Report
of the

Surrey Workshop

of the

IAPSO
Tide Gauge Bench Mark Fixing Committee

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Report of the Surrey Workshop of the IAPSO Tide Gauge Bench Mark Fixing Committee

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TABLE OF CONTENTS

OVERVIEW

TECHNOLOGY STATUS REPORTS

REGIONAL PROJECTS

ANNEXES

FOREWORD

This report contains results of the second workshop of the International Association for Physical Sciences of the Ocean (IAPSO) Commission on Mean Sea Level and Tides (MSLT) ad hoc geodetic committee to study the geodetic fixing of tide gauge bench marks, held at Deacon Laboratory, Godalming, Surrey, United Kingdom, December 13-15, 1993. For convenience, this meeting will be referred to simply as the Surrey workshop in this report.

A total of 35 scientists, primarily geodesists and oceanographers, from 13 nations attended the workshop technical sessions. A representative of the International Oceanographic Commission (IOC) Secretariat also attended. The number of participants in this workshop was about three times as great as at the first workshop held at Woods Hole Oceanographic Institution during November 1988. The increase in the number of participants was particularly gratifying because it was not initiated by the President of the IAPSO Commission (David Pugh) or the committee Chairman (Bill Carter), but rather resulted from requests from individual scientists and organizations to participate in the workshop after the initial plans had been completed. Clearly, interest and attendance were increased because the time and location of the workshop were conveniently set relative to a number of meetings on related subjects held in Europe. The International Association of Geodesy (IAG) Special Study Group 5.149 on Vertical Datum Investigation, c Chaired by Erwin Groten, met in the same facilities immediately following the Surrey workshop. But the development of absolute sea level monitoring programs by several nations around the world during the past 5 years was the principal factor in the excellent participation in the workshop.

There were two implications of the relatively large number of participants in this workshop. First, the facilities at Deacon Laboratory and the small town of Godalming were stretched to near full capacity. The participants owe a debt of gratitude to David Pugh, Clemence Hill, and other members of the Deacon Laboratory staff for their exceptional efforts that made the available facilities work. They even found time to organize a traditional Christmas dinner that will remain a fond memory of the workshop. Thank you David, Clemence, and colleagues.

Second, the relatively large attendance greatly increased the breadth and depth of the scientific expertise represented by the participants, making it possible to explore issues that cross the traditional lines that separate geodesy and geophysics from oceanography. There were extensive interdisciplinary discussions during the formal workshop sessions and after hours, which contributed to progress in designing a global sea level monitoring network compatible with the geodetic capabilities and oceanographic needs.

INTRODUCTION

This report is organized into four primary sections, the EXECUTIVE SUMMARY, OVERVIEW, TECHNOLOGY STATUS REPORTS, and ANNEXES. The EXECUTIVE SUMMARY presents the conclusions and recommendations of the workshop in abbreviated format. The OVERVIEW reviews the central issues, discussions, and conclusions of the workshop. The TECHNOLOGY STATUS REPORTS, contributed by highly qualified specialists, document the current capabilities and operational characteristics of each observing technique. During the workshop, the technology status reports provided the basis for the discussions and ultimately the decisions and recommendations concerning the mix and contributions of the observing techniques to the global monitoring system. The ANNEXES contain general information, such as a copy of the workshop agenda and names and addresses of the participants.

EXECUTIVE SUMMARY

Advances in the Global Positioning System (GPS) now make it the method of choice for measuring vertical crustal motions at tide gauge stations to be used to monitor changes in absolute global sea level.

The minimum accuracy for vertical crustal velocities to be useful for sea level studies is estimated to be 1 to 2 mm per year over 5 year intervals and 0.3 to 0.5 mm per year over intervals of a few decades. The most cost effective operating mode to achieve these accuracies with GPS is to place permanent receivers directly at selected tide gauge stations and to continuously operate them throughout the life of the monitoring program.

Several sets of tide guage stations were selected, including GLOSS sites with long records primarily for secular sea level change studies; some sites with short or no records at present but which could be of potential interest for secular change studies in otherwise data sparse regions; and stations, primarily at ocean islands, taken from the WOCE sea level network, for interannual studies.

The International GPS and Geophysical Service (IGS) of the International Union of Geodesy and Geophysics, already operates a global network of approximately 30 GPS stations, collects the data with rapid turn around, distributes the full data set to researchers, and computes Earth rotation time series and station coordinates with delays of less than 1 week. An expansion of the IGS network to include measurements at tide gauge stations appears to be the best opportunity to realize a global sea level monitoring network in the immediate future.

The central role now foreseen for GPS should not be interpreted as reason to discontinue or reduce ongoing efforts in complementary techniques, most particularly Very Long Baseline Interferometry (VLBI) and absolute gravimetry. The unique information from those techniques will provide constraints on the Earth models used in the analysis to extract changes in sea level.

Recommendation 1: The President of MSLT Commission should formally request that the IGS take on the additional duties of organizing and managing the operation of the GPS global sea level monitoring network as a fully integrated component of the IGS-IERS International Terrestrial Reference Frame (ITRF). The products should be coordinates and velocities of the tide gauge stations bench (reference) marks in the ITRF system.

Recommendation 2: The Permanent Service for Mean Sea Level (PSMSL) archiving system should be designed to provide the vertical crustal velocities derived from selected IGS solutions, along with explanatory information including experts that can be contacted by users of the data.

OVERVIEW

Introductory Remarks

The central finding of the first workshop held by the committee at Woods Hole Oceanographic Institution in November 1988 [Carter et al., 1989] was that the global absolute sea level monitoring system must be "developed around the International Earth Rotation Service (IERS) Terrestrial Reference Frame (ITRF)." Progress made by the international geodetic community to refine, extend, and densify the ITRF during the past 5 years has been excellent, and it was the consensus of the participants of the Surrey workshop that this remains the best, and perhaps only workable approach currently available.

However, the relative accuracies, operating ease, and costs of the various geodetic positioning techniques, most importantly Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and the Global Positioning System (GPS) have changed dramatically over the past 5 years, and the recommended mix and roles of the techniques required updating to reflect those technological developments.

The Role of GPS

In 1988, GPS was only partially completed and was operating in an experimental mode. GPS is now a fully operational system (the GPS system was officially declared operational by the United States Department of Defense in February 1994) and is the method of choice for the highest accuracy positioning over all spatial scales, including even global networks.

How did GPS develop from a promising new geodetic technique to the method of choice in just 5 years? In brief, and perhaps somewhat oversimplified terms:

- The cost of GPS receivers dropped by a factor of 5 or more, making it possible to purchase state-of-the-art receivers for about $20,000 US.

- GPS receivers reached levels of reliability and user friendliness that stations can be operated in relatively remote locations, yielding high quality data for months-on-end, virtually hands-off.

- The GPS constellation reached full population with 24 satellites providing multi-satellite global coverage 24 hours a day.

- The expansion of INTERNET to previously excluded nations and remote regions made it economically feasible to transfer data from a global network of GPS stations rapidly (within hours of collecting the observations) to data storage and computing centers.

- Computer memory and data storage with sufficient capacity to process and store the data flow from tens of continuously operating GPS stations became available for costs under $100,000 US. Computer technology is expected to stay abreast of or exceed the requirements as the GPS network expands to hundreds of stations in the next few years.

- Computer software developed by several groups can routinely process the observational data from tens of continuously operating GPS receivers, within hours of receipt of the data.

As the necessary technological components began to fall into place, the international GPS community organized a number of short observing campaigns and pilot services. These activities eventually led to the formation of the International GPS and Geophysical Service (IGS) under the auspices of the International Union of Geodesy and Geophysics (IUGG). In order to ensure that civilian organizations and researchers have access to precise GPS orbits, the IGS initiated efforts to develop a global network of approximately 30 continuously operating GPS tracking stations. That network is now fully operational, routinely making observations, compiling and archiving data at regional centers, distributing data to computational centers around the world, and producing precise orbit and Earth rotation parameters that are used regularly by surveyors and scientists in many countries. The success of the IGS has demonstrated that:

- All of the components described above can be integrated into a reliable highly automated monitoring system that can be operated by a consortium of loosely associated organizations pooling their resources.

- Continuously operated GPS stations can monitor the horizontal and vertical velocities of points anywhere on Earth, separated by distances up to thousands of kilometers, with day to day repeatability of a centimeter or better. Based on this demonstrated level of performance it is plausible to assume that station velocities can be determined with accuracies of perhaps 1 mm per year over integration periods of 3 to 5 years. This projection is supported by recent success in determining crustal motions associated with earthquakes in California. Researchers were able to extract horizontal and vertical coseismic displacements immediately following the earthquakes with millimeter resolutions, using data from continuously operating GPS stations.

In 1992, the IERS officially adopted GPS as one of its primary techniques, of equal status with VLBI, SLR, and Lunar Laser Ranging (LLR). In fact, GPS is now the principal source of polar motion and length-of-day values at periods of one day or less. The IERS and IGS efforts to expand and densify the ITRF are closely coordinated and rely heavily on GPS.

The Woods Hole report foresaw the use of GPS primarily as the means to interconnect tide gauges located within hundreds of kilometers of one another to form regional networks, and to tie those networks to the VLBI and SLR stations that formed the highest accuracy core of the ITRF. Based on the cost of receivers, mean time between failures, and data collection, transmission, storage and processing resource requirements, it was assumed the GPS would be used in the "survey mode". That is, GPS receivers would be used to make repeat observations at selected stations for periods of days, separated by periods of months to years. Additionally, estimates of distances over which sub-centimeter accuracies could be achieved ruled out stations in remote locations thousands of kilometers from a VLBI or SLR station. Today the preferred mode of operation, based on total resource requirements and achievable accuracy, is to use permanent GPS receivers operating continuously over the full span of the program.

Having agreed that the extraordinary progress in GPS has dramatically changed the constraints on the number and locations of tide gauge stations at which vertical crustal motion might reasonably be monitored, the question that followed naturally was:

What set of tide gauge stations would comprise a reasonable global absolute sea monitoring network?

A small working group, chaired by Gary Mitchum, and comprised mostly of oceanographers, was asked to consider this question. Based on their collective experience, limited reference material immediately available, and working within tight time constraints, the working group developed a preliminary answer: to first approximation, the network might look much like that selected for the World Ocean Circulation Experiment (WOCE). A number of stations in the WOCE list would probably be deleted, while other stations should be added to improve the network for the specific problem of monitoring the secular change in global sea level.

The working group's preliminary report stimulated questions from other participants in the workshop about the criteria for selecting a tide gauge station for inclusion in such a network. Of central importance was the value of stations along continental margins that are clearly affected by shallow water and coastal geometries. One specific example concerned tide gauges located deep within fjords along the Norwegian coastline. In regions of this type it was concluded that it would be highly desirable to develop new tide gauge stations closer to deep waters, and at least one potential island site was identified. Gary Mitchum and members of his working group agreed to continue to work on the design of a network and to provide a written report for inclusion in the Workshop Report [see Mitchum page 9, this report].

In addition to the network design issue, Mitchum's working group also decided to address the question: How accurate must geodetic measurements of vertical crustal motion be to be useful to oceanographers?

The working group concluded that the answer depended on the time scale of the phenomena being studied. For sea level variability on time scales of a few years to decades, oceanographers would like to know if the sea level changes indicated by relatively short tide gauge records are real, i.e., represent changes in water level rather than vertical crustal motions. The working group concluded that the geodetic measurements must provide vertical crustal velocities at least as accurate as 1 to 2 mm per year on time scales of 5 years.

For global absolute sea level studies, the time scales of interest are decades to centuries. The minimum required accuracies were set at 0.3 to 0.5 mm per year over time scales of a few decades.

Based on the current and projected performance of GPS, the requirements reported by the working group, and the ongoing operations of the IGS, there was nearly universal agreement among the participants of the Surrey workshop that:

- GPS receivers should be placed permanently at selected tide gauge stations and operated continuously. This approach would allow tide gauges in remote locations, including isolated islands, to be monitored.

- The IGS should be asked to organize and manage a sea level monitoring GPS network in the same way that they are currently managing the satellite orbit - earth orientation network. One major advantage foreseen is that the sea level monitoring network would automatically be tied directly to the ITRF. In fact, many of the tide gauge stations might be directly incorporated into the ITRF as primary stations.

Contributions From Other Techniques

Based on the central role of GPS described above one might ask the questions:

Can GPS do the entire job by itself? If not, what contributions are needed from other techniques such as VLBI, SLR, and absolute gravimetry? Do those potential contributions justify the investment of resources required?

The answers to these questions depend on the current and projected capabilities and costs of each technique considered, and the uniqueness of the information that it might contribute.

Currently, VLBI is the technique most closely coupled with GPS. Nearly all VLBI observatories are equipped with GPS receivers that operate continuously to collect the observations required to compute precise GPS orbits. This coupling of VLBI and GPS originated in the technological strengths and environmental problems common to the two techniques, and the recognition that collocation of GPS and VLBI tracking stations makes it possible to accurately develop an integrated terrestrial reference frame. The VLBI network also provided highly accurate initial coordinates for the GPS tracking stations. As the accuracies of the two techniques have converged, intercomparisons have been used to identify problems and verify results. Striving for millimeter accuracies on global scale networks, i.e., roughly one part in ten billion on the scale of the Earth's diameter, is a formidable goal and being able to verify results by at least two methods is essential. In addition, VLBI is clearly the method of choice by the IERS for the determination of Universal Time (UT1), precession, and nutation, and there will be some number of geodetic VLBI observatories operated for the foreseeable future. See paper on networks by Bosworth, page 41 this report.

Absolute gravimetry has the potential for very high accuracy vertical crustal motion measurements and, when used in conjunction with GPS or VLBI, can provide unique information for detecting and modelling relocations of mass in the interior of the Earth. A new generation of absolute gravimeters has been developed since the Woods Hole workshop, geodetic organizations in several nations (Canada, England, Germany, France, Japan, and the United States) have purchased them, and the number, distribution, and accuracy of absolute gravity measurements are expected to increase rapidly in the decade ahead. See paper on absolute gravimetry by Lambert, page 33 this report.

Discussions of the relative accuracies and unique capabilities of GPS, VLBI, and absolute gravimetry led to a more fundamental question about the interpretation of geodetic measurements with respect to changes in global sea level. Suppose we were to assume that GPS could provide "perfect" time series of the changes of the radius vectors from the center of mass of the earth to tide gauge bench marks. If these values were combined with "perfect" water level measurement time series, would they yield "perfect" measurements of the change in absolute sea level. Given the sparse coverage of tide gauge stations in many regions, could the radius vectors change because of a shift in the center of mass of the earth and not be detectable? Is the center of mass of the Earth stable at the millimeter level over time scales of years?

Currently both SLR and GPS researchers perform least squares adjustments in which they solve for the position of the center of mass, using various spans of data. The apparent center of mass locations scatter by centimeters. This scatter is not thought to be real changes in the center of mass, but rather an indication of how well this parameter can be estimated from the current distribution and accuracy of observations. While there were a variety of opinions voiced about the long term stability of the center of mass and the ability of different techniques to track it, there was widespread agreement that it would be very dangerous for researchers to mix tide gauge positions collected over periods of years from different techniques, or even from the same technique if the observations were not reduced in a completely uniform manner. This implies that vertical velocities for tide gauge stations will have to be estimated by geodetic experts using large global solutions of carefully quality controlled data. One practical result of this process is that:

- The Permanent Service for Mean Sea Level (PSMSL) archiving system should be designed to provide the vertical crustal velocities derived from selected IGS solutions, along with explanatory information including experts that can be contacted by users of the data.

Another conclusion that can be drawn from this discussion is that at the millimeter level it may not be currently possible to define exactly what is meant by global sea level. It is clear, for example, that glacial rebound changes the shape of the geoid and redistributes the water in the ocean, changing the relative sea level at any point by an amount different from the vertical crustal motion at that point, even in the absence of any change in the global volume of the oceans. If the rate of change in the volume of the oceans remains at roughly the magnitude that is implied by the 1.7 mm per year increase in global sea level estimated from existing data, the analysis is going to have to use sophisticated earth models that will combine a variety of data including, for examples: Earth orientation measurements, vertical and horizontal crustal motion, satellite and surface gravity changes, satellite altimetry over oceans, ice masses and land surfaces.

REPORT OF OCEANOGRAPHY WORKING GROUP

Gary T. Mitchum, Department of Oceanography, University of Hawaii

A working group was formed that included most of the oceanographers present at the meeting. It was apparent from the earlier discussions in the plenary meetings that it was possible to provide vertical coordinates at sea level stations, and that these coordinates would be relative to a reference ellipsoid. This group was asked to consider possible oceanographic applications of absolute sea level defined in such a reference frame, to estimate the accuracies necessary to make such applications feasible, and to suggest a preliminary list of sea level stations where this absolute leveling of the benchmarks would be most useful.

