference level, where the velocity is assumed known. The choice is commonly a level where the velocity is guessed to be zero: the "level of no motion." This level is hard to determine, if it even exists [cf., Wunsch and Gaposchkin, 1980].

A potentially attractive alternative is to measure the sea surface topography of the ocean and use it as the reference level, given that the surface velocities are related to the surface topography through the hydrostatic and geostrophic equations :

$$v_s = (g / f_o) * d\zeta / dx \quad (3)$$

where v_s is the surface velocity and ζ the height of the sea surface referred to a constant geopotential surface.

This approach is developed through satellite altimetry. For straits, or between islands, simpler sea level gauge measurements can apply. Monitoring geostrophic flows by pairs of level stations requires the following geodetic information:

1. precise and accurate sea level measurements,
2. the sea level height must be referred to the same geopotential surface.

Point 1 involves measurements of the order of few centimeters over long periods of time: the link of the sea level gauge benchmarks to an absolute reference system is then a necessity to ensure an adequate error budget, by removing differential earth movements unrelated to the hydrodynamic and thermodynamic variations of the sea surface.

Notice however that point 2 is a major difficulty, as the geoid surface is difficult to determine within the precision required.

The geoid is an equipotential surface of the Earth's gravity field. In a geometric sense, the geoid is a surface associated with the mean ocean surface. The geoid can act as the equipotential surface from which sea surface topography is measured. Consequently, our knowledge of ocean currents (*i.e.*, the surface velocities) depends on our knowledge of the geoid and/or its slopes.

The geoid can be represented in spectral form through a set of potential coefficients derived from satellite observations. Although these coefficients can be estimated to degree and order 50 (corresponding to a resolution of 400 km), only the lower degree coefficients (say, up to degree 10, corresponding to a resolution of 2000 km) have sufficient accuracy to allow separation of geoidal signals from global sea surface topography models [Tapley *et al.*, 1988; Marsh *et al.*, 1988].

The geoid can also be represented in a spatial sense through computations using potential coefficient models with surface gravity information. The geoid slope can be obtained from such data with accuracies of approximately 1.5 cm/10 km decreasing to 14 cm/100 km in areas of reasonable gravity coverage. Such coverage exists in some land areas but not necessarily on many ocean areas. Many studies now indicate geoid difference determinations to an accuracy of 1 to 2 ppm for distances up to 100 km [Torge *et al.*, 1989]. The accuracy is poorer for longer lines. The use of gravity measurements for these computations has to be carefully considered in ocean applications because such measurements are made with respect to the ocean surface and not the geoid. The errors on these geoid slope determinations place limitations on the accuracy of the current velocity determinations described earlier.

Satellite radar altimetry is demonstrating its capabilities for monitoring the global sea surface (see for example, Born *et al.*, 1986 using Seasat altimeter data and Douglas *et al.*, [1987] using Geosat altimeter data). The positioning of sea level gauges within a geocentric reference system would significantly contribute to the improvement of these capabilities. Sea level measurements have already been applied, or are planned for, different types of applications:

1. to provide time series of regional sea level changes for comparisons to those produced by altimetry. [See Cheney *et al.*, 1987].
2. to calibrate satellite radar altimeter instruments in orbit, by specific checks of the altimeter measured distance between the satellite and the sea level, with the one derived from satellite laser ranging and local sea level observation related to the laser site. For each satellite

altimetric mission, calibration sites are especially instrumented to provide the needed instrument bias and drift corrections.

3. to reduce altimetric satellite orbit error, by merging information content from satellite tracking data collected from altimetric satellites and other satellites with the altimetric data set, within some objective analyses procedure aiming to produce maps of the ocean surface topography [e.g., Wunsch 1986].

The positioning of sea level gauges in an absolute reference system will bring a major contribution in this context:

1. it will provide the way to link different satellite altimetric missions together. It is especially recommended to localize the laser calibration sites in geocentric coordinates.
2. it will help to reduce the long wavelength orbit errors in the radar satellite altimetric products, in an absolute sense. This error reduction will improve the use of altimetry for large scale ocean circulation studies and monitoring.

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ABSOLUTE AND TIDAL GRAVIMETRY

Absolute and Relative Gravity Measurements for Tide Gauge Benchmark Control

Each of the various geodetic techniques that can be brought to bear on the problem of tide-gauge height control has its own strengths which must be considered within the context of its relative cost. For the case of gravity measurements, three types of measuring devices are available. Before discussing them, it is important that the required sensitivity of gravity measurements be addressed.

Gravity Variation and its Relation to Apparent Mean Sea-level

The free-air gravity gradient near the earth's surface is approximately $3 \mu\text{Gal}/\text{cm}$. Uplift due to deformation in the crust that does not include the introduction of additional mass near the observation point (dilatant expansion, for example) would be accompanied by a decrease in gravity of $3 \mu\text{Gal}$ for each cm of uplift. If, however, the mechanism responsible for the deformation includes mass influx (as in the case of a volcano, for example) the associated gravity change would be smaller, depending on the density of the incoming material.

Considering the case of an island tide-gauge which included a gravity benchmark adjacent to it, if a 1 cm apparent increase in sea-level were recorded by the tide gauge, as much as a $3 \mu\text{Gal}$ increase in gravity would occur simultaneously if the sea-level change were due to subsidence of the island. If, however, the signal recorded by the tide gauge were the result of an actual global

mean sea-level increase, the associated gravity increase would only be that due to the gravitational attraction of the additional seawater which, depending on the geometry at the site, would not exceed $0.4 \mu\text{Gal}$ [Agnew, 1983] (there is another much smaller contribution due to crustal loading). Thus gravity information in conjunction with tide-gauge records can help separate sea-level changes from crustal deformation. With the addition of other geodetic surveys, the mechanism responsible for any deformation can be further constrained.