The discussion initially centered on the difference between a geometric reference frame (i.e., vertical coordinates relative to a reference ellipsoid), and a frame where heights are measured relative to a constant gravitational potential surface, which the oceanographers commonly refer to as the geoid. The geoid is the preferred reference frame for oceanography largely because this is the frame in which our dynamical equations are derived. For example, in order to interpret sea level differences as absolute surface velocities, it is necessary to measure sea level relative to the geoid or, equivalently, to know the geoidal gradient between the two sea level stations. We thought that this was an important point to make for our geodetic colleagues. Ideally, we need a satellite mission that will allow the determination of small wavenumber features of the geoid.

From this point, the discussion assumed that the reference frame we could have would be a geometric one, and we turned to the oceanographic applications that would still be improved by such knowledge. Two problems were identified as most significant; the determination of sea level rise and studies of oceanic variability at decadal and longer time scales. For each of these problems the necessary accuracy in the vertical coordinates for the sea level stations was the main point of the discussion. We soon concluded that it was essential to estimate the uncertainty in terms of land rise/fall rates, rather than as a height error. In both of these applications it is land motion that must be determined in order to make the oceanographic problem tractable.

In the case of the global mean sea level rise rate, it was noted that these estimates are made difficult because the sea level change cannot be separated from land motion in relative sea level measurements. Present rates of sea level rise are estimated as 1-2 cm/decade. It is important to note, however, that we are really interested in whether this rate is accelerating or not, as would be associated with greenhouse warming through melting of ice on land

and thermal expansion of seawater. We concluded that useful absolute coordinates for the sea level stations would need to be good to 0.5 cm/decade when data from 30-40 years was used to estimate the land rise/fall rate. This insures that the residual land motion rate is small enough to allow detection of temporal changes in the present rate of sea level rise of about the same order. Of course this estimate is conservative in the sense that we are not allowing for a significant error reduction by spatial averaging.

The case of decadal-scale oceanic variations is a bit more subtle. In this case we are interested in sea level variations with periods of several years to several decades, which in principle can be handled adequately with relative sea level data. The problem arises, however, when the time scale of the variations of interest is comparable to the length of the sea level time series. In this case it becomes difficult to differentiate a low frequency variation from a land motion trend due to the small number of degrees of freedom. This problem is pervasive due to the fact that most open ocean sea level records are at best a few decades long. If we are to study variations on time scales of a comparable length, then it would be very helpful to have an a priori estimate of the non-oceanographic trend. Given that the decadal events can be only a few centimeters in amplitude, it is obvious that an unknown trend on the order of a few cm/decade will greatly complicate any detailed analyses. In this case we estimate that measurements of the land motion should be accurate to 1-2 cm/decade.

After determining these accuracies, 0.5 and 1-2 cm/decade for the sea level rise and decadal variability problems, respectively, we noted that these estimates both imply an accuracy in determining land motion of order 3 cm/decade using 1 year of data. This assumes two things. First, that these annual determinations are taken each year for long periods of time in order to allow the averaging over the longer time periods cited above. Second, that the annual estimations are statistically independent, which requires that the error sources for the land motion estimation decorrelate on time scales less than a year or so.

After setting limits on the required accuracies, it remained to suggest a set of sea level stations where such measurements would be most effective. In this case the sea level rise problem and the study of decadal variations require somewhat different sets of stations. In the case of sea level rise, stations with very long and well-maintained records are necessary. In the case of the decadal variations, stations that are well-distributed spatially and representative of the open ocean are preferred. For this case, island stations are especially appropriate. Since most of the very long sea level records are along continental margins and are poorly distributed in space, these requirements are somewhat at odds.

Our suggestion regarding station selection is to start with the WOCE sea level station list as being appropriate for studies of decadal variations. Note that the WOCE sea level station set was chosen specifically for good spatial coverage and for being representative of open ocean conditions. This list will be supplemented with a few additional island stations that have become available since the WOCE list was created. For the sea level rise problem, this list of stations also needs to be supplemented by a set of stations having long records and locations best suited for estimating changes in sea level rise rates.

STATIONS USEFUL FOR SEA LEVEL STUDIES OF VARIOUS KINDS

The following stations were identified, in a 'schematic' way, by the working group chaired by Gary Mitchum as being of interest for GPS measurements for several oceanographic reasons. An '*' in the column headed 'LONG TERM STUDIES' flags GLOSS stations with at least 40 years of data in the PSMSL dataset, while '+' flags several stations in data sparse areas which could be of potential importance to long term studies. Unflagged stations were selected primarily from the WOCE sea level network, and are mostly at ocean islands. These are of interest from the points of view of decadal variability of deep ocean sea level, and as sites which could provide a densification of the IGS network in oceanic regions. Station names are mostly those used in PSMSL reports.

STATION	GLOSS NO.	LATITUDE	LONGITUDE	LONG TERM STUDIES
Djibouti	2	11-36.0N	43-90.0E	
Aden	3	12-47.0N	44-59.0E	*
Salalah	4	16-56.0N	54-00.0E	
Mombasa	8	4-03.0S	39-40.0E	
Exuma	12	23-46.0N	76-06.0W	
Durban	13	29-53.0S	31-02.0E	
Reunion	17	20-55.0S	55-18.0E	
Port Louis Harbour	18	20-09.0S	57-30.0E	
Rodrigues	19	19-40.0S	63-25.0E	
Marion Island	20	46-52.0S	37-52.0E	
Crozet Island	21	46-25.0S	51-52.0E	
Mawson	22	67-36.0S	62-52.0E	
Kerguelen Island	23	49-21.0S	70-12.0E	
Mirny	25	66-33.0S	93-01.0E	
Diego Garcia	26	7-00.0S	72-30.0E	
Gan	27	0-42.0S	73-10.0E	
Male	28	4-11.0N	73-31.0E	
Karachi, Manora Island	30	24-48.0N	66-58.0E	*
Cochin	32	9-58.0N	76-16.0E	*
Madras	34	13-06.0N	80-18.0E	*
Vishakhapatnam	35	17-41.0N	83-17.0E	*
Ko Lak	39	11-48.0N	99-49.0E	*
Ko Taphao Noi	42	7-50.0N	98-26.0E	*
Cocos Island	46	12-07.0S	96-53.0E	
Christmas Island	47	10-25.0S	105-40.0E	

Fremantle II	53	32-03.0S	115-44.0E	*
Esperance	54	33-52.0S	121-54.0E	
Hobart	56	42-53.0S	147-20.0E	
Sydney, Fort Denison	57	33-51.0S	151-14.0E	*
Bundaberg	59	24-50.0S	152-21.0E	
Darwin	62	12-28.0S	130-51.0E	
Rabaul	65	4-12.0S	152-11.0E	
Honiara	66	9-26.0S	159-57.0E	
Bitung	69	1-32.0N	124-50.0E	
Jolo, Sulu	70	6-04.0N	121-00.0E	*
Davao	71	7-05.0N	125-38.0E	*
Legaspi, Albay	72	13-09.0N	123-45.0E	*
Manila, S. Harbor	73	14-35.0N	120-58.0E	*
Port Elizabeth	76	33-58.0S	25-38.0E	
Quarry Bay	77	22-18.0N	114-13.0E	+
Pusan	84	35-06.0N	129.02.0E	+
Kushimoto	85	33-28.0N	135-47.0E	*
Mera	86	34-55.0N	139-50.0E	*
Yuzhno Kurilsk	90	44-01.0N	145-52.0E	*
Petropavlovsk-Kamchatsky	93	52-59.0N	158-39.0E	+
Syowa	95	69-00.0S	39-35.0E	+
Kaliningrad	97	54-57.0N	20-13.0E	*
Tuapse	98	44-06.0N	39-04.0E	*
Wellington II	101	41-17.0S	174-47.0E	*
Chichijima	103	27-05.0N	142-11.0E	
Wake Island	105	19-17.0N	166-37.0E	
Midway Island	106	28-13.0N	177-22.0W	*
Honolulu	108	21-18.0N	157-52.0W	*
Johnston Island	109	16-44.0N	169-32.0W	*
Kwajalein	111	8-44.0N	167-44.0E	*
Majuro	112	7-06.0N	171-22.0E	
Tarawa	113	1-22.0N	172-56.0E	
Nauru	114	0-32.0S	166-54.0E	
Ponape	115	6-59.0N	158-14.0E	
Truk Atoll	116	7-27.0N	151-51.0E	
Kapingamarangi	117	1-06.0N	154-47.0E	*
Saipan	118	15-14.0N	145-45.0E	
Malakal	120	7-20.0N	134-28.0E	
Funafuti	121	8-32.0S	179-13.0E	
Suva	122	18-08.0S	178-26.0E	
Noumea	123	22-18.0S	166-26.0E	

Auckland II	127	36-51.0S	174-46.0E	*
Chatham Island	128	43-50.0S	176-30.0W	
Bluff Harbor	129	46-36.0S	168-21.0E	
Macquarie Island	130	54-30.0S	158-56.0E	
Dumont d'Urville	131	66-40.0S	140-01.0E	
Isla da Pascua	137	27-09.0S	109-27.0W	
Rikitea	138	23-08.0S	134-57.0W	
Rarotonga	139	21-12.0S	159-46.0W	
Papeete	140	17-31.0S	149-30.0W	
Nuku Hiva	142	8-56.0S	140-05.0W	
Penrhyn	143	9-01.0S	158-05.0W	
Pago Pago	144	14-17.0S	170-41.0W	*
Kanton	145	2-48.0S	171-43.0W	
Christmas	146	1-59.0N	157-28.0W	
Guam	149	13-26.0N	144-39.0E	*
Seward	150	60-07.0N	149-26.0W	*
Sitka	154	57-03.0N	135-20.0W	*
Prince Rupert	155	54-19.0N	130-20.0W	*
Tofino	156	49-09.0N	125-55.0W	*
San Francisco	158	37-48.0N	122-28.0W	*
La Jolla	159	32-52.0N	117-15.0W	*
Cabo San Lucas	161	22-53.0N	109-55.0W	
Socorro Island	162	18-44.0N	111-01.0W	
Quepos	167	9-24.0N	84-10.0W	
Balboa	168	8-58.0N	79-34.0W	*
Galapagos Islands	169	0-26.0S	90-17.0W	
Buenaventura	170	3-54.0N	77-06.0W	*
Tumaco	171	1-50.0N	78-44.0W	*
La Libertad II	172	2-12.0S	80-55.0W	*
Callao	173	12-10.0S	77-12.0W	
Antofagasta	174	23-39.0S	70-25.0W	*
Valapariso	175	33-02.0S	71-38.0W	*
Juan Fernandez	176	33-37.0S	78-50.0W	
San Felix	177	26-17.0S	80-80.0W	
Puerto Williams	180	45-56.0S	67-37.0W	
South Georgia	187	54-15.0S	36-45.0W	
Faraday	188	65-15.0S	64-16.0W	
Puerto Deseado	190	47-45.0S	65-55.0W	*
Isla Fiscal	195	22-52.0S	43-08.0W	+
Fernando de Noronha	198	3-52.0S	32-25.0W	
Porto de Natal	197	5-46.0N	35-12.0W	+

Penedro Sao Pedro e Paulo	199	1-00.0N	29-23.0W	
Marseille	205	43-18.0N	5-21.0E	*
San Juan	206	18-28.0N	66-07.0W	
Cartagena	207	10-24.0N	75-33.0W	*
Settlement Point	211	26-41.0N	79-00.0W	
Progresso	213	21-18.0N	89-39.0W	+
Siboney	215	23-05.0N	82-28.0W	
Key West	216	24-33.0N	81-48.0W	*
Galveston II	217	29-19.0N	94-48.0W	*
Miami	218	25-54.0N	80-07.0W	
Duck, N.C.	219	35-13.0N	75-38.0W	
Atlantic City	220	39-21.0N	74-25.0W	*
Bermuda	221	32-22.0N	64-42.0W	*
Halifax	222	44-40.0N	63-35.0W	*
Alert	225	82-20.0N	62-20.0W	+
Angmagssalik	228	65-30.0N	37-00.0W	
Reykjavik	229	64-09.0N	21-56.0W	
Barentsburg	231	78-04.0N	14-15.0E	*
Maloy	235	61-56.0N	5-07.0E	*
Newlyn	241	50-06.0N	5-33.0W	*
Brest	242	48-23.0N	4-30.0W	*
La Coruna I	243	43-22.0N	8-24.0W	*
Ponta Delgada	245	37-44.0N	25-40.0W	*
Cascais	246	38-41.0N	9-25.0W	*
Gibraltar	248	36-07.0N	5-21.0W	
Ceuta	249	35-54.0N	5-19.0W	
Dakar	253	14-38.0N	17-27.0W	
Porto Grande	254	16-52.0N	24-59.0W	
Ascension	263	7-55.0S	14-25.0W	
St. Helena	264	15-58.0S	5-42.0W	
Ilha da Trindade	265	20-30.0S	29-18.0W	
Tristan da Cunha	266	37-03.0S	12-18.0W	
Simonstown	268	34-11.0S	18-26.0E	
Bouveteya	269	54-22.0S	3-22.0E	
Port Victoria	273	4-40.0S	55-28.0E	
Murmansk	274	68-58.0N	33-03.0E	*
Casey	278	66-17.0S	110-32.0E	
Cuxhaven 2	284	53-52.0N	8-43.0E	*
Nawiliwili	285	21-57.0N	159-22.0W	
Kahului	286	20-45.0N	156-28.0W	
Hilo	287	19-44.0N	155-04.0W	*

Pensacola	288	30-24.0N	87-13.0W	*
Fort Pulaski	289	32-02.0N	80-54.0W	*
Newport	290	41-30.0N	71-20.0W	*
South Caicos	296	22-00.0N	72-00.0W	
Zanzibar	297	6-09.0S	39-11.0E	
Montevideo	300	34-54.0S	56-15.0W	*
Adak	302	51-52.0N	176-38.0W	*
Massacre Bay	303	52-50.0N	173-12.0E	
Port Stanley	305	51-45.0S	57-56.0W	
Signy	306	60-42.0S	45-36.0W	
Dikson	312	73-32.0N	80-39.0E	+
Tiksi	313	71-40.0N	128.45.0E	+
Arica		18-28.0S	70-20.0W	
Caldera		27-04.0S	70-50.0W	
Diego Ramirez		56-33.0S	68-40.0W	
Heard Island		53-00.0S	73-25.0E	
Malpelo Island		4-00.0N	81-21.0W	
Amsterdam Island		38-43.0S	77-35.0E	
Scott Base		77-51.0S	166-40.0E	
Prudhoe Bay		70-12.0N	148-15.0W	
Provideniya		64-18.0N	173-07.0W	
St. Croix		17-42.0N	64-46.0W	
S Sound, Gd Cayman		19-16.0N	81-23.0W	
Lake Worth		26-37.0N	80-02.0W	
Hualien		23-58.0N	121-37.0E	
Ishigaki		24-20.0N	124-09.0E	
Naze		28-23.0N	129.30.0E	
Nishinoomote		30-44.0N	131-00.0E	
Spring Bay		42-32.9S	147-55.8E	
Cresent City		41-45.0N	124-11.0W	
Dutch Harbor		53-53.0N	166-32.0W	
Ketchikan		55-20.0N	131-38.0W	
Kodiak Island		57-48.0N	152-24.0W	
Lobos		6-56.0S	80-43.0W	
Neah Bay		48-22.0N	124-37.0W	
San Diego		32-43.0N	117-10.0W	
Talara		4-35.0S	81-17.0W	
Hanimaadu		6-46.0N	73-10.0E	
Pointe La Rue		4-40.0S	55-32.0E	
Charleston		32-47.0N	79-56.0W	
Lome		6-08.0N	1-17.0E	

TECHNOLOGY STATUS REPORTS

THE GLOBAL POSITIONING SYSTEM

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Abstract

In recent years, much has changed in the application of the Global Positioning System (GPS) to high-precision geodesy. We review the current status of GPS (early 1994), and conclude that the role of GPS should be reassessed with regard to tide-guage benchmark fixing. The two key developments in GPS are (i) the rapid expansion in infrastructure for continuous monitoring on a global scale, and (ii) that GPS can now deliver 1-cm level coordinate precision on a global scale, every day. GPS is therefore no longer restricted to local or regional studies, and the opportunity exists for producing solutions for the motion of tide-guage benchmarks using one globally consistent system in the IERS Terrestrial Reference Frame.

Introduction

Since the 1988 workshop at Woods Hole [Carter et all., 1989], high precision geodesy using the Global Positioning System (GPS) has evolved from a promising experimental technique into a mature system with an established infrastructure. Also, since that time, GPS geodetic precision has improved substantially, especially over long distances (greater than 1000 km), as progress has been made in (i) the GPS satellite constellation, (ii) tracking networks on the ground, and (iii) analysis techniques and software [Blewitt, 1993]. Even for global scale networks, GPS has recently shown levels of precision which are competitive with Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). From this perspective, it is important that we reassess the status of GPS with regard to tide-guage benchmark fixing, considering that the conclusion from the Woods Hole meeting on the role of GPS were, of course, based on an assessment of the state-of-the-art in 1988.

In this report, we briefly review the status of GPS in areas having relevance to the problem of tide-guage benchmark fixing. We also address aspects of geodesy which are not unique to the GPS technique, but, nevertheless, require attention if we are to better interpret estimates of vertical coordinates. The International GPS Service for Geodynamics (IGS) is identified as a group that has much to offer towards meeting our scientific goals. We discuss ways in which we can build upon the existing IGS infrastructure and make use of IGS data products to address the problem of monitoring many continuous receivers at tide-guage benchmarks.

Infrastructure: Space and Ground

The GPS Constellation:

In 1988, the GPS satellite constellation was incomplete, and, despite very good results under certain conditions, the use of GPS was considered experimental rather than operational. In February 1994, the United States Department of Defense declared GPS operational. The GPS constellation has now grown to its full complement of (at least) 24 operational satellites, providing at least 4 satellites in view anywhere on the globe, any time of the day. As many as 8 or more satellites are in fact visible at some locations for parts of the day. This increase in the number of visible satellites has (i) enabled precise positioning 24 hours a day, (ii) improved satellite orbit determination, therefore improving baseline estimation over long distances, and (iii) brought a noticeable improvement in vertical coordinate precision due to the increased resolution in wet tropospheric delay.

The International GPS Service for Geodynamics (IGS):

Another vital development is the emergence of the International GPS Service for Geodynamics, which oversees the acquisition, distribution, and analysis of data from the global GPS network [Mueller, 1990]. After an initial pilot period starting June 1992, the IGS was sanctioned by the IAG, and became fully operational in January 1994. Every day, each of 7 IGS Analysis Centers reduce data from approximately 20-40 stations of the global GPS network, producing precise estimates of satellite positions, daily positions of the Earth's pole, and the tracking station coordinates.

The public nature of the results has resulted in many intercomparisons between various groups, which has in turn served to improve the reliability and precision of the products. There is evidence from various indicators of accuracy that station coordinates as expressed in a global reference frame can now be estimated at the one centimeter level. Coordinate (and velocity) solutions are submitted by IGS analysis centers to the International Earth Rotation Service (IERS) for subsequent incorporation into the IERS Terrestrial Reference Frame (ITRF). The ITRF was identified in the Woods Hole meeting as the appropriate reference frame for monitoring global sea-level change.

The IGS and Regional Processing:

Currently, daily station coordinate solutions are not routinely distributed; however, there are plans by IGS to make these products available too. Moreover, IGS has plans to integrate results from various global and regional analyses so that unified solutions can be made routinely available. We should therefore assume that within the next few years, researchers will have access to daily, unified network solutions of perhaps over 100 stations worldwide. This provides an opportunity for sea-level researchers to routinely monitor many tide-guage benchmarks motions in a global reference frame in a self-consistent way.

Hardware

Continuous Operation Capability:

The most important development in hardware has been the introduction of "affordable" commercial GPS receivers that produce dual frequency carrier phase and pseudorange observations. Moreover, these receivers have the capability and level of reliability that allow remote operations. The current price of such receivers is approximately $30,000 US.

Data can now be retrieved in a few minutes for 24 hours of 30-second data, via modem over telephone lines, often to a local Internet connection. Data are then typically distributed via the Internet to data archiving centers, and thence to analysis groups. In contrast, the typical mode of operation in 1988 was to set up a receiver for several days, collect the data on cassettes, and then analyze the data to produce an epoch result. The development of continuous monitoring has spurred automatic analysis techniques, and now it is economical to set up continuous operations. Continuous GPS typically produces daily estimates of station locations, and thus provides more information on geodetic signals.

Information Technology:

Due to the development of continuous operations, the category of "hardware" now necessarily involves computing facilities for data communication, storage, and analysis. This is in contrast with 1988, where the limiting factor was not the computer, but able bodies to analyze and make sense of the data. Current computer technology has so far kept pace with the demands of the ever expanding global networks, and analysis groups can routinely deal with data from approximately 20 to 40 stations. Typical computer costs for such centers are approximately $100,000 US.

Unfortunately, analysis time increases at least quadratically with the number of stations; so how are we to cope with a global network of hundreds of stations? This does not appear to be a serious problem, since techniques have been developed to effectively partition the lease squares problem, reducing the computational burden to a manageable level even on today's computers. It is not expected that GPS orbit determination accuracy will improve using more than approximately 40 well-distributed tracking stations. Therefore, regional network estimation can proceed using orbits which have already been determined by the IGS analysis centers. However, the handling of data from potentially hundreds of regional stations (retrieval, storage, distribution, and integration of regional and global solutions from the various groups) may be a more difficult problem to tackle. The IGS is currently looking into these questions.

Antennas:

It is possible that improvements to antenna hardware may produce better results. It is likely that multi-pathing effects at certain sites are dominant error sources, but this is not so much a problem with the antenna hardware as the siting of the antenna and its environment. This is evident by comparing the precision of results obtained from different sites which have identical hardware configurations. More research into antenna siting is recommended, but often the problem is a practical one. For example, some sites have antennas mounted next to metallic structures, such as communication towers, simply because it is convenient or difficult to find another location for the antenna. To place an antenna far from the facility housing the receiver would require long, very low-loss cables, which are quite expensive (several thousand US dollars), and even then the antenna may be exposed to wildlife, theft, vandalism, or other factors.

Mixing antenna types was a serious problem in 1988 and is now less of a problem. Every antenna produces additional phase delays to the observations as a function of elevation and azimuth. With identical antenna types at each end of a baseline, these phase delays almost cancel when differencing the data, provided the antennas are oriented so that a reference mark is pointing North, or some other agreed to direction. (Equivalently, software which does not difference data, but instead models the one-way phase observable, would absorb the phase variation into the satellite clock parameter). However, if different antenna types are used, the effect will not approximately cancel, and systematic errors often larger than 1 cm will be introduced.

Results from the IGS have been relatively immune from these effects, since almost all antennas are of a similar type (cross dipole on top of a choke ring backplane), but this situation is likely to change as regional networks are currently being established which use a variety of receiver/antenna types. Fortunately, these effects can be calibrated as a function of elevation and azimuth using a special antenna test range, and software can now account for these calibrations. Several groups are now reporting improved results using mixed antenna types and calibrations.

It should be noted that for networks larger than the regional scale, these effects no longer cancel even for identical antenna types. Therefore, antenna calibrations (if they prove to be valid) should even improve results from the IGS global network.

Selective Availability and Anti-Spoofing

Since 1988, the GPS signals have been intentionally degraded by the U.S. Department of Defense by two very different mechanisms: (i) "Selective Availability" (SA), and (ii) "Anti-Spoofing" (AS). For precise geodesy, AS has posed more (but not serious) problems than SA.

Selective Availability (SA):

Selective Availability is effectively a dithering of the satellite's reference frequency (10.23 MHz) in an unpredictable way. Nominally, SA appears to cause variations in the observed delays by tens of meters. Fortunately, SA looks smooth over tens of seconds, and is not sufficiently variable to corrupt the actual measurement process. Secondly, the effect cancels between two receivers tracking the same satellite, provided the receivers are programmed to record data at the same nominal time. All of today's geodetic-quality receivers record on the integer second, so no special correction for SA is required. In conclusion, SA has negligible effect for our purposes.

Anti-Spoofing (AS):

Anti-Spoofing is an intentional encryption of the P-code. L1 phase and pseudorange observables can still be extracted because the C/A code is unaffected by AS. There are techniques (which will not be explained here) that today's receivers use to extract L2 phase and pseudorange observations, however there is an increase in noise as compared to observations extracted using the P-code. Fortunately, geodetic precision is not sensitive to the quality of the pseudoranges, as long as they are sufficiently precise for certain algorithms to work (data editing and ambiguity resolution). The increase in L2 phase noise can become significant (centimeter-level) at elevation angles below 20 degrees, and instances of cycle slips in the data have increased at low elevations. Analysis groups have adjusted their estimation strategies and data editing algorithms in an attempt to minimize negative effects of AS. Some groups have increased the elevation mask from 15 degrees to 20 degrees.

The degree of increased data noise and cycle slips is a function of receiver type, and older receivers are being replaced in the IGS global network in favor of receivers with newer and better algorithms for tracking under AS conditions. Fortunately, IGS orbit quality statistics based on comparing orbit and pole solutions between different group's solutions have not shown any noticeable change since AS was permanently switched on in early 1994. In conclusion, although AS has caused groups to reconfigure their hardware and software, it does not appear to be causing significant degradation in geodetic precision.

Software and Data Analysis

Software:

During the years since 1988, GPS processing software has reached the state of maturity where independent analyses of the same data yield coordinate estimates that agree at the few millimeter level. Pairwise comparisons of orbit positions estimated by the various IGS analysis centers agree at the level of 20 cm. This shows that, despite very different algorithms and methods used in software, the underlying models must be reasonably consistent.

It should be emphasized, however, that still the best results can only be obtained by a few software packages developed by universities and government organizations. Commercial software typically only deals with local or regional scales, and is unsuitable for the demands of high-precision global-scale geodesy.

Reference Frame Considerations:

An important development in the early 1990's was the development and application of "fiducial-free" methods to determine station coordinates. In the 1980's, GPS station coordinate estimates were typically derived by holding a subset of station coordinates fixed to previously determined values (e.g., by VLBI). In fact, the Wood's hole design for benchmark fixing assumes this model, in which GPS provides a regional geodetic tie to the global VLBI/SLR network. However, it is now known that the global GPS network is sufficiently robust that all station coordinates can be precisely estimated without having to hold any subset fixed to externally provided values.

In this view of global geodesy, the GPS stations can be thought of vertices of a polyhedron, which has (i) an arbitrary orientation in inertial space, since we have no absolute celestial reference (however, polar motion is precisely measured at the 0.5 masec level, and GPS is currently the dominant IERS technique for polar motion estimation); (ii) a reasonably defined origin at the Earth center of mass (which is resolved at the few centimeter level on a daily basis); and (iii) a well defined scale, by definition of the speed of light.

Geophysical phenomena can be observed through effects on the deformation of this polyhedron, without having to know absolute orientation or origin. Origin stability can be enforced by assuming that there is no net translation of the polyhedron with respect to a plate motion model (this is the approach that must be taken in VLBI, which is insensitive to the Earth center of mass). With GPS and SLR, this constraint may be slightly relaxed by assuming that the Earth center of mass moves linearly with time (but it remains to be seen if GPS provides sufficiently resolution of the center of mass for this to approach to be physically meaningful). However, it is not clear that sensitivity to motions of the Earth center of mass is a practical advantage for the problem of monitoring global sea-level change. For example, a motion of the Earth center of mass indicates mass redistribution on a global scale, in which case the geoid must be deforming too, thus the problem is more complicated than it first appears.

Future Prospects:

GPS data reduction software is still continuing to be refined, particularly in the area of orbit determination. There is still room for improvement in the estimation of wet tropospheric delay, which directly affects the estimation of the vertical component. An important step forward during the late 1980's was the application of Kalman filtering techniques to the stochastic estimation of tropospheric delay. Even today, however, it is most common to assume azimuthal symmetry in tropospheric water vapor content at a given site, and it is possible that innovative techniques could be applied to allow for tropospheric variations in azimuth.

Another area which could be improved is ambiguity resolution. Ambiguity resolution has been demonstrated to produce significant improvement in baseline length estimates over global scales, however it is a computationally intensive procedure, and it is not clear how well it will improve the sensitivity to vertical signals.

Loading Effects

Ocean tidal loading:

Ocean tidal loading on the Earth's crust can cause vertical motion with amplitudes of several centimeters at some sites. Although the effect tends to average over the day, many analysis centers do not in fact form truly daily solutions (for reasons that go beyond the scope of this report). For example, if a 30-hour data window were used, vertical station coordinates estimates may be displaced at the 1-cm level. Simply ignoring ocean tidal loading in the observable model is common practice at present, but it may not be an adequate approach if we hope to be able to detect changes in station coordinates at the few millimeter level. Non-tidal ocean loading may need special attention in some locations.

Atmospheric tidal loading:

Atmospheric pressure loading is another important effect, sometimes producing vertical variations at the few centimeter level at high latitudes. RMS variations are as high as 5 mm. Correlation between GPS vertical estimates and modeled displacements from atmospheric loading have recently been confirmed [Van Dam et al., 1994]. Fortunately, atmospheric pressure tends to slowly vary over the course of a day, and so to a good approximation, vertical station coordinate estimates can be corrected after the fact rather than at the observation level.

One complication with atmospheric pressure loading is the uncertainty in models of the inverted barometer effect. A pure inverted barometer response of the ocean will tend to reduce atmospheric loading effects by approximately 50% for coastal sites. Therefore, the extent of the inverted barometer response should really be understood at all near-coastal sites.

We recommend that attention be paid to the quality of pressure measurements which are used to compute atmospheric loading effects. Recent exploratory analyses have used gridded pressure data from the National Meteorological Center (NMC), which are output from atmospheric models, and can differ from in situ barometer measurements at the level of 10 mbars. We must ensure that attempts to correct for atmospheric pressure loading do not suffer from slowly varying biases in pressure data or due to changes in atmospheric models. Installing barometers at all GPS sites does not itself entirely solve the problem, because (i) loading cannot be computed as accurately if only pressure at the site is available, and (ii) we would have to take the additional step of ensuring that all barometers were not producing biased measurements, and that involves periodic calibration.

Precision and Accuracy

Position:

The long-term repeatability of daily determination of global station coordinates is currently at the 1 cm level (1 s.d.) for horizontal components, and 1-2 cm for vertical components. Intercomparisons of GPS, VLBI, and SLR coordinates show RMS differences at the same level. Over regional scales, relative positioning is currently at the 2-5 mm level for horizontal coordinates, and at the 1 cm level for vertical.

Velocity:

Global velocities based on approximately 1 year of continuous data agree with values from the ITRF (IERS Terrestrial Reference Frame) at the level of 5 mm/yr for horizontal components, and 7 mm/yr for vertical. However, we believe that this is currently limited by the relatively short time window (1 year), and that these numbers will improve in time. Over a period of 5-10 years we might expect 1 mm/yr accuracy for vertical rates.

Discussion and Conclusion

High-precision geodesy using GPS has changed so much since 1988 that its role in tide-guage benchmark fixing clearly needs to be redefined. There is now no compelling reason to limit the role of GPS to local or regional geodetic ties. A more reasonable approach would be to incorporate GPS data taken at the benchmarks into an analysis of the global IGS network. In this way, a set of coordinates and velocities could be derived for all GPS sites in a globally consistent framework.

The problem of tide-guage benchmark fixing should also not be narrowly viewed as simply obtaining a time-series of coordinates of tide-guage benchmarks. Other receivers well away from the tide guage can also provide valuable information. For example, the newly installed Fennoscandian regional network will provide valuable information on vertical motion due to post-glacial rebound. By refining post-glacial rebound models, we could then predict the vertical motion due to this effect at the tide-guage sites.

It is also recommended that continuous monitoring systems be installed wherever possible in order to provide more information on the various possible types of vertical signal that may be present, to provide a better assessment of error, and to improve the precision of the estimates. Of course, continuous GPS may not be feasible at many sites, either because of economical or logistical reasons. If epoch campaigns are used, then even more attention must be paid to effects such as ocean loading and atmospheric loading.

On the practical side, it would be natural to build onto the existing IGS infrastructure. This is not to say that the IGS necessarily has to take on the burden of the analysis of continuously operating tide-guage benchmark stations. Rather, IGS products can be used to produce a self-consistent set of motion estimates. For example, precise IGS orbits, and the data from nearby IGS reference stations can be used to estimate the position of the benchmark with respect to the IGS stations. IGS results of the motion of those reference stations (which become more refined as time goes on) can then be used to infer the motion of the benchmark itself. Since IGS uses the ITRF, the benchmark motion would also be expressed in that frame.