An important question is what other effects can cause gravity variations that might be misinterpreted as crustal deformation? There are several important mechanisms to be considered, including atmospheric pressure variations, polar motion, and anomalous tidal terms. These, however, are usually just at the level of detectability and can be corrected for. The gravitational attraction of ground water, on the other hand, is potentially quite large and not so easily recognized. It is not unusual for gravity variations of many tens of μGal to be caused by aquifer activity. In many cases, the local hydrology can be quite complex and the ground water picture not well characterized by the monitoring of even unpumped wells. The only way to avoid the difficulty is to avoid monitoring gravity on crustal material of high porosity. Gravity measurements performed for reasons of vertical geodetic control should be done on or near outcrops of crystalline rock.

Gravity Measuring Devices

Three types of instruments can be used to make measurements of the Earth's gravity and variations of it with time, and all three will find some use in helping to quantify vertical motions of tide-gauge benchmarks. For instrument reviews see Marson and Faller [1987] and Goodkind [1986].

The first and most common type of gravity meter is the relative spring gravity meter (manufactured, for example, by LaCoste & Romberg, Austin, Texas). These instruments consist of a delicately balanced mass-spring system and are quite portable. They are capable of determining the difference in gravity between two sites with a precision of several μGal , depending on the distance between the sites.

Another type of relative gravity meter is a superconducting system developed by Prothero and Goodkind [1968] and manufactured by GWR Instruments (San Diego, Calif.) Figure 3. In these

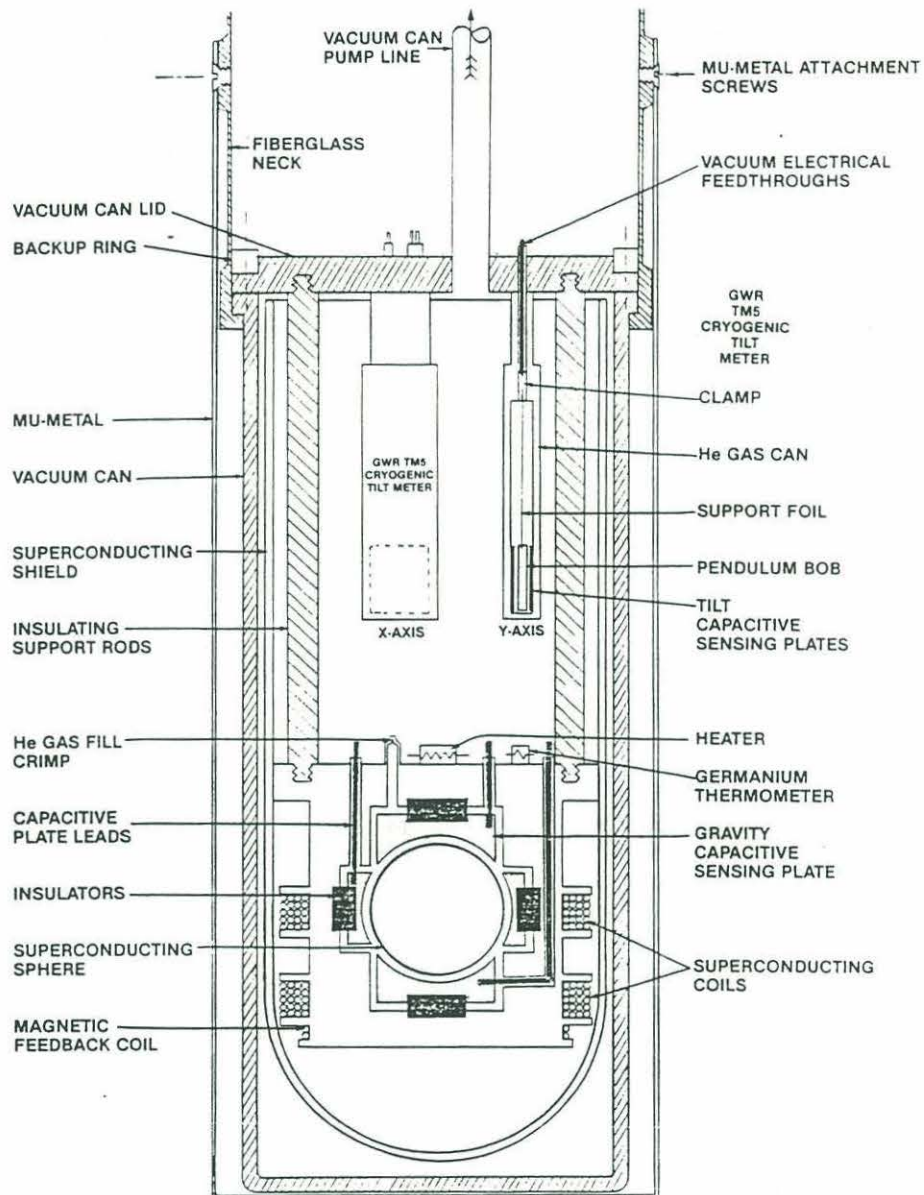


Figure 3. Superconducting Gravimeter

devices, a superconducting sphere is levitated by persistent currents in superconducting coils within a vacuum chamber immersed in liquid helium. The force needed to maintain the sphere's vertical position is the most sensitive measure of local gravity change available. The instrument is used to monitor gravity variation with time at a single location, not from one site to another. The advantage of a superconducting gravity meter is that it can sense gravity changes of the order of $0.1 \mu\text{Gal}$ that occur at day or week long periods, and several μGal variations that occur at annual rates. The disadvantage for tide-gauge benchmark monitoring is that the potential for instrumental drift varies from instrument to instrument. Richter [1983], for example, reported a drift of $21 \mu\text{Gal}$ per year. A drift rate of only $3 \mu\text{Gal}$ per year has been found recently in one instrument [R. Warburton, private communication, 1988] and work is underway to achieve even higher stability [J. Goodkind, private communication, 1988]. These recent developments are quite promising: when small drift rates become routine in these instruments, they will be capable of playing a key role in gravity monitoring near tide-gauge benchmarks.

A third type of gravity meter, and one that has already shown itself to be useful to long-term vertical crustal deformation studies, is the absolute gravity meter. In this type of instrument, a mass is made to freely fall in a vacuum while its position is tracked with a laser interferometer (Figure 4). Use of atomic length and time standards (a stabilized laser and a rubidium frequency standard) allow the falling object's acceleration to be determined with parts-per-billion accuracy. If great care is used in eliminating sources of systematic error, such as non-gravitational forces on the falling mass, frequency dependent timing errors, and vibrations in the optical system, gravity determinations can be made with an accuracy ranging from 3 to $10 \mu\text{Gal}$. A site can be surveyed in a day or two; the instruments can be transported in small vans and require sheltered sites for the measurements.

The key to absolute gravity meters' usefulness in monitoring the vertical positions of tide-gauge benchmarks is their reliance on standards of length and time, which constitute the units of gravity ($1 \text{ Gal} = 1 \text{ cm/s}^2$). These are inherently free of drift and can be periodically checked against primary standards. Thus long-term records of gravity determined with absolute meters should not be contaminated by drift.

This is not to say that systematic errors that vary with time are not potential sources of difficulty. Much effort has gone into the characterization of the accuracy of absolute gravity measurements, and the suite of instruments around the world are periodically brought together

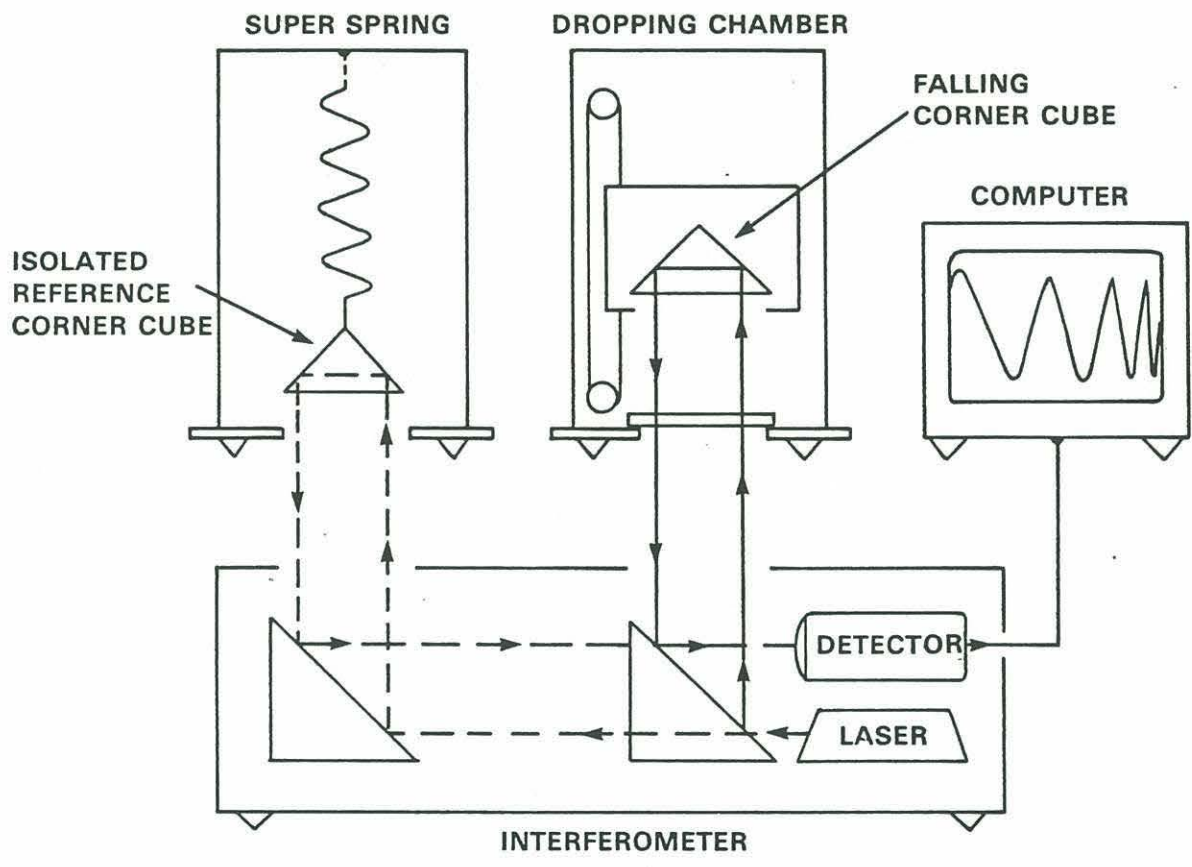


Figure 4. Schematic representation of the JILA Absolute Gravity Meter.

and compared to ascertain the true capability of absolute gravimetry. In the most recent comparison measurement at the International Bureau of Weights and Measures in Paris [Arnautov *et al.*, 1987], the assessment of roughly 15 μGal was assigned for the accuracy of absolute gravity measurements in general, while particular instruments almost certainly achieve higher accuracy. Quite promising results have been reported with a series of new instruments constructed at the Joint Institute for Laboratory Astrophysics [Niebauer *et al.*, 1986; Peter *et al.*, 1989]; intercomparison between instruments have, in some cases, been within 3 μGal (A. Lambert and G. Peter, private communication, 1988).