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SATELLITE LASER RANGING (SLR)

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The 1993 distribution of global Satellite Laser Ranging (SLR) sites is shown in **Figure 1.** Over 40 permanent stations tracked 10 operational satellites in 1993, and the number of laser-tracked satellites will rise to 13 in 1994 and 16 in 1995. Over the same two year period, several new permanent stations are expected to become operational at sites in China, Russia, South Africa, Italy, Chile, and Saudi Arabia.

Besides contributing over 100 sites (including mobile SLR sites) to the Terrestrial Reference Frame (TRF), SLR uniquely defines the TRF origin (i.e., the Earth center of mass). As can be seen from **Figure 2**, SLR determinations of the origin from LAGEOS tracking, relative to the global network of SLR stations, have been stable at roughly the one centimeter level, i.e. an order of magnitude more stable than similar estimates obtained from daily global GPS solutions. This is largely due to the compact "cannonball" nature of geodetic satellites and to the relative insensitivity (submillimeter) of SLR to highly variable atmospheric components, such as tropospheric water vapor and ionospheric electron density. Independent SLR, VLBI, and GPS determinations of station locations at collocated sites have generally shown an agreement at the one to two centimeter level following an appropriate seven parameter coordinate transformation (3 translational, 3 rotational, and 1 scale) [TBD]. The scale agrees at the one to two parts per billion level (corresponding to 6 to 12 mm in the vertical), a value consistent with residual atmospheric model uncertainties in each of the three techniques.

Many SLR and VLBI sites now host IGS GPS receivers, and this trend towards increased collocation is expected to continue over the next decade. SLR-derived site positions have a well-defined origin and are free from model errors associated with GPS orbits and clocks, Selective Availability (SA) and Anti-Spoofing (AS), tropospheric water vapor, and ionospheric effects. GPS, on the other hand, benefits from an excellent satellite geometry and a continually improving global network.

With the launch of two laser retroreflector-equipped GPS satellites, GPS-35 in August 1993 and GPS-36 in March 1994, the potential for synergistic SLR/GPS operations has been greatly enhanced. As illustrated in **Figure 3**, lasers have demonstrated single shot range precisions to GPS of about one centimeter (one sigma RMS about a typical short orbital arc of 40 minutes duration) with averaged data (5 minute normal points) fitting the short arc to better than 2 mm. As of this writing, 100 day GPS-35 arcs have been fit to the global laser data set with a weighted RMS of only

29 mm using the NASA-developed GEODYN orbital analysis program [Degnan and Pavlis, 1994]. Preliminary comparisons between one-day laser and one-day radiometric GPS-35 orbits, performed independently by the NASA Goddard Space Flight Center and the University of Texas Center for Space Research, show disagreement at roughly the 0.5 to 1.0 meter level. This suggests that SLR-constrained GPS orbits have the potential to unambiguously separate GPS ephemeris from clock errors and improve the accuracy of groundbased GPS measurements.

On a global scale, SLR has also been the primary precise orbit determination (POD) system for a series of civilian oceanographic satellites, beginning with the short-lived SEASAT satellite in 1979. SLR's insensitivity to atmospheric variables and centimeter absolute range accuracy also make it uniquely well-suited to the task of periodically calibrating the onboard microwave altimeters during direct overflights of the laser station. SLR's sensitivity to higher order components, and even temporal changes, in the Earth's gravity field provides a crucial data set for determining the medium to long wavelength components of the marine geoid to which the dynamic sea topography is referenced to produce altimetrically-derived mean sea level estimates and global circulation models. Furthermore, the totally passive, fail-safe, and inexpensive space segment of the SLR technique provides excellent insurance against catastrophic failures in altimetric missions which rely on precise but unproven radionavigation devices. As a concrete illustration, SLR is the only tracking system presently supporting the European ERS-1 ice and oceans mission following an unfortunate failure of the prototype German PRARE (Precise Range And Range-rate Equipment) radionavigation transceiver shortly after launch in 1991.

SLR is routinely producing 3 to 4 centimeter accuracy orbits (force model limited) as the primary POD system for the U.S./French TOPEX/Poseidon mission, launched on 10th of August 1992. Measurements of the TOPEX/Poseidon ephemeris by SLR have been used to calibrate and test the performance of two onboard radio-navigation devices, a flight GPS receiver built by JPL and the French DORIS (Doppler Orbitography and Radio positioning by Satellite) receiver. SLR is presently evaluating the performance of a flight PRARE transceiver onboard the Russian METEOR 3 satellite in the presence of a limited regional PRARE network in Europe, ERS-2, scheduled for launch in January 1995. This satellite will again carry a small laser retroreflector array in addition to the PRARE transceiver and will be supported by global networks of SLR stations and PRARE transceivers.

In summary, while GPS is clearly the technique of choice for precisely locating a dense network of tide gauges, SLR can play a major supporting role in determining mean sea level, dynamic ocean topography, and global ocean circulation by:

1.) Providing unique determination of the TRF origin (Earth center-of-mass) which are stable at the one centimeter level.

2.) Contributing over 40 continuously operating collocated SLR/GPS intercomparison sites globally which are free from GPS orbit, clock, ionospheric, and wet tropospheric errors.

3.) Tracking special retroreflector-equipped GPS satellites so that radiometrically-derived GPS precise orbits can be: directly referenced to the highly stable SLR reference frame; independently checked and even improved; used to unambiguously determine onboard clock errors; and used to ferret out residual errors in tropospheric and GPS satellite force models.

4.) Supporting global oceanographic and ice missions and models through precise orbit determination and independent optical calibration of microwave and laser altimeters (ERS-1, ERS-2, TOPEX/Poseidon, etc.)

5.) Further refining the spatial resolution of global Gravity field and marine geoid through the tracking of new low altitude satellites such as MSTI-2 (U.S., 1994, 425 Km) and GFZ-1 (Germany, 1995, 350 Km).

6.) Monitoring mass movements in the atmosphere and ocean through temporal changes in the gravity field (in addition to Earth Orientation Parameters).

7.) Providing calibration and test support to a new generation of satellite radionavigation devices (e.g. GPS, DORIS, PRARE) important to present future oceanographic and ice missions.

1993 SLR OCCUPATIONS

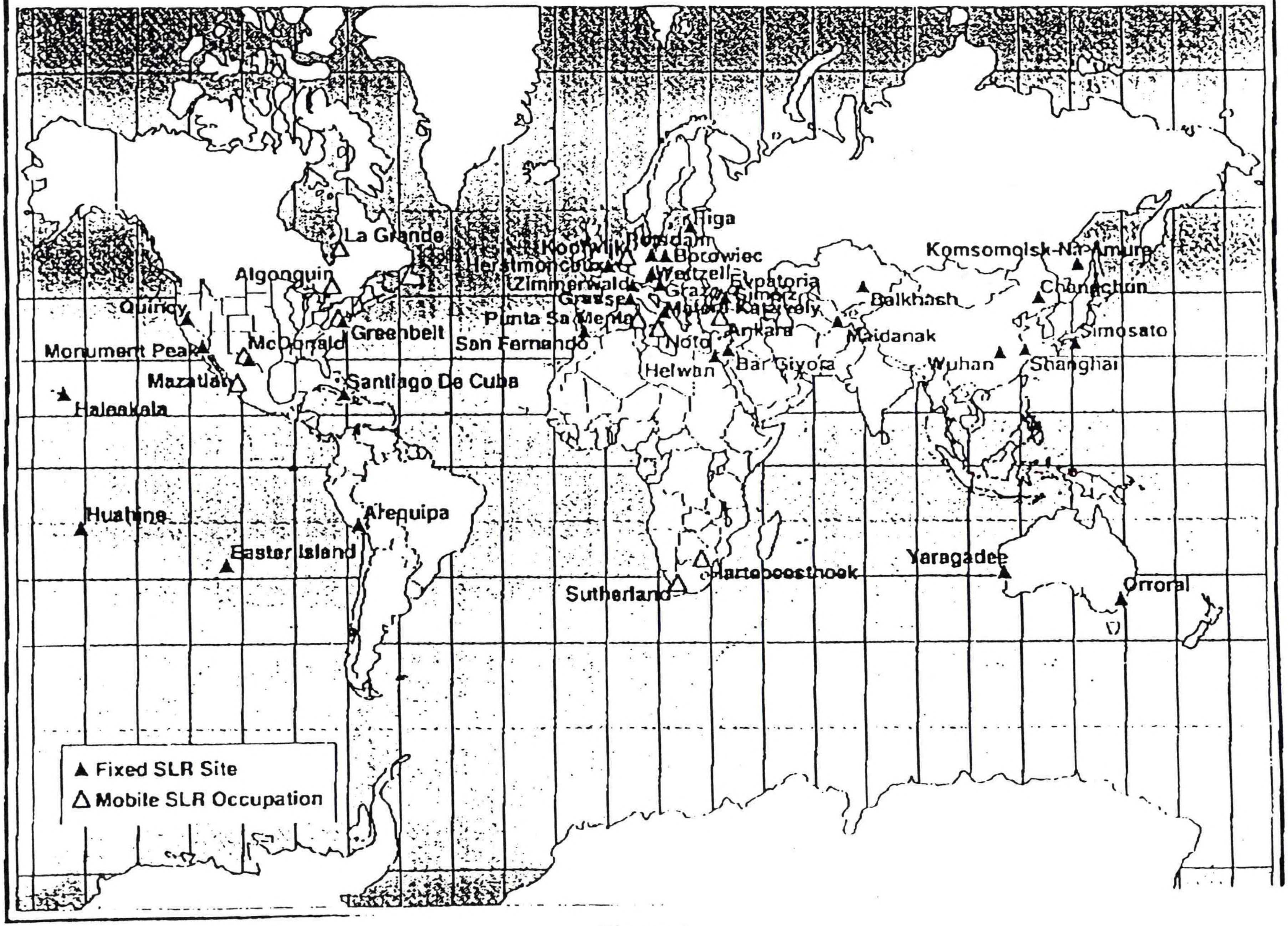

Figure 1

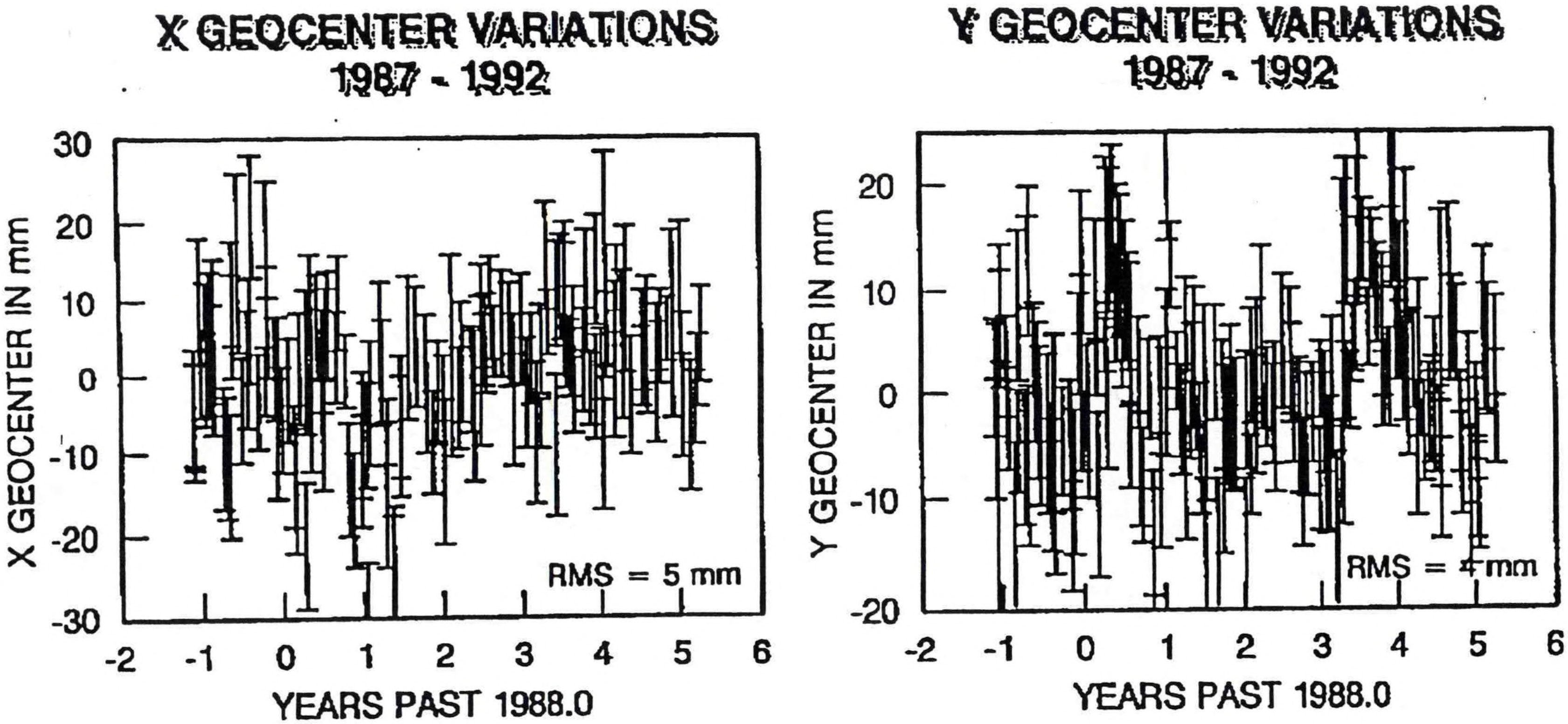
X GEOCENTER VARIATIONS
1987 - 1992
X GEOCENTER IN mm
30
20
10
0
-10
-20
-30
-2
-1
0
1
2
3
4
5
6
YEARS PAST 1988.0
RMS = 5 mm
Y GEOCENTER VARIATIONS
1987 - 1992
Y GEOCENTER IN mm
20
10
0
-10
-20
-2
-1
0
1
2
3
4
5
6
YEARS PAST 1988.0
RMS = 4 mm

Figure 2

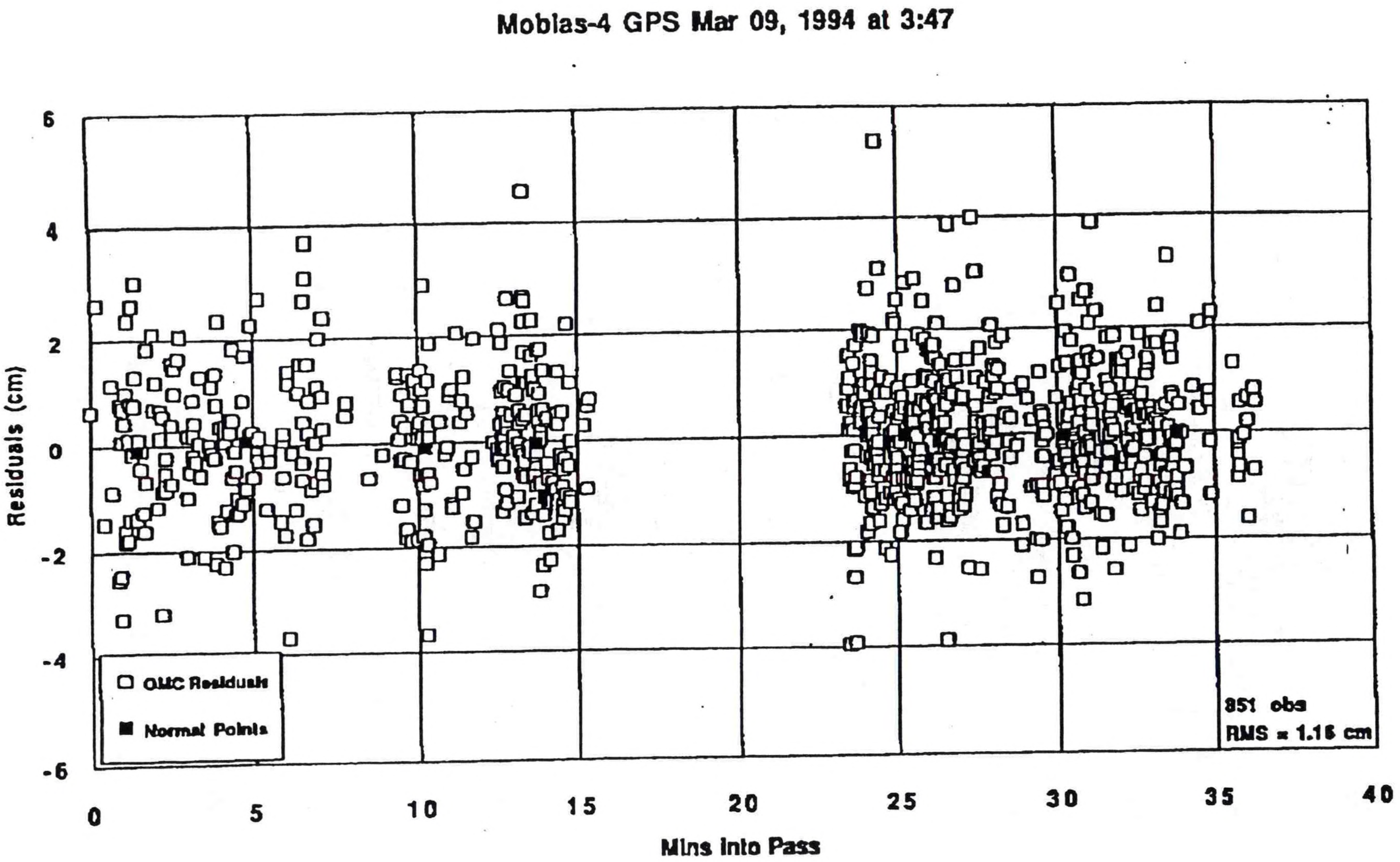
Moblas-4 GPS Mar 09, 1994 at 3:47
Residuals (cm)
6
4
2
0
-2
-4
-6
0
5
10
15
20
25
30
35
40
Mins Into Pass
OMC Residuals
Normal Points
851 obs
RMS = 1.16 cm

Figure 3

ABSOLUTE GRAVITY: APPLICATION TO GLOBAL SEA LEVEL STUDIES

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Preamble

At the meeting of the ad hoc geodetic committee of IAPSO at Woods Hole Oceanographic Institute in November 1988 the following technical conclusion was reached by the committee: "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 microgal per year (equivalent to vertical crustal motion of 0.3 to 1 cm per year)". This brief report examines 1) how close are we to achieving the technical capabilities expressed in the 1988 conclusions? 2) are the 1988 objectives still valid? 3) what steps need to be taken to achieve the required capabilities? 4) what is the role of absolute gravity in the measurement of global sea level? It is not meant to be an exhaustive review of the subject of absolute gravity but rather tries to identify the important issues using mainly North American examples to provide a starting point for discussions at the present ad-hoc geodetic committee workshop.