A Strategy for Utilizing Absolute Gravity Meters Near Tide-gauge Benchmarks

An accuracy of 6 μGal for absolute gravity determinations (this is probably being achieved currently and can be counted on in the future) corresponds to a sensitivity in height of 2 cm; this is comparable to GPS determinations over 100 km baselines and slightly better than VLBI or SLR over intercontinental distances. The relative cost of adding absolute gravity measurements to all VLBI site occupations would represent only a slight increment to what is already allocated for space-based techniques.

A number of technical issues must be considered when planning sites of absolute gravity measurements. Current instruments require a building to house the equipment for each measurement. There is nothing inherent in the instruments' designs that would prohibit a self-contained, weather-proof system from being developed [Zumberge *et al.*, 1986], but until that is done, site locations must be decided upon with present limitations in mind. In addition to the hydrological considerations already mentioned, the vicinity of the coastline to a gravity site is an important factor in the quality of any absolute determination for two reasons. First, the seismic noise from surf action has been noticed to seriously increase the variance of individual gravity measurements. The problem is greatly alleviated by locating sites more than a few km from the coast. Secondly, ocean tidal loading and attraction corrections must be applied to absolute gravity measurements. These corrections can be several μgals but comparisons of model calculations and tidal gravity measurements [Baker 1980] show that, with care, corrections can be made that are accurate to a few tenths of a μgal . However, at elevated sites within a distance of 1 km or so of the coastline, the vertical attraction of the nearby tidal mass layer becomes important and can contribute several μgals . Ocean tidal loading would be a serious contributor to total uncertainty

since the ocean loading and attraction corrections (unlike the solid-earth body tide correction) are not easily predictable for near-coastal sites.

A reasonable approach to incorporating absolute gravity determinations into the plan for vertical control of tide-gauge benchmarks would be to:

make absolute gravity measurements coincident with all VLBI site occupations;

establish new absolute gravity sites between 1 and 10 km from primary tide-gauges; and

make GPS ties between each absolute gravity site and its associated tide-gauge benchmark. It should be noted that local GPS (or leveling) ties near tide gauge benchmarks can also be affected by ocean loading tilts of the order of 1 mm/km.

Relative measurements should also be made to nearby benchmarks to strengthen the local gravity network. Superconducting gravity meters should be installed permanently at key primary sites to interpolate between absolute occupations and provide further constraint on long-term behavior in cases where the super-conducting drift has been well characterized.

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THE INTERNATIONAL EARTH ROTATION SERVICE

The International Earth Rotation Service (IERS) started operation on January 1, 1988. It replaces the International Polar Motion Service (IPMS) and the earth rotation section of the Bureau International de l'Heure (BIH). IERS was organized jointly by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG), and is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS).

The IERS is responsible for:

1. Defining and maintaining a conventional terrestrial reference system based on observing stations that use high-precision techniques of space geodesy;

2. Defining and maintaining a conventional celestial reference system based on extragalactic radio sources, and relating it to other celestial reference systems;
3. Determining the earth orientation parameters (the terrestrial and celestial coordinates of the pole and universal time) connecting these systems;
4. Organizing operational activities for observation and data analysis, collecting and archiving appropriate data and results, and disseminating the results to meet the needs of users.

IERS consists of Coordinating Centers for each of the principal observing techniques (very long baseline interferometry, satellite laser ranging and lunar laser ranging) and a Central Bureau. The Coordinating Centers are responsible for developing and organizing the activities in each technique to meet the objectives of the service. The Central Bureau combines the various types of data collected and disseminates the results to the user community.

IERS TERRESTRIAL FRAME

The Conventional Terrestrial Reference System (CTRS) adopted by IERS for either the analysis of individual data sets by techniques (VLBI, SLR, LLR) or the combination of individual solutions into a unified set of data will follow these characteristics [see Boucher, 1987]:

- a. It is geocentric. The geocenter is defined for the whole Earth, including oceans and atmosphere.
- b. Its scale is the one of a local Earth frame, in the meaning of a relativistic theory of gravitation.
- c. Its orientation is given by the BIH orientation at 1984.0.
- d. Its time evolution follows a no global net rotation or translation condition.

When one wants to realize such a CTRS through a reference frame (CTRF), *i.e.*, a network of stations, reference points, or ground marks with coordinates - or set of station coordinates (SSC),

it is furthermore recommended to include the permanent solid Earth tidal deformation, so that the adopted coordinates will differ from the instantaneous coordinates by only periodic terms.

The methods followed by various analysis centers depends on their own views on modelling, but also on the techniques themselves.

For the origin, only data which can be modelled by dynamical techniques (presently SLR and LLR for IERS) can reconstitute the geocenter. VLBI system can be put to a geocentric position by adopting for a station its geocentric position at a reference epoch as provided from external information. It is recommended to use a value coming from the Initial IERS Terrestrial Reference Frame (ITRF-O) - see below.