Instrumentation

The absolute gravimeter measures the acceleration of a mass (corner cube) in free fall (or rise and fall) in a vacuum using a laser wavelength standard (HeNe polarization stabilized or Iodine stabilized) and an atomic (Rubidium) frequency standard. A gravity value is obtained by making on the order of one thousand drops over the period of the order of one day. The design in most widespread use today (Faller et al., 1983) compares the acceleration of the falling mass in a Michelson interferometer to the acceleration of a reference corner cube isolated from accelerations of the floor. A number of these instruments were built by the Joint Institute of Laboratory Astrophysics (JILA), Boulder, Colorado. These instruments, including electronics, originally weighed about 700 kg and could be transported between stations in six boxes. Miniaturization of electronic components can reduce this to 550 kg (J. Liard, pers. comm.). This instrument is rather cumbersome to use in the field. Nevertheless, it has been used successfully at outdoor, remote sites in Canada. A new improved version of this design (FG5) went into production by the AXIS Instrument Company, Boulder, Colorado. Improvements include a vertical in-line interferometric measurement system which eliminates tilt effects due to floor recoil, a temperature compensated super spring, a reduced number of components in the vacuum chamber giving improved vacuum characteristics, better control of cart positioning which reduces the uncertainty of the start position of the drop, general ruggedization and an integrated iodine-stabilized laser. This instrument is roughly the same size and weight as the JILA instrument. Other designs (e.g., Marson and Faller, 1986; Kuroishi et al., 1992; Hanada et al., 1987; Arnautov et al., 1983) are in regular use or are planned (Cerutti et al., 1992; Zumberge et al., 1993).

Typically the standard error of a series of drops over a period of a day for the JILA instruments is at the sub-microgal level. However, the scatter in results over time at a site is normally around 2-3 microgal or three or four times larger (e.g., Peter et al., 1992; Lambert et al., in press). The main contributors to the scatter are thought to be small differences in vacuum conditions, unmodelled errors in the laser wavelength and frequency standards, changes in the phase response of electronic components, recoil effects at some sites (Klopping and Peter, 1990) and unmodelled environmental effects. Recently, intercomparisons among several FG5 instruments and a JILA instrument demonstrated agreement at the 1-2 microgal level where environmental effects were taken into account (Klopping, pers. comm.). Thus, an instrument precision of better than 2 microgal appears to be achievable which makes the detection of gravity changes at the 1 to 3 microgal per year level relatively easy (technical objectives set in 1988). This is encouraging for geodynamic applications, including the correction of sea level gauges. This high precision is only useful, however, if systematic errors can be controlled or determined independently.

A recent international intercomparison of 9 absolute gravimeters (Boulanger et al., 1991) showed that, in general, systematic errors in a selection of instruments, including the JILA instrument, were around 7 microgal. This is in agreement with theoretical claims of 6-10 microgal for the accuracy of the JILA absolute gravimeter based on studies of known error sources which gave a total uncertainty of about 4 microgal (e.g., Faller et al., 1983). Thus, systematic errors of the order of 6-10 microgal can be present even though repeatabilities of 2-3 microgal are achieved. Unfortunately, systematic errors are subject to change when conditions in the dropping chamber are modified or components of the system are replaced with components of slightly different specifications either as a result of failure or simply to upgrade to a better component. Experience in the Canadian absolute gravity program with JILA-2 has shown that offsets have occurred probably as a result of maintenance work over the 6 years of operation. Two offsets of 13.7 and -8.7 microgal and duration one year and three months, respectively, were identified by carrying out an analysis on 350 measurements from all over Canada. Larger-than-expected errors in the Rubidium frequency standard were also discovered through calibrations at the National Research Council. The lesson to be learned is that more emphasis needs to be put on the detection and measurement of changes in systematic error at the 1-2 microgal level.

The detection and measurement of changes in systematic error can be achieved by 1) frequent measurements at a base station which is monitored by a superconducting gravimeter, 2) frequent intercomparisons with other absolute gravimeters, and 3) in-situ verification of the correct operation of the electronics from the optical sensor onward and in-situ calibration of the wavelength and frequency standards. The availability of GPS-disciplined frequency standards, Iodine-stabilized laser wavelength standards and optical calibration devices should ensure that these errors will be controlled sufficiently in the future. According to AXIS Instrument's specifications, the new FG5 instrument should be free of systematic errors above 2 microgal. Thus, an absolute gravity accuracy of 2 microgal or control of systematic errors at that level will probably be achieved in the very near future.

Environmental Corrections

Unlike relative gravity measurements absolute gravity measurements come under the full influence of polar motion, atmospheric mass movements and tides. These effects must be largely removed in order to allow accurate measurement of long-term trends in gravity for crustal movement studies. Polar motion effects of up to 13 microgal are successfully removed using an expression (Wahr, 1985) involving pole position data available from the International Earth Rotation Service. Atmospheric effects are usually removed to first order by a linear function of the observed atmospheric pressure at the station. For periods of less than one day, however, errors of the order of 30% (1-5 microgal) are possible with this simplified approach and more sophisticated correction methods must be used (Rabbel and Zschau, 1985; Merriam, 1993). Due to modified crustal loading effects, 2 microgal gravity anomalies are also possible at a land-ocean interface (VanDam and Wahr, 1987). This would be particularly important when monitoring gravity near sea-level gauges. Another effect that is important near the shoreline is the ocean tide effect. Gravity variations as large as 10 microgal in amplitude can arise close to the shoreline. Fortunately, numerical representations of the global ocean tides (Schwiderski, 1980; Le Provost et al., 1994) are available and numerical representations of the coastal tides (e.g., Baker, 1991; Lambert, 1991) are available in many places or can be developed, if needed.

Local groundwater effects on gravity are probably the most difficult to model. The effects can be minimized by establishing absolute gravity stations on crystalline bedrock wherever possible. However, even on bedrock, significant water table effects can exist, depending on the topography. Gravity variations recorded using superconducting gravimeter GWR-12 at the Canadian Absolute Gravity Site, Gatineau, Quebec correlate with water level variations in a shallow well (10 cm = 1 microgal; D.R. Bower, pers. comm.). Some effort should go into designing gravity monuments for use in non-bedrock areas which allow for estimation of ground moisture variations.

ROLE OF ABSOLUTE GRAVITY

Two thirds of the long (> 60 years) tide gauge records considered by Douglas (1991) in a recent calculation of the rate of global sea level rise were rejected by him on the grounds that they were contaminated by tectonic effects. The importance of correcting estimates of the global rise in mean sea level for vertical crustal movements using space positioning and absolute gravity techniques has been clearly identified (e.g., Diamante et al., 1987; Baker, 1993). Observations of surface displacements and surface gravity change, in general, bear a different relationship to the subsurface displacement field. Thus, gravity provides an extra constraint on subsurface deformation. The difference in sensitivity to the subsurface deformation is expressed in terms of the deformation gravity gradient, dg/dz. Theoretical calculations (e.g., Rundle, 1978) show that the deformation gravity gradient takes on particular values depending on the deformation process. According to theory the deformation gravity gradient should lie between fairly narrow limits for postglacial rebound (-0.15 to -0.20 microgal/mm) and thrust faulting (-0.18 to -0.25 microgal/mm) which affect a large number of sea-level gauges. Recent observations from Fennoscandia, however, give a somewhat higher than expected value of -0.24 + 0.03 microgal/mm for the deformation gravity gradient associated with postglacial rebound (Ekman and Makinen, 1990). More local processes related to the opening and closing of cracks, pores or cavities with or without the involvement of fluids can result in a wide range of deformation gravity gradients.

Absolute gravity measurements can assist the determination of global sea level change in two ways: 1) to verify vertical land velocities at sea-level gauges determined by space geodetic techniques (GPS, VLBI, SLR), and 2) to contribute to the verification of crustal deformation models at inland sites. Space geodetic techniques could be affected by systematic propagation errors, particularly tropospheric effects that are most important in measurements of station height. In addition, vertical land movements at sea-level gauge sites could be the result of a composite of processes having different time scales, some natural and some caused by human activity. Agreement between geometric and gravity techniques over the long term (> 20 years) would provide some confidence that no shorter term processes are contaminating the gauge movements and that there are no unexpected systematic errors in either technique. Absolute gravity observations (e.g., Tushingham et al., 1991) can play a key role in constraining postglacial rebound models (e.g., Tushingham and Peltier, 1991), widely used in the correction of sea-level rates, and in constraining subduction models in many parts of the world where a large number of GLOSS sea-level gauges are located.

The modelling of the Cascadia subduction zone on the west coast of North America (Dragert et al., in press) is an example of how high-precision gravity measurements can help to verify a particular subduction model. Three different versions of the subduction model were considered each having a different down-dip length of "locked" zone. Comparisons between theoretically predicted vertical velocity and levelling results along three profiles definitely favours a "locked" zone 60 km in length. Sea-level gauge trends, however, appear not to show the same agreement even though 1) the sea-level records have been carefully differenced to remove the effects of inter-annual variations, 2) a global trend of 1.8 mm/yr has been removed, and 3) corrections for postglacial rebound were made using ICE-3G. Fortunately, high-precision differential gravity observations were made between 1986 and 1990 normal to the subduction zone. These data, though preliminary (the time span is short), tend to support the 60 km "locked" zone when a 2 microgal/cm deformation gravity gradient is assumed. This demonstrates the utility of having an independent technique such as gravity available. It is important to establish the correct deformation model, particularly where the coastline coincides with the steep part of the vertical velocity curve. A rapid change of vertical velocity over a short distance makes comparisons difficult between sea level gauges only a few tens of kilometers apart. Profiles of absolute gravity and vertical movement measurements need to be established across several subduction zones to determine whether gravity change and vertical movement follow a consistent relationship. This would greatly facilitate the determination of absolute sea-level change in many tectonically active areas.

In order to fulfill the role of absolute gravity in the determination of global sea level as described above, we must be able to measure secular gravity changes at the tenth of a microgal per year level. **Figure 1** shows how long we must carry out regular absolute gravity (station height) measurements to resolve different rates of change of gravity (vertical velocity) assuming a measurement accuracy of 2 microgal (1 cm) and normally distributed errors. A deformation gravity (vertical velocity) assuming a measurement accuracy of 2 microgal (1 cm) and normally distributed errors. A deformation gravity gradient of 0.2 microgal/mm has been assumed in relating the gravity change to the vertical movement. Curves are plotted for a frequency of one measurement per year, two measurements per year and twelve measurements per year. From the figure we see that the time needed to measure the gravity change rate with a precision of 0.2 microgal/yr (1mm/yr) by annual measurements is 10 years. A precision of 0.02 microgal/yr (0.1mm/yr) could be achieved by monthly measurements in 20 years and by annual measurements in 50 years. At the measurement accuracies assumed, decadal land movements at the 0.2 microgal (1mm/yr) level could only be detected by monthly or continuous measurements. (Note added: Requirements for global sea level studies in terms of vertical land velocities and measurement time intervals were determined at the present meeting and are given elsewhere in this report).

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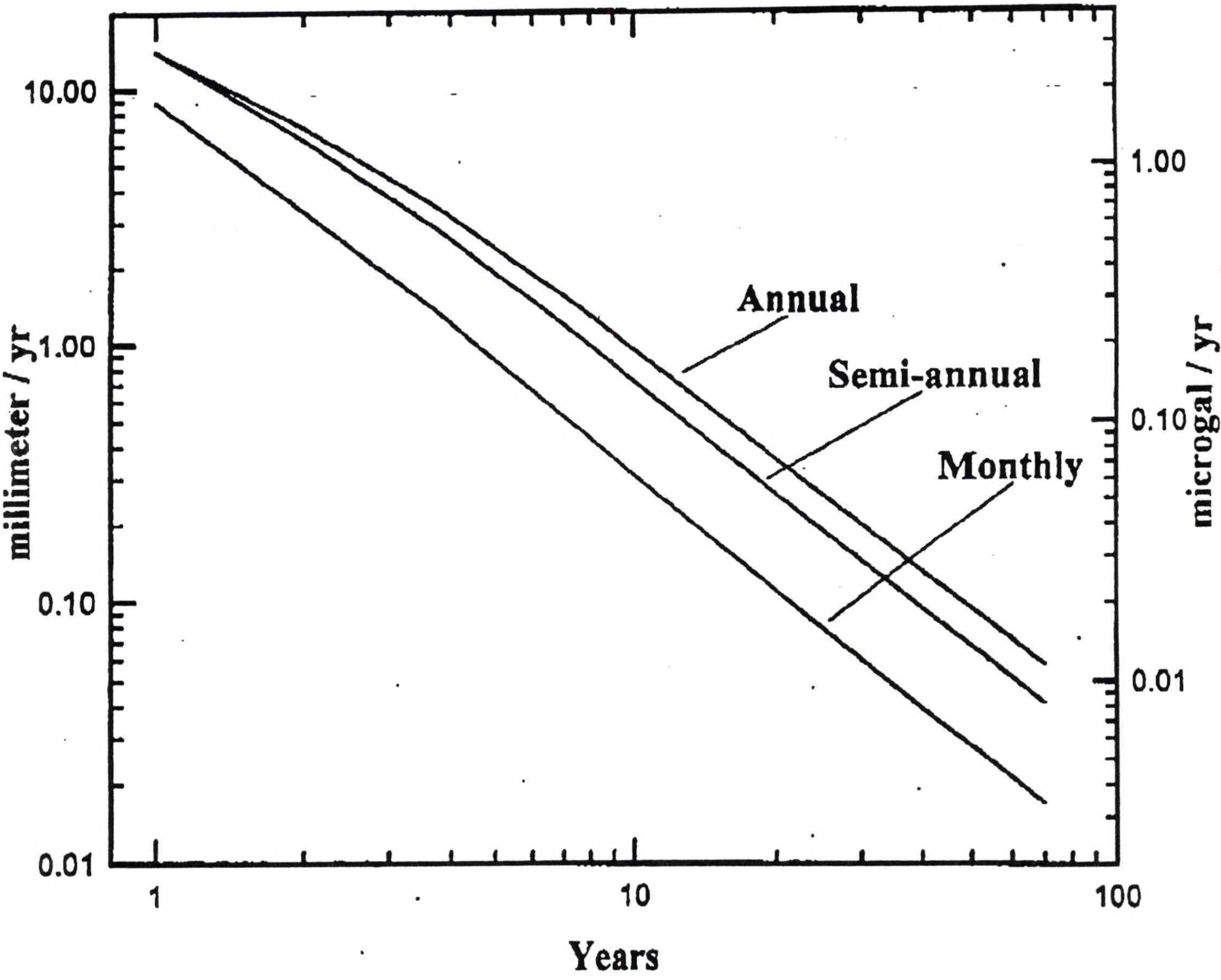
Figure 1. Precision of vertical velocity and gravity change rate as a function of the duration of the observations. Results are given for annual, semi-annual and monthly observations of gravity and height. A measurement accuracy of 2 microgal or 10 mm is assumed.



GLOBAL NETWORKS

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Introduction

For the past twenty years, NASA, through its Goddard Space Flight Center (GSFC) in Maryland and the Jet Propulsion Laboratory in California, has led a global team of U. S. and foreign agencies and institutions in the development and use of Space Geodesy for monitoring the motion and deformation of the solid Earth.

Modern NASA Space Geodesy used three techniques to make highly accurate measurements. The first technique uses laser range to satellites equipped with corner cube retroreflectors. This Satellite Laser Ranging (SLR) technique provides information on station position in geocentric coordinates to subcentimeter accuracies and allows determination of the orbits of Earth satellites to accuracies of a few centimeters. This capability is particularly useful for satellites carrying spaceborne altimeters and radars. A second technique, Very Long Baseline Interferometry (VLBI), uses the accurately-timed reception at multiple observatories of microwave transmissions from astronomical sources to determine baseline lengths and Earth rotational parameters. SLR and VLBI use both fixed and mobile stations. The third technique, use of the Global Positioning System (GPS) satellite transmissions, is, because of mobility and low costs, rapidly becoming the technique of choice for most applications. With the completion of the U. S. Department of Defense's 24-satellite GPS constellation, four or more satellites are visible at any time at any point on the Earth.

Typically, the accuracy of these systems has improved by an order of magnitude for each decade of a system's existence. Thus, while SLR and VLBI allow determinations of vertical position to several millimeters, GPS determination of vertical is currently less accurate. A rigorous program of intercomparison of system performance through collocation of systems is used to identify and correct system biases. This process, combined with hardware and software improvements, is continuing, and the goal of millimeter accuracies should be achievable for most network stations within the next few years.

Today, there exists active global networks of SLR, VLBI, and GPS stations which can begin to provide a geodetic reference system for Mean Sea Level and Post-Glacial Rebound research. Other global networks, some in existence for many decades, support measurement of gravity (gravimeters and gradiometers), the Earth's magnetic field (magnetometers), and seismic motion (seismometers). These networks offer an infrastructure which can be used to support geodetic instrumentation.

The sites within these networks are predominantly located in the interior of continents, while tide gauges for Mean Sea Level measurements are necessarily in coastal areas or at island locations. The problem of maintaining geodetic control of tide gauges at millimeter precision is resolvable if the accuracy of the global networks can be transferred, regardless of distance, to the gauge locations.

In this paper, these global networks are reviewed and the spatial location of a set of tide gauges to fixed geodetic reference stations is examined.

Space Geodesy Networks

The SLR, VLBI, and GPS stations provide data on a regular basis to the International Earth Rotation Service (IERS) which also maintains the International Terrestrial Reference Frame (ITRF). Almost all of the sites within the networks are owned and operated by the individual countries: there is a loose relationship between site organizations but no single manager or operator. International scientific organizations, primarily Commissions of the IUGG and IAG, provide guidance and, in some cases, standards for operations and data archival. Since funding availability for station hardware and operations is often a problem, the quality of the network data can vary considerably.

Figures 1, 2, and **3** show the current locations of the SLR, VLBI, and GPS sites, respectively. The majority of these sites are located at mid latitudes. The VLBI Network in North America includes 10 stations which comprise the NRAO VERY Long Baseline Array (VLBA), an astronomical observation system. The SLR Network includes fixed stations and a mobile station which moves between Huahine and Easter Island in the Pacific. Most of the GPS receivers of the International GPS Geodynamics Service (IGS) Network are located at VLBI and SLR sites. A proposed U. S. Coast Guard Differential GPS Network (**Figure 4**) will greatly increase coverage of the east and west coasts of the United States and up to and including Alaska.

Table 1 lists all of the sites within the Space Geodesy networks along with the data quantities for 1993. This data is archived at the Crustal Dynamics Data Information System (CDDIS) at GSFC and are retrievable through E-mail and other means. Data from the sites are forwarded (**Figure 5**) to central processing facilities and from there to the CDDIS for archiving. Data from most sites are available in a few days: for other sites data availability can be a matter of weeks or months.

Geophysical Networks

The Global Seismograph (**Figure 6**) is the most expansive of all networks, and includes many islands. The Intermagnet Network (**Figure 7**) is actually a subset of the global Geomagnetic Network of stations. The Superconducting Gravimeter Network (**Figure 8**) is relatively new and is mostly concentrated in Europe. This Network is of particular interest since it can provide information on Post-Glacial Rebound.

Geodetic Monitoring Of Tide Gauges

For the purposes of this study, the Tidal Gauge Network chosen was the Revised Local Reference (RLR) sites provided by the Proudman Laboratory. The location of these gauges are shown in **Figure 9**. Those sites with 50 years or more of data are indicated in the figure.

It has been assumed that the geodetic control accuracies needed for tide gauges involved in Mean Sea Level research can be specified as determination of the vertical position to at least a few millimeters and determination of vertical rates to 1-2 millimeters per year. Currently, the state-of-the-art for the transfer of geodetic control at the few millimeter-level using reference stations and GPS receivers collocated at or very near tide gauges is probably limited to distances of a few hundred kilometers. Some of the error sources are inaccuracies in the determination of the GPS satellite orbits and ionospheric effects.

To assess the magnitude of the geodetic control problem, the RLR tide gauges have been classified according to distance from a reference station (either a SLR or a VLBI station or a fixed GPS site). Five categories have been selected:

1. 0 Km to <= 200 Km
2. 200 Km to <= 500 Km
3. 500 Km to <=1000 Km
4. 1000 Km to <=2000 Km
5. > 2000 Km

While a detailed study has not been done, it is likely based on experience that accuracies of a few millimeters are realizable for Category 1. For Category 2 this would probably increase to 3-5 millimeters. For distances between 500 and 1000 Km (Category 3), the accuracy would probably still be subcentimeter. However, beyond 1000 Km centimeter-level accuracies can be anticipated.

Figure 10 shows that most of the RLR gauges located near coast lines or on nearby islands fall into Categories 1, 2, or 3. Locations in the western and southern parts of the Pacific are generally Category 4 or 5. Since it is assumed that RLR gauges with 50 years or more of data are more valuable, a separate analysis of these sites is shown in **Figure 11**. Quantitatively, the distribution of gauges according to this criteria is summarized in Table 2. More than half of the RLR gauges and almost three-quarters of the "50 year" sites are within 500 Km of a fixed geodetic station.

To examine the distribution more closely, six geographic regions have been selected: North America (**Figure 12**); South America (**Figure 13**); Europe (**Figure 14**); Japan (**Figure 15**); Australia (**Figure 16**); and the Pacific Basin (**Figure 17**). Some of the Alaskan, West Coast, Gulf, and Central American sites are Category 3 or greater. This situation should improve (except for Central America) when the proposed U. S. Coast Guard Differential GPS Network (**Figure 4**) is implemented. However, the addition of several planned GPS sites in South America does little to improve the coverage (**Figure 18**). The Pacific Basin is most troubling. Establishment of reference stations in this region by the deployment of mobile SLR or VLBI stations is unlikely because of the costs. An array of a dozen or so fixed, and perhaps unattended, GPS receivers tied to the global networks could eventually provide the needed control.

Conclusions and Recommendations

1. The geodetic reference networks are a resource for Mean Sea level research: they can be used to provide improved geodetic control for many tide gauge locations; for determining accurate obits of space-borne satellite altimeters and radars; and for support of measurements of Post-Glacial Rebound.

2. Only a limited number of the tide gauges in the RLR Network are within 200 Km of reference station and thus most likely to benefit now from the improved geodetic control achievable by using high accuracy reference stations. However, half of the RLR sites and some three-quarters of these gauges, which have a date record of fifty years or longer, are within 500 Km of a reference station. It is this set of gauges which will benefit as the accuracy of the reference stations is improved.

3. For tide gauges more than 500 Km from a reference station further action is needed. This could be in the form of visits by mobile SLR and VLBI facilities to establish geodetic control points or the installation of permanent GPS receivers. A prioritization of the more important tide gauges is needed to justify the expenditures of resources for this purpose.

4. The Mean Sea Level research community should make its needs for improved geodetic control known as a means of encouraging site owners to accelerate the upgrade of their stations.

5. As system accuracies approach, the millimeter-level intercomparison of systems becomes increasingly important both for validation of techniques and for identification of system biases.

6. Consolidation of activities at fixed sites, and the use of the existing infrastructure of other discipline networks will benefit Mean Sea Level research by concentrating funds and efforts.

Table 1.
Fixed SLR, VLBI, and GPS Site Locations

Site Name	Country	East Longitude	North Latitude	Data Quantities*		
				SLR	VLBI	GPS
Albert Head	Canada	-123.48	48.38			334
Algonquin	Canada	-78.07	45.95		27	334
Arequipa	Peru	-71.63	-16.47	1,290		
Balkhash	Russia	74.57	46.50	179		
Bar Giyyora	Israel	35.08	31.72	347		
Bermuda	United Kingdom	-64.65	32.35			103
Borowiec	Poland	17.08	52.28	303		
Brewster, WA	USA	-119.68	48.13		7	
Changchun	Peoples Republic of China	125.33	43.83	371		
Easter Island	Chile	-109.38	-27.15	66		0
Effelsberg	Germany	6.88	50.52		1	
Evpatoria	Ukraine	33.20	45.12	0		
Fairbanks, AK	USA	-147.48	64.97		141	318
Fort Davis, TX	USA	-103.95	30.63		27	
Fortaleza	Brazil	-38.58	-3.75		43	129
Goldstone, CA	USA	-116.78	35.25		2	333
Grasse	France	6.92	43.75	771		
Graz	Austria	15.50	47.07	1,071		334
Green Bank, WV	USA	-79.83	38.43		108	
Greenbelt, MD	USA	-76.83	39.02	1,423	10	224
Haleakala, HI	USA	-156.27	20.72	1,641		
Hancock, NH	USA	-71.98	42.93		4	
Hartebeesthoek	South Africa	27.70	-25.88		41	333
Harvest Platform, CA	USA	-120.68	34.47			328
Helwan	Egypt	31.35	29.87	495		
Herstmonceux	Great Britain	0.33	50.87	2,000		280
Hobart	Tasmania	147.43	-42.80		38	300
Huahine	French Polynesia	-151.03	-16.73	99		
Jozefoslaw	Poland	21.50	51.03			119
Kashima	Japan	140.67	35.95		23	
Katzively	Ukraine	33.97	44.38	29		
Kiruna	Sweden	20.15	67.53			146
Kitt Peak, AZ	USA	-111.62	31.97		2	
Kokee Park, HI	USA	-159.67	22.13		117	322
Komsomolsk-Na-Amure	Russia		50.87	142		
Kootwijk	The Netherlands	5.82	52.18			329
Kourou	French Guiana	-52.62	5.13			328
Lake Mathews, CA	USA	-117.44	33.86			185
Los Alamos, AZ	USA	-106.25	35.78		18	
Madrid	Spain	-4.25	40.43		6	333
Maidanak	Uzbekistan	66.93	38.68	305		
Maspalomas	Canary Islands	-15.63	27.77			334
Matera	Italy	16.70	40.65	685	33	309
Mauna Kea, HI	USA	-155.47	19.80		2	
McDonald, TX	USA	-104.02	30.68	1,231		157
McMurdo	Antarctica	166.67	-77.85			307
Medicina	Italy	11.65	44.52		6	
Metsahovi	Finland	24.40	60.22	0		323

Table 1. (Continued)
Fixed SLR, VLBI, and GPS Site Locations

Site Name	Country	East Longitude	North Latitude	Data Quantities*		
				SLR	VLBI	GPS
Mizusawa	Japan	141.20	39.10		√	
Monument Peak	USA	-116.42	32.88	2,557		
North Liberty, IA	USA	-91.57	41.77		12	263
Noto	Italy	14.98	36.88		4	
Ny Alesund	Norway	11.87	78.93		0	270
O'Higgins	Antarctica	-59.90	-63.32		10	
Onsala	Sweden	11.93	57.40		25	332
Orroral	Australia	148.93	-35.63	1,456		
Owens Valley, CA	USA	-118.30	37.23		0	
Palos Verdes, CA	USA	-118.40	33.75			182
Pamate	French Polynesia	-149.57	-17.57			304
Pasadena, CA	USA	-118.17	34.20			326
Penticton	Canada	-119.62	49.32			332
Perth	Australia	115.82	-31.97			94
Pie Town, NM	USA	-108.12	34.30		3	309
Pinyon Flat, CA	USA	-116.45	33.62			298
Potsdam	Germany	13.07	52.38	404		
Quincy, CA	USA	-120.93	39.97	1,556		303
Richmond, FL	USA	-80.38	25.62		0	256
Riga	Latvia	24.13	56.88	450		
Saint John's	Canada	-52.68	47.60			334
San Fernando	Spain	-6.20	36.47	232		
Santiago	Chile	-70.67	-33.15		31	324
Santiago De Cuba	Cuba	-75.82	20.00	114		
Scripps, CA	USA	-117.25	32.87			291
Shanghai	Peoples Republic of China	121.43	31.18	263	4	
Simeiz	Ukraine	33.59	44.26	144	0	
Simosato	Japan	135.93	33.57	425		
St. Croix	Virgin Islands	-64.58	17.75		2	
Taiwan	China	121.53	25.02			324
Tidbinbilla	Australia	148.98	-35.40		7	331
Tokyo	Japan	139.48	35.70	0		
Tromso	Norway	18.93	69.67			326
Trysil	Norway	12.38	61.42		3	
Tsukuba	Japan	140.08	36.10			287
Urumqi	Peoples Republic of China	87.63	48.72		0	
Usuda	Japan	138.37	36.13			287
Vandenberg, CA	USA	-120.50	34.57			269
Westford, MA	USA	-71.48	42.62		54	263
Wettzell	Germany	12.88	49.15	1,758	100	321
Wuhan	Peoples Republic of China	114.32	30.58	95		
Yaragadee	Australia	115.35	-29.05	2,824		306
Yellowknife	Canada	-114.48	62.48		5	334
Zimmerwald	Switzerland	7.47	46.88	793		330
Totals (Data):				25,519	916	14,138
Totals (Stations):	92 fixed sites:			37	40	52

*Notes:

SLR figures reflect total passes tracked for 1993 (through Nov. 24, 1993)
VLBI figures represent total station days planned for 1993
GPS figures represent total station days for 1993 (projected through Nov. 30, 1993)

Table 2.
Number of Revised Local Reference (RLR) Sites in Each Distance Category

						All Sites	50 year Sites
1.	0 km	<	Tide Gauge	<=	200 km	219	59
2.	200 km	<	Tide Gauge	<=	500 km	259	62
3.	500 km	<	Tide Gauge	<=	1000 km	196	18
4.	1000 km	<	Tide Gauge	<=	2000 km	126	10
5.	2000 km	<	Tide Gauge			106	16
						906	165