The scale is obtained by an adequate relativistic modelling. This is particularly true for VLBI and LLR which are usually modelled in a barycentric frame. The use of the values recommended by IERS for c and GM is also mandatory:

$$c = 299792.458 \text{ km/s}$$

$$GM = 398600.440 \text{ km}^3/\text{s}^2$$

The orientation should be defined by adopting BIH (or IERS) Earth Rotation Parameters (ERP) values at a reference epoch. In some cases, (SLR), an additional constraint in longitude is necessary. The use of ITRF-O values is recommended for this purpose.

The time evolution of the orientation will be ensured by using a no net rotation condition either directly, or by adopting a plate motion model which fulfills this condition (AMO-2 model from Minster and Jordan [1978]).

As we have seen, an Initial IERS Terrestrial Reference Frame (ITRF-O), shown in figure 5, may be useful. Table 4 gives approximate coordinates and velocities for IERS primary sites. More details can be found in the draft of the IERS terrestrial reference frame report. This frame is basically an improved solution of the latest BIH frame (BTS 87) (BIH Annual Report, 1988).

We call "primary site" any site where a three dimensional position can be estimated within a few centimeters in the IERS system, and for any epoch, within the present years.

The criteria to select such a site are:

- a. To have a permanent instrument (SLR or VLBI) preferably. For a mobile unit, the relocation should be guaranteed by an accurate survey within a few mm.
- b. To use the best technology: 3rd generation lasers, or S/X Mark III VLBI with H-masers.
- c. To get regular measurements in order to estimate positions at regular epochs (typically monthly) at cm level, and for which the interpolation will keep this cm level for any epoch within the specific time span, which should include present days.

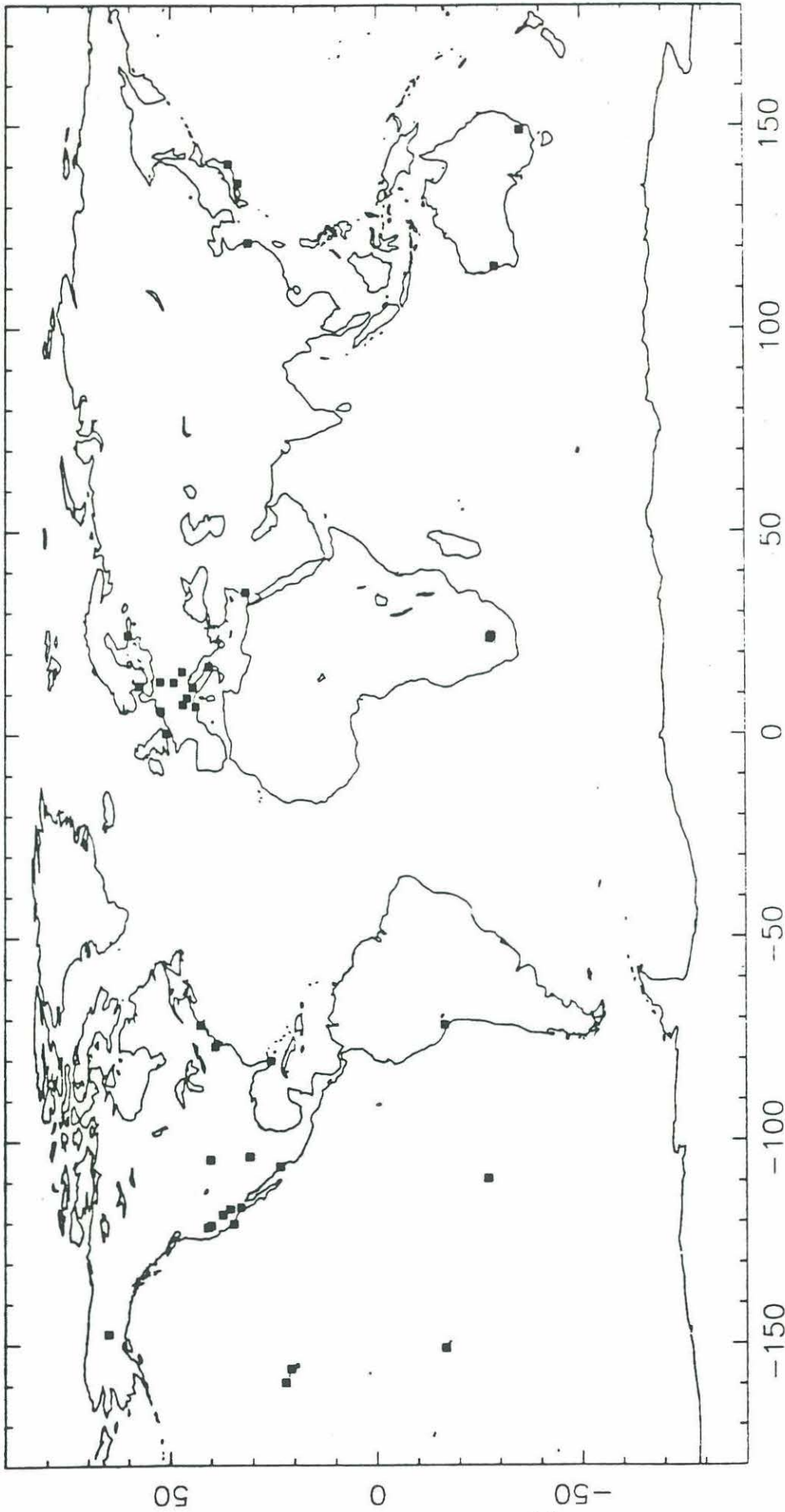


Figure 5. Locations of primary stations in the IERS Terrestrial Reference Frame (ITRF).