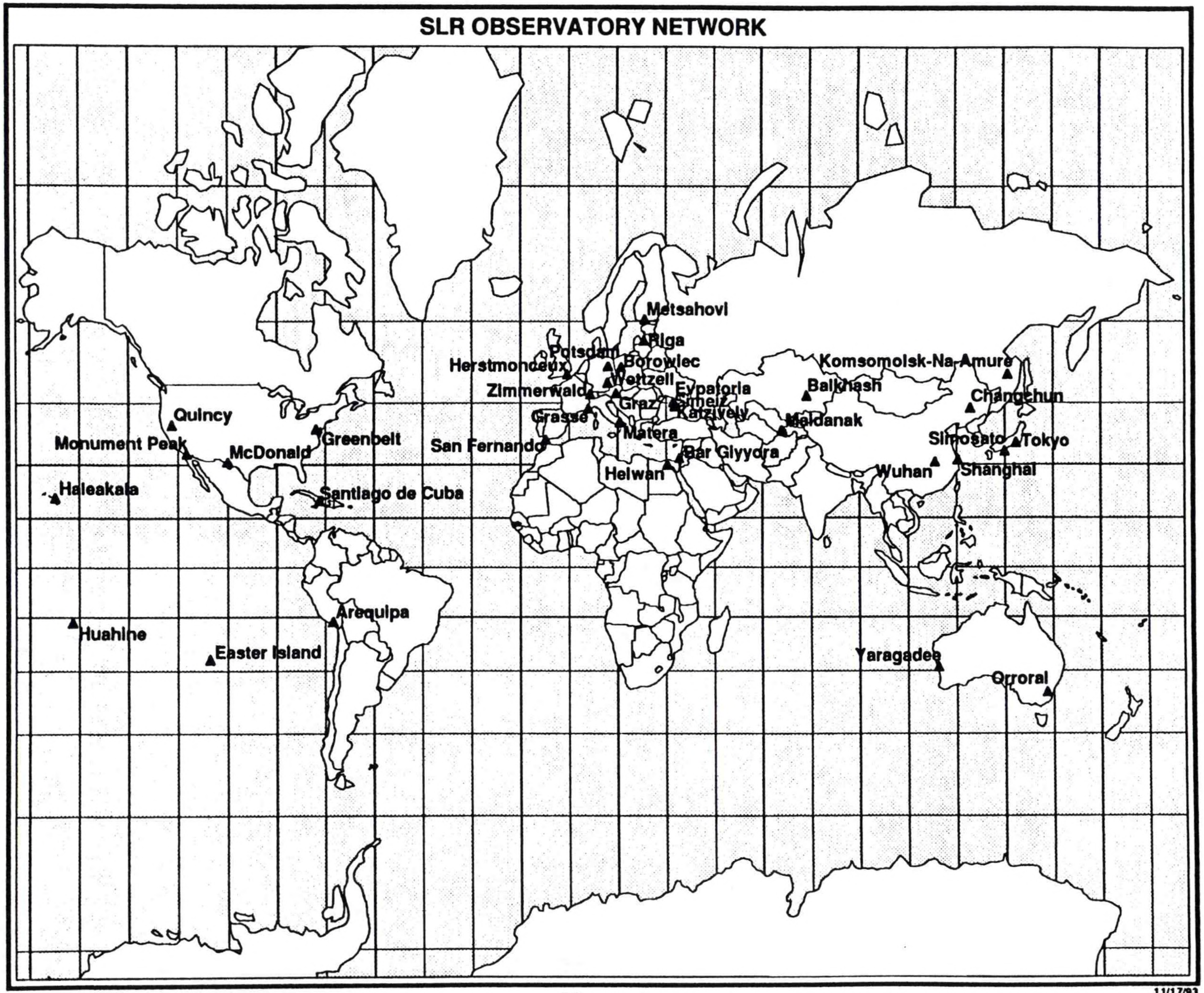

SLR OBSERVATORY NETWORK
Metsahovi
Riga
Potsdam
Borowiec
Herstmonceux
Wettzell
Zimmerwald
Graz
Evpatoria
Simeiz
Katzively
Grasse
Matera
San Fernando
Bar Giyyora
Helwan
Komsomolsk-Na-Amure
Balkhash
Changchun
Maidanak
Simosato
Tokyo
Wuhan
Shanghai
Yaragadee
Orroral
Quincy
Monument Peak
McDonald
Greenbelt
Haleakala
Santiago de Cuba
Arequipa
Huahine
Easter Island
11/17/93

Figure 1

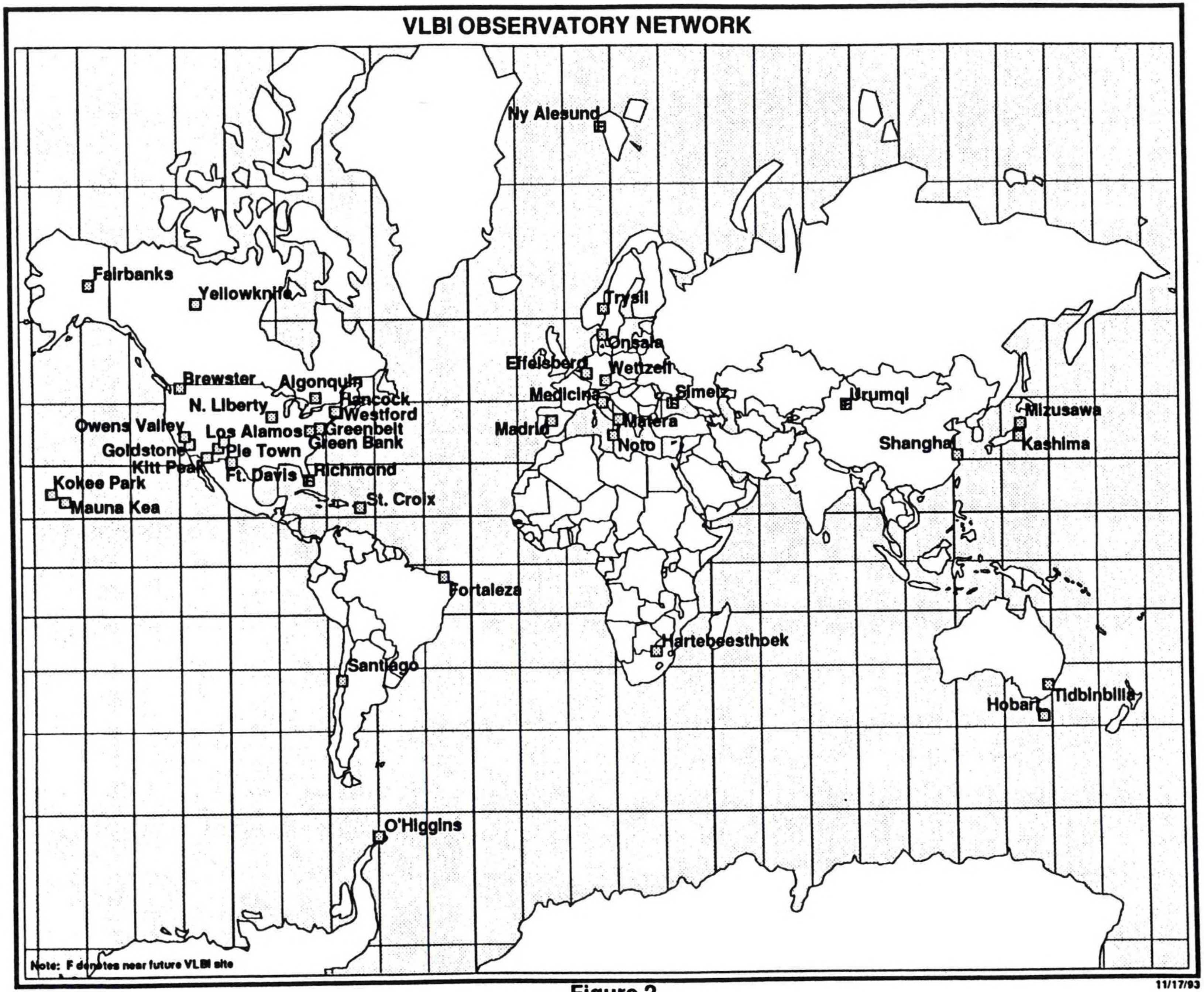
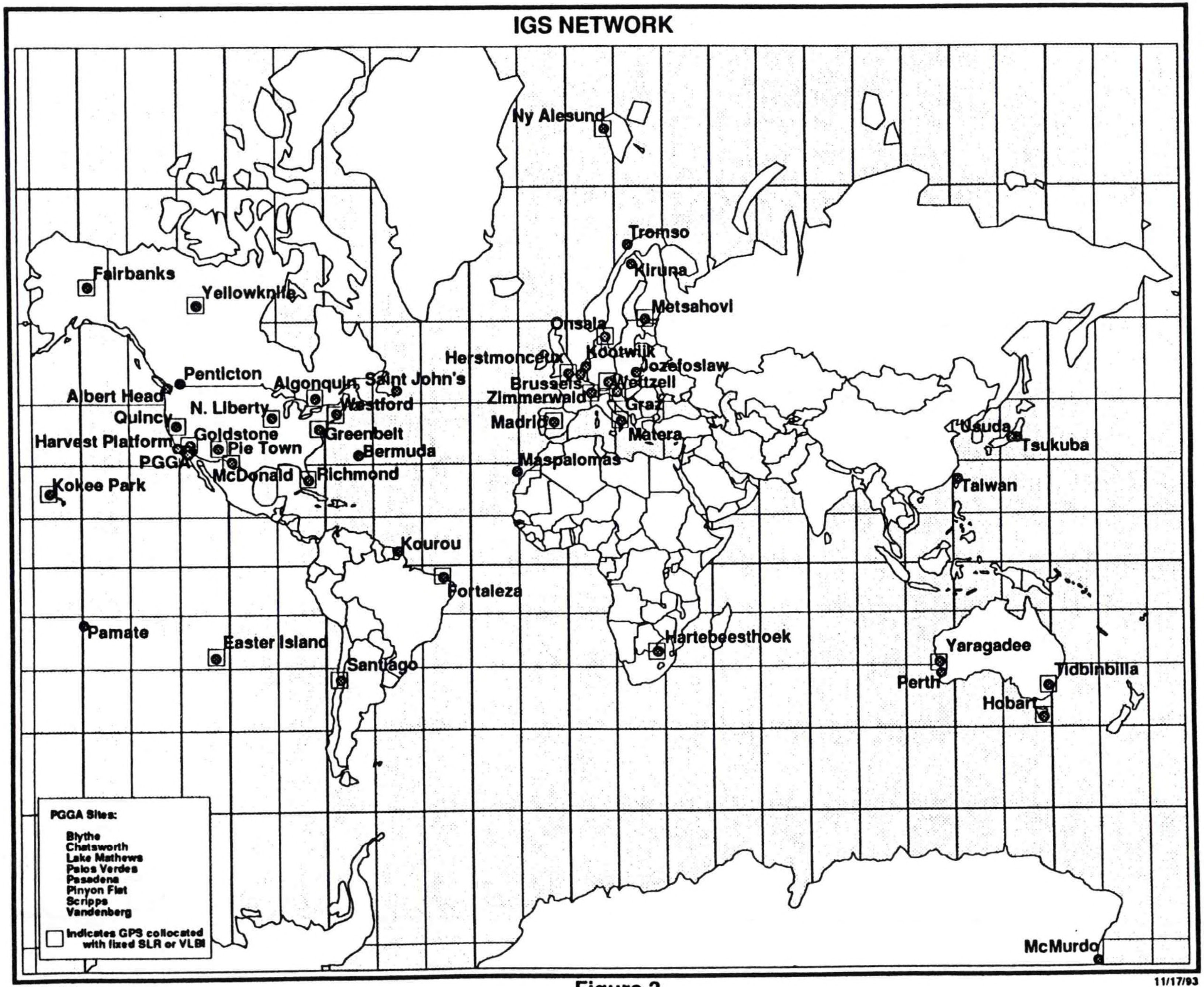

VLBI OBSERVATORY NETWORK
Ny Alesund
Fairbanks
Yellowknife
Brewster
Algonquin
N. Liberty
Hancock
Westford
Owens Valley
Los Alamos
Greenbelt
Green Bank
Goldstone
Pie Town
Kitt Peak
Ft. Davis
Richmond
Kokee Park
Mauna Kea
St. Croix
Fortaleza
Santiago
O'Higgins
Effelsberg
Trysil
Onsala
Wettzell
Medicina
Simeiz
Madrid
Matera
Noto
Hartebeesthoek
Urumqi
Shanghai
Mizusawa
Kashima
Hobart
Tidbinbilla
Note: F denotes near future VLBI site
11/17/93