Table 4
Initial IERS Terrestrial Reference Frame (ITRF-O)
Reference epoch 1984.0 AMO-2 model

Point number	Name	X m	Y m	Z m	V _x mm/y	V _y mm/y	V _z mm/y
10002 M001	Grasse	4581933.	556384.	4389077.	-14.1	18.0	12.4
10402 M003	Onsala	3370764.	711471.	5349802.	-17.2	14.4	9.0
11001 M001	Graz	4194424.	1162702.	4647245.	-16.8	16.8	11.0
12711 M001	Bologna	4461385.	919555.	4449529.	-15.5	17.7	11.9
12734 S001	Matera	4641965.	1393069.	4133262.	-16.2	18.1	12.1
13212 M002	Herstmonceux	4033586.	24250.	4924304.	-13.7	16.4	11.2
14001 M001	Zimmerwald	4331274.	567584.	4633139.	-14.8	17.3	11.7
14106 M001	Potsdam	3800621.	882005.	5028859.	-16.9	15.7	10.1
14201 M001	Wetzell	4075575.	931832.	4801568.	-16.5	16.5	10.8
20702 M001	Bar Giyyora	4443967.	3121945.	3334694.	-24.3	15.3	18.0
21701 M001	Kashima	-3997912.	3276621.	3724030.	-21.5	-11.7	-12.8
21726 M001	Simosato	-38822373.	3699359.	3507585.	-22.4	-11.2	-12.6
40405 M001	Goldstone	-2353394.	-4641529.	3676899.	-15.8	-1.5	-12.0

40420 M001	Vandenberg	-2668815.	-4530761.	3598687.	-15.5	- 1.4	-13.2
40439 M001	Owens Valley	-2410422.	-4477802.	3838686.	-16.4	- 1.6	-12.2
40440 M001	Haystack	1492453.	-4457278.	4296815.	-18.2	- 2.8	3.4
40442 M004	Fort Davis	-1330832.	-5328746.	3235663.	-14.2	- 1.5	- 8.4
40445 M001	Maui	-5460006.	-2404428.	2242187.	-15.3	67.3	34.9
40451 M110	Washington	1130731.	-4831322.	3994136.	-17.1	- 2.6	1.7
40489 M001	Hat Creek	-2523871.	-4123580.	4147719.	-17.6	- 1.8	-12.4
40504 M001	Mazatlan	-1660089.	-5619100.	2511637.	-11.4	- 1.0	- 9.8
41703 M001	Easter Island	-1884984.	-5357606.	-2892852.	85.9	-25.3	- 9.0
42202 M002	Arequipa	1942784.	-5804081.	-1796911.	- 5.4	- 4.7	9.3
50103 M103	Orroral	-4466609.	2683169.	-3667428.	-36.2	- 2.7	42.2
50107 M001	Yarragadee	-2389006.	5043329.	-3078525.	-51.4	8.0	53.0
92202 M001	Motu Hiumoo	-5345882.	-2958272.	-1824430.	-43.8	57.2	35.4

References:

Boucher, C., Definition and Realization of Terrestrial Reference Systems for Monitoring Earth Rotation, *IUGG General Assembly, Vancouver - Symp. no. 4.*, 1987.

IERS, The Initial IERS Terrestrial Reference Frame, draft 1988.

BIH Annual Report for 1987, Paris, 1988.

Minster, J.B. Jordan, T.H., Present-day Plate Motions, *J. Geophys. Res.*, 83, 5331, 1978.

STRATEGY

The strategy recommended by the committee is conceptually simple and builds on ongoing international activities. The global absolute sea level monitoring system should be developed around the IERS terrestrial reference frame, using GPS to connect regional networks of tide gauges to the IERS observatories.

With the completion of the GPS system in the next 2-3 years, it will become feasible to connect gauges within 1000 kilometers of IERS observatories with sub-centimeter uncertainties. In that time frame, there will be about a dozen IERS observatories, mostly in the northern hemisphere, well located for this purpose. The number and distribution is expected to grow to about 30 to 40 stations with adequate global coverage within a decade.

It should be noted that this strategy has already been adopted by NOAA, as part of its Climate and Global Change Program, and pilot regional networks have been established in the Hawaiian Islands; along the Atlantic coast of the United States and Bermuda; and around the coast of South Africa (see figures 6, 7, and 8). The results of the initial epoch GPS surveys have not achieved the sub-centimeter accuracies that ultimately will be needed, but many of the field procedures, data reduction and analysis techniques, and lines of international cooperation are being worked out [Carter *et al.*, 1988].

Absolute gravity observations can contribute to fixing the tide gauge bench marks in two ways: directly, in monitoring contemporary vertical motions of individual gauges, and indirectly, by

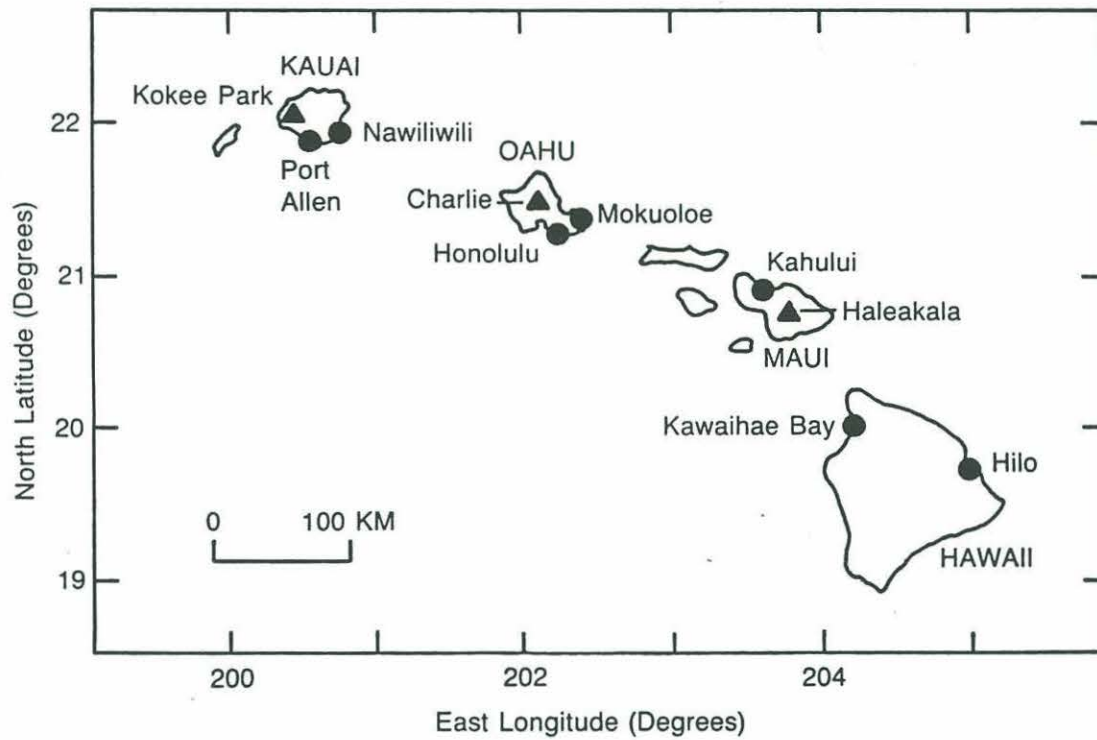


Figure 6. Map showing the locations of the tide gauge stations (circles) and space geodesy stations (triangles) included in the Hawaiian regional absolute sea level monitoring network.

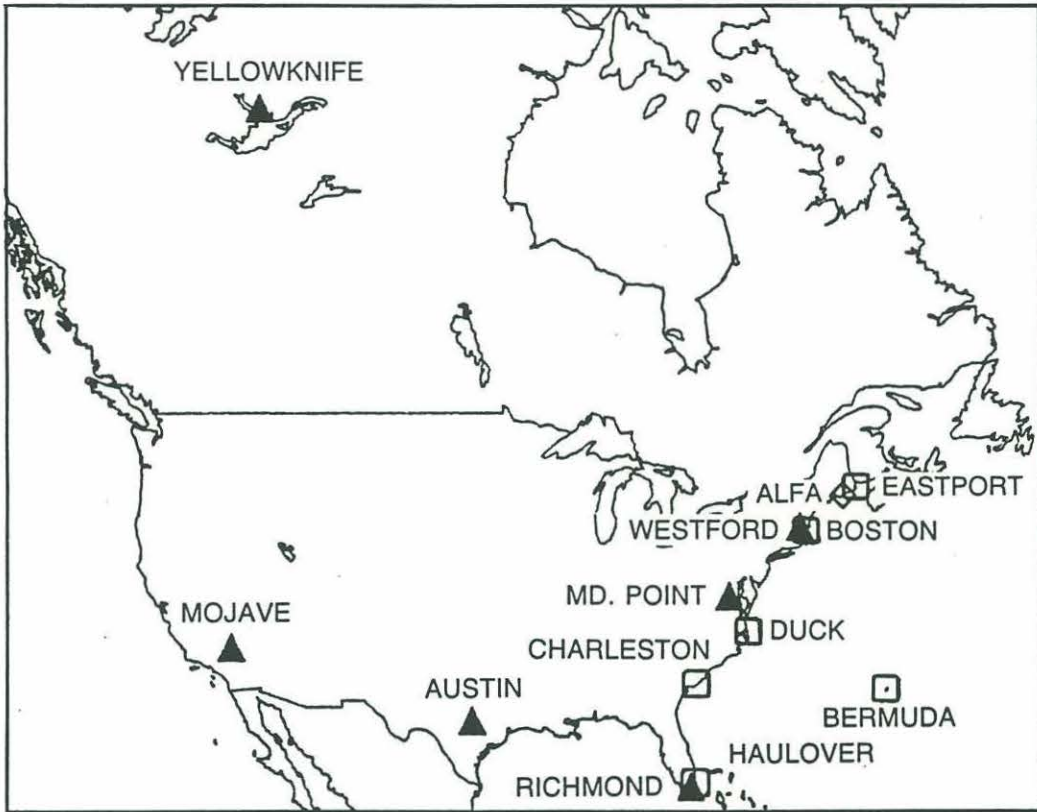


Figure 7. Map showing the locations of the tide gauge stations (squares) and space geodesy stations (triangles) included in the Atlantic Coast - Bermuda regional absolute sea level monitoring network.

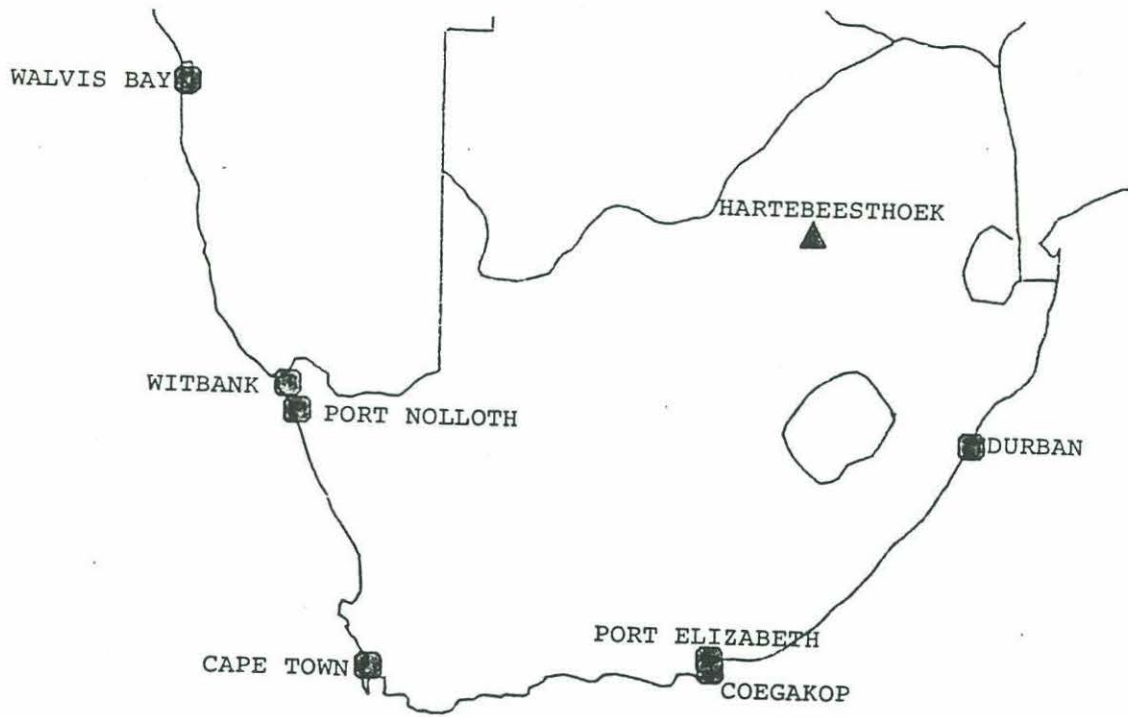


Figure 8. Map showing the location of tide gauge stations (squares) and VLBI observatories (triangles) included in the South African regional absolute sea level network.

measuring the global vertical deformations associated with glacial rebound and other tectonics that will be used to correct current and historical tide gauge observations.

The strategy for the direct monitoring of individual tide gauges is to:

Establish an absolute gravity station 1 to 10 kilometers inland of each gauge to be monitored, and make repeated measurements at regular intervals with sufficient frequency to determine any detected vertical motions with a resolution better than 1 mm per year. Relative motion between the gravity stations and the tide gauges should be monitored with GPS or classical leveling.

The strategy for measuring the effects of glacial rebound is to:

Establish networks of absolute gravity stations in the regions of maximum vertical motions (North America and Scandinavia) and make repeated measurements at regular intervals with sufficient frequency to determine the pattern and rate of the vertical motion with a resolution better than 1 mm per year. These observed rates can then be used to verify and calibrate models (*e.g.*, Peltier's) which can then be used to compute rates for individual gauges.

It is critically important that the effects of ocean tides on stations near the coastline and of the atmosphere at all stations be measured and/or modeled with sufficient accuracy that they do not become confused with gravity changes due to vertical crustal motions. For this purpose, superconducting tidal gravity meters should be permanently installed and operated at certain key "primary sites." Highest priority should be given to North America and Scandinavia where the absolute and cryogenic meter measurements can be integrated to produce the best possible time series of glacial rebound measurements.

The observational strategies discussed above will yield time series of coordinates of tide gauge bench marks, and changes in absolute gravity at nearby points and at stations within networks covering regions of maximum glacial rebound. These data will need to be distributed to the international scientific community for analysis. The "raw" observational data sets will be quite large and will be "reworked" by a few specialists (mostly at the organizations that do the surveys) as improved computer programs and models are developed. It would be expensive and ineffective to attempt to centralize the storage and distribution of the raw observational data. Rather, only

the dates of measurements and the derived coordinates and absolute gravity values should be stored at a centralized facility, and users requiring more detailed information, including raw data, should be referred to the organization that made the observation. This approach has been adopted by the IERS, and appears to be working well. The centralized data base, consisting only of decade long time series of coordinates and gravity values for a few hundred stations, will easily fit on a few floppy disks in ASCII characters, and copies can be produced inexpensively on a personal computer. An obvious choice to store and distribute these data is the Permanent Service for Mean Sea Level (PSMSL), but redundant services could be provided by several centers at little cost.

Reference:

Carter, W.E., C. Chin, J.R. MacKay, G. Peter, W. Scherer, and J. Diamante, Global Absolute Sea Level: The Hawaiian Network, *Marine Geodesy*, 12, 1988.

ANNEX A

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16. Abstract (Limit: 200 words) Under the auspices of the International Association for Physical Sciences of the Ocean (IAPSO) a committee was established to identify the oceanographic and geophysical requirements for fixing Tide Gauge Bench Marks (TGBM's) in an absolute terrestrial coordinate system; to evaluate the technology for fixing TGBM's; and to make recommendations to the Commission on Mean Sea Level and Tides (IAPSO) of a strategy for coordinated global fixing of TGBM's and for making the results centrally available. To meet these goals, the committee met for a several day session at the Woods Hole Oceanographic Institution in November, 1988. From this workshop came a series of technical conclusions, plus specific recommendations to achieve the goals of the committee. Included in these discussions were Very Long Baseline Interferometry, Satellite Laser Ranging, Lunar Laser Ranging, Global Positioning System, and Absolute Gravity Meters, as well as mechanisms for logging and distributing the results from these systems, perhaps via the Permanent Service for Mean Sea Level (PSMSL) in Britain.			
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