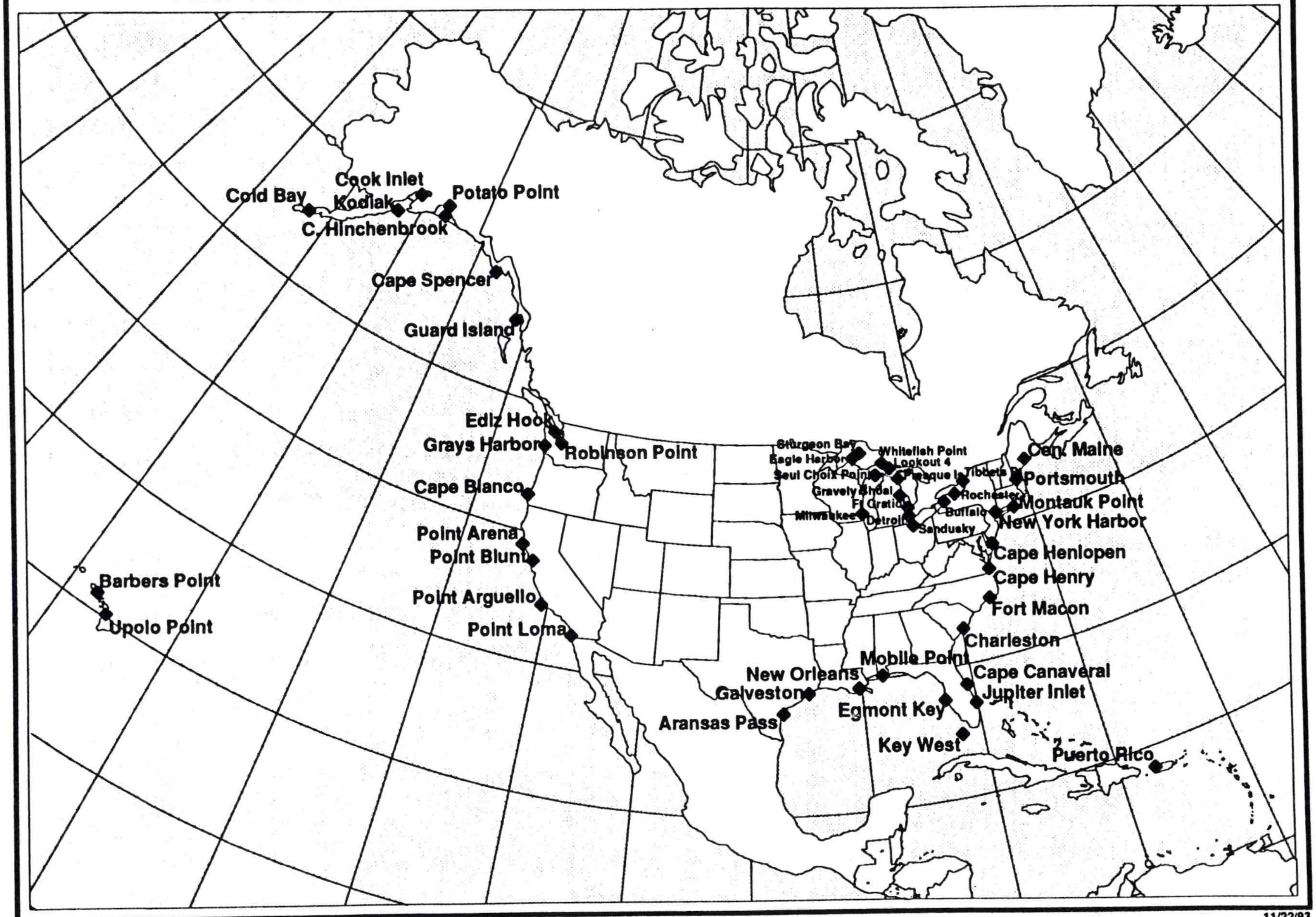
Figure 2



11/17/93

Figure 3

PROPOSED LOCATIONS OF COAST GUARD DIFFERENTIAL GPS NETWORK



11/22/93

Figure 4

DATA TRANSMISSION METHODS FROM PERMANENT VLBI, SLR, AND GPS SITES

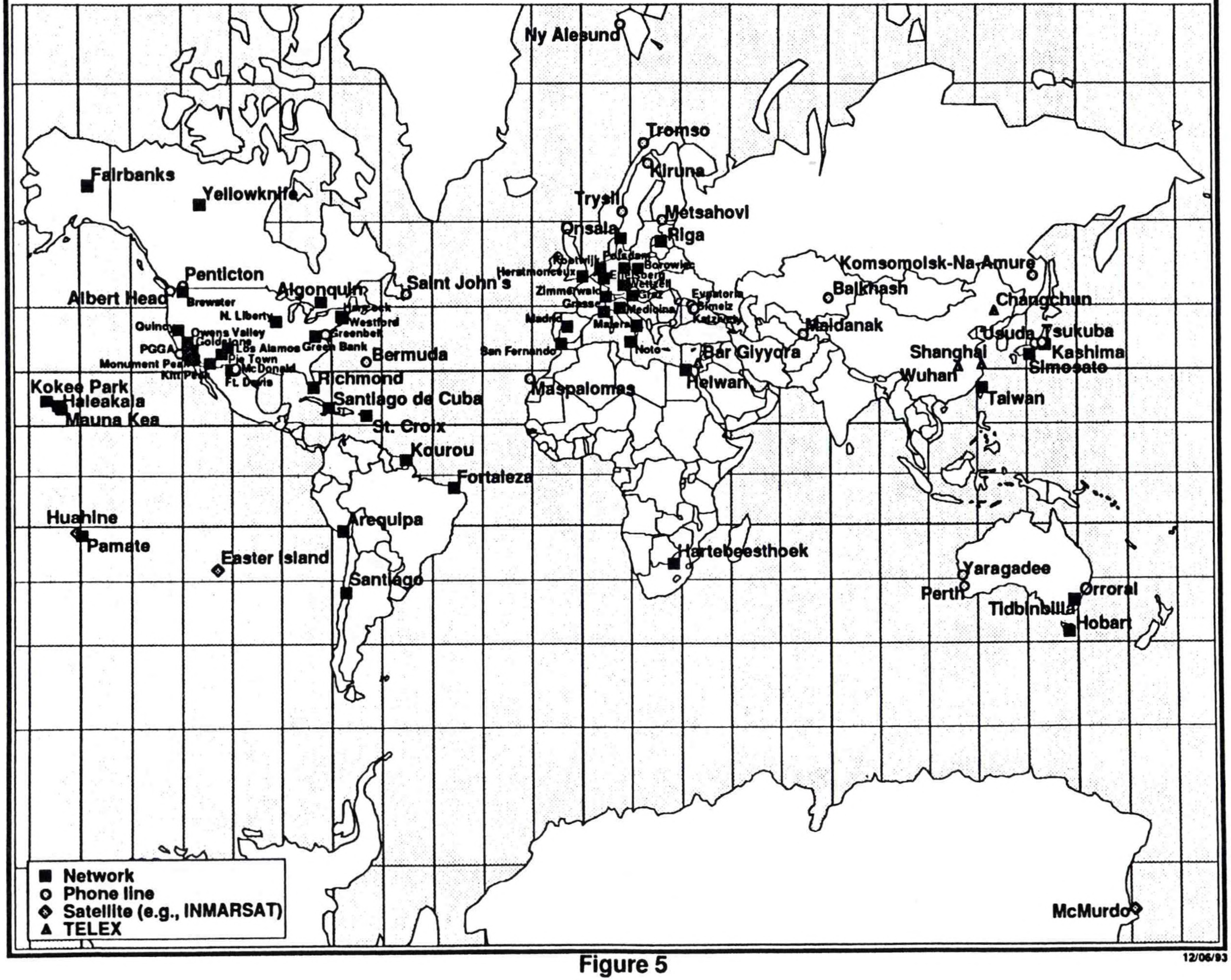


Figure 5

12/06/93

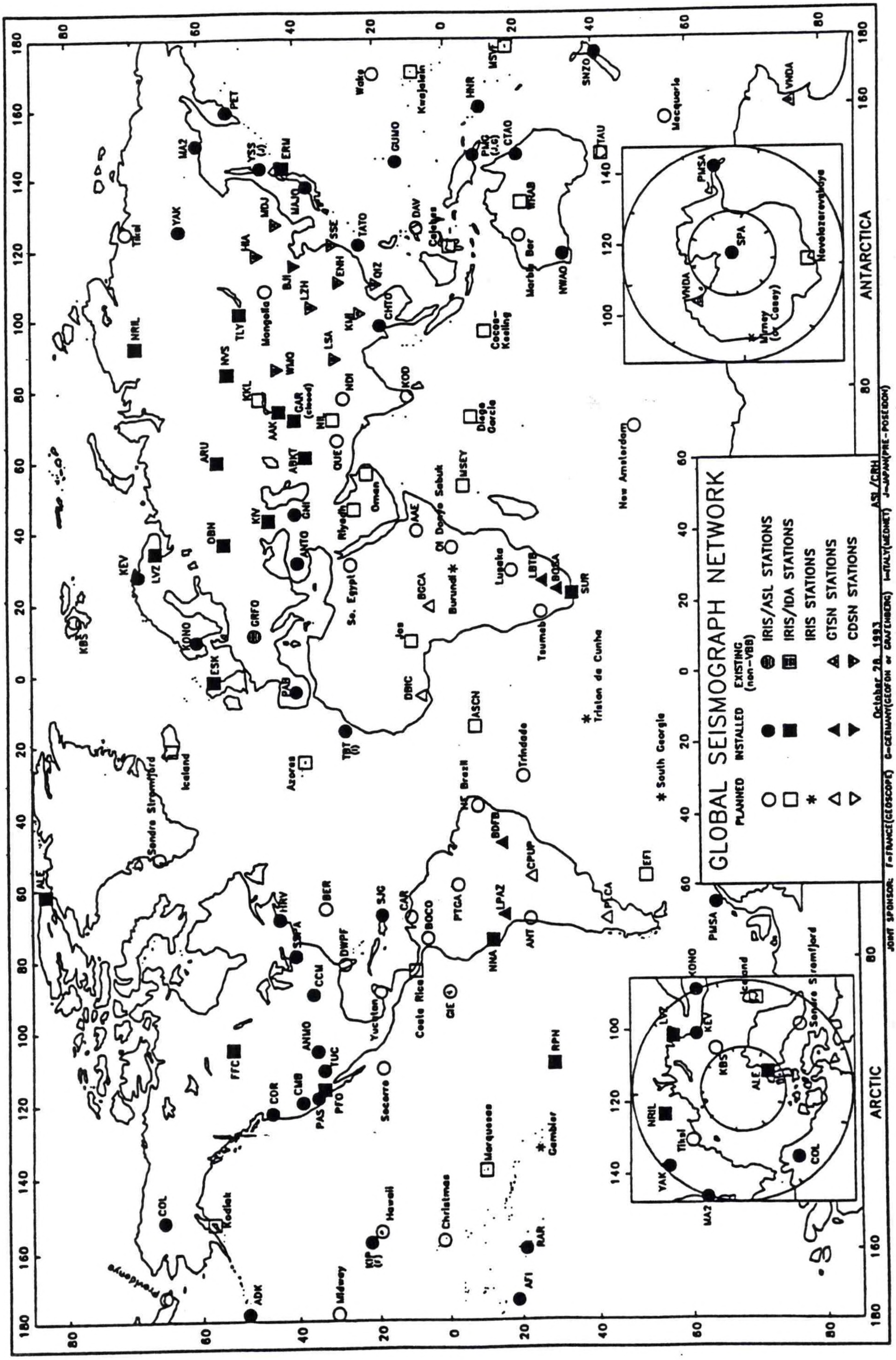

GLOBAL SEISMOGRAPH NETWORK
PLANNED
INSTALLED
EXISTING (non-VBB)
○ ● IRIS/ASL STATIONS
□ ■ IRIS/IDA STATIONS
* IRIS STATIONS
△ ▲ GTSN STATIONS
▽ ▼ CDSN STATIONS
October 28, 1993
ASL/CRH
JOINT SPONSOR: F=FRANCE(GEOSCOPE) G=GERMANY(GEOFON or GRAFENBERG) I=ITALY(MEDNET) J=JAPAN(PRE-POSEIDON)
ARCTIC
ANTARCTICA
ALE
KEV
LVZ
KONO
ESK
GRFO
PAB
ANTO
GNI
KIV
OBN
ARU
ABKT
AAK
GAR
NIL
NRIL
NVS
TLY
YAK
MA2
PET
YSS
ERM
MDJ
MAJO
BJI
HIA
SSE
ENH
LZH
LSA
WMQ
KMI
QIZ
CHTO
TATO
GUMO
DAV
HNR
PMG
CTAO
NWAO
SNZO
TAU
SPA
PMSA
VNDA
COL
ADK
KIP
AFI
RAR
RPN
COR
CMB
PAS
PFO
TUC
ANMO
CCM
SSPA
HRV
SJG
BOCO
PTGA
LPAZ
NNA
BDFB
CPUP
PLCA
ANT
TBT
ASCN
DBIC
BGCA
LBTB
BOSA
SUR
FFC
Wake
Kwajalein
Tiksi
Mongolia
KKL
NDI
QUE
Riyadh
Oman
Diego Garcia
Cocos-Keeling
Marble Bar
USEY
AAE
Ol Doinyo Sabuk
Lugeke
Burundi
Tsumeb
Jos
So. Egypt
New Amsterdam
Tristan de Cunha
South Georgia
EFI
Trindade
NE Brazil
Azores
Iceland
Sondre Stromfjord
KBS
BER
DWPF
CAR
Costa Rica
Yucatan
GIE
Socorro
Marquesas
Gambier
Christmas
Hawaii
Midway
Kodiak
Providenya
Macquarie
Novolazarevskaya
Mirney (or Casey)
MSVF

Figure 6

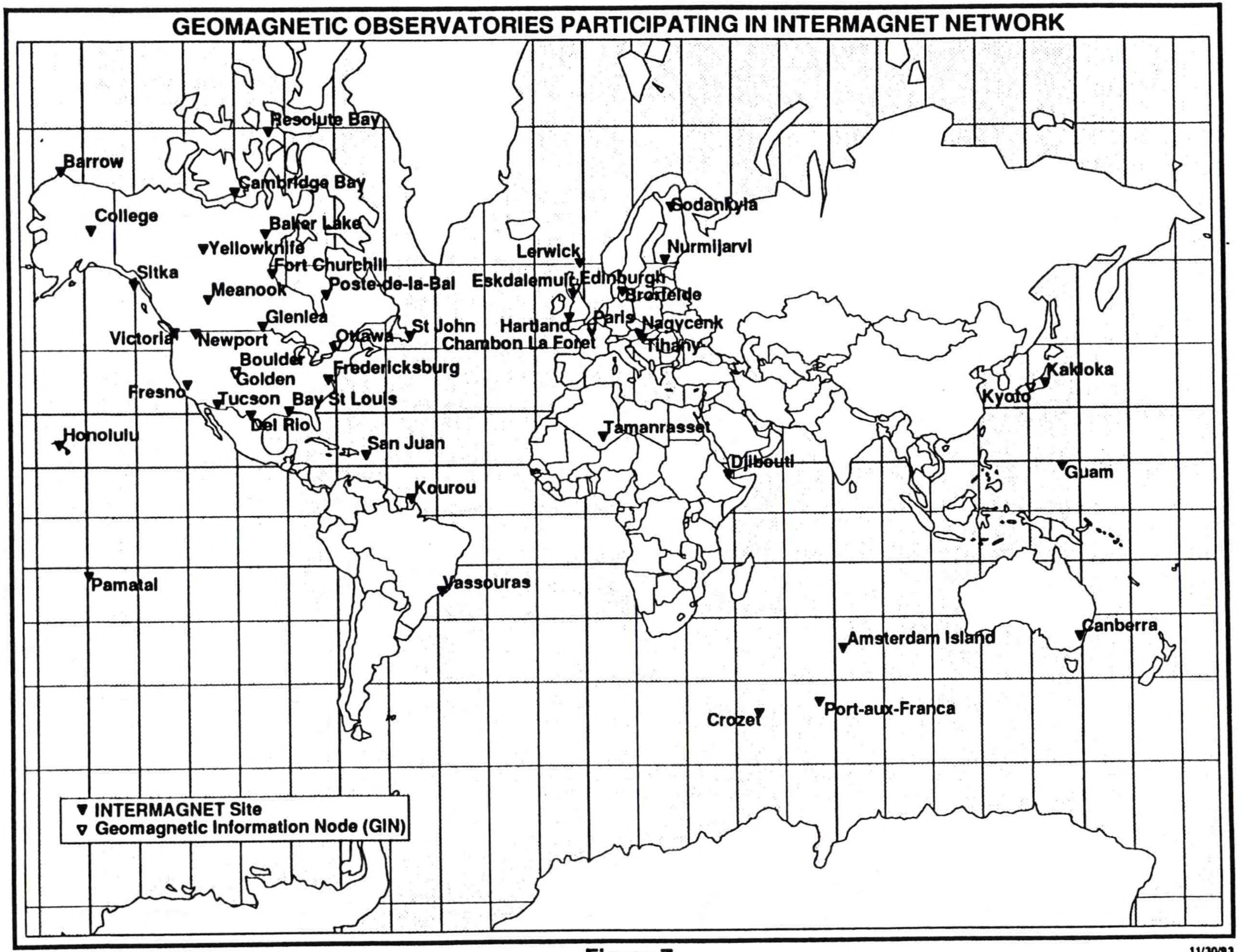


Figure 7

11/30/93

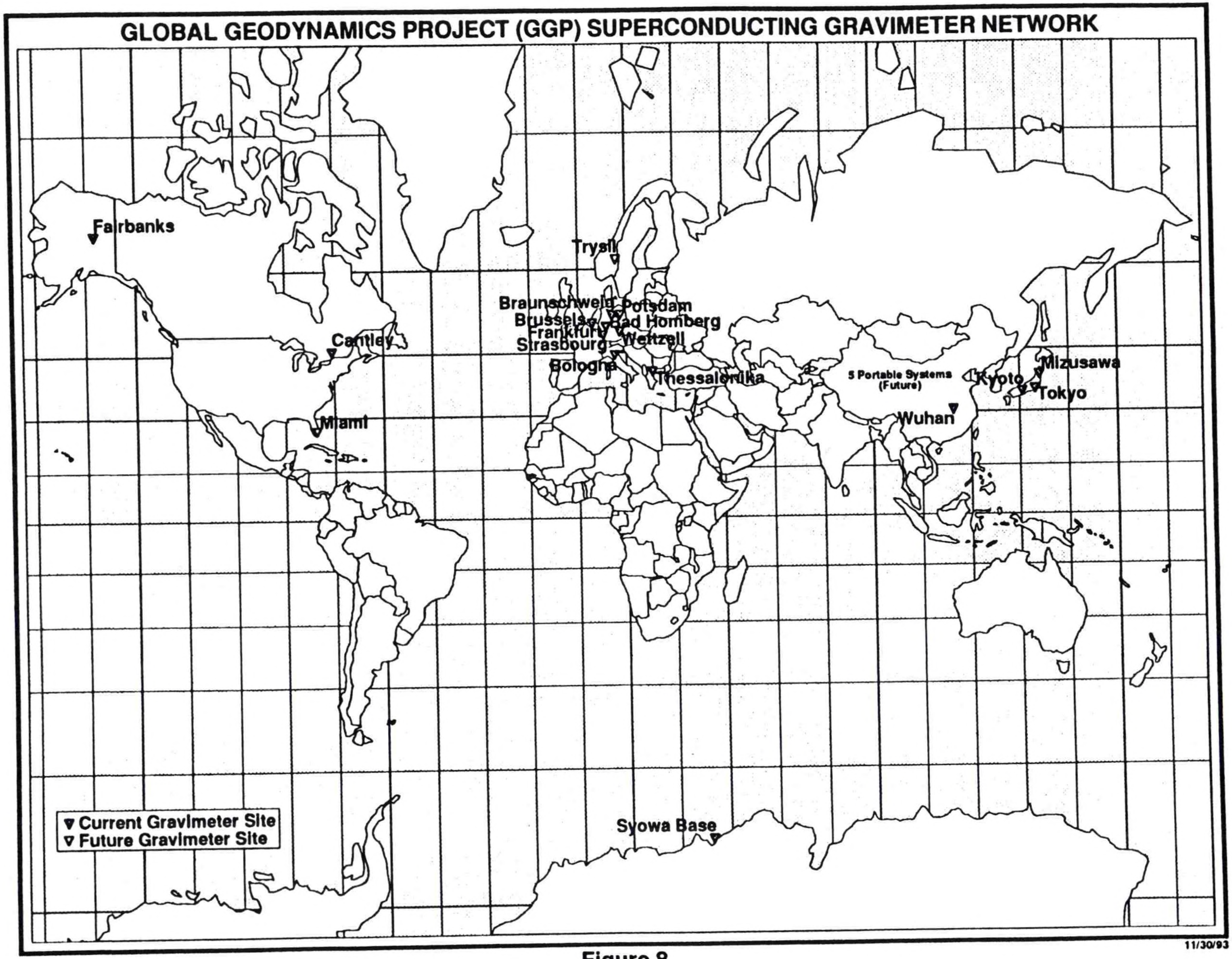

GLOBAL GEODYNAMICS PROJECT (GGP) SUPERCONDUCTING GRAVIMETER NETWORK
Fairbanks
Cantley
Miami
Trysil
Braunschweig
Potsdam
Brussels
Bad Homberg
Frankfurt
Wettzell
Strasbourg
Bologna
Thessaloniki
5 Portable Systems (Future)
Wuhan
Kyoto
Mizusawa
Tokyo
Syowa Base
▼ Current Gravimeter Site
▽ Future Gravimeter Site
11/30/93

Figure 8

TIDE GAUGE NETWORK — REVISED LOCAL REFERENCE (RLR) SITES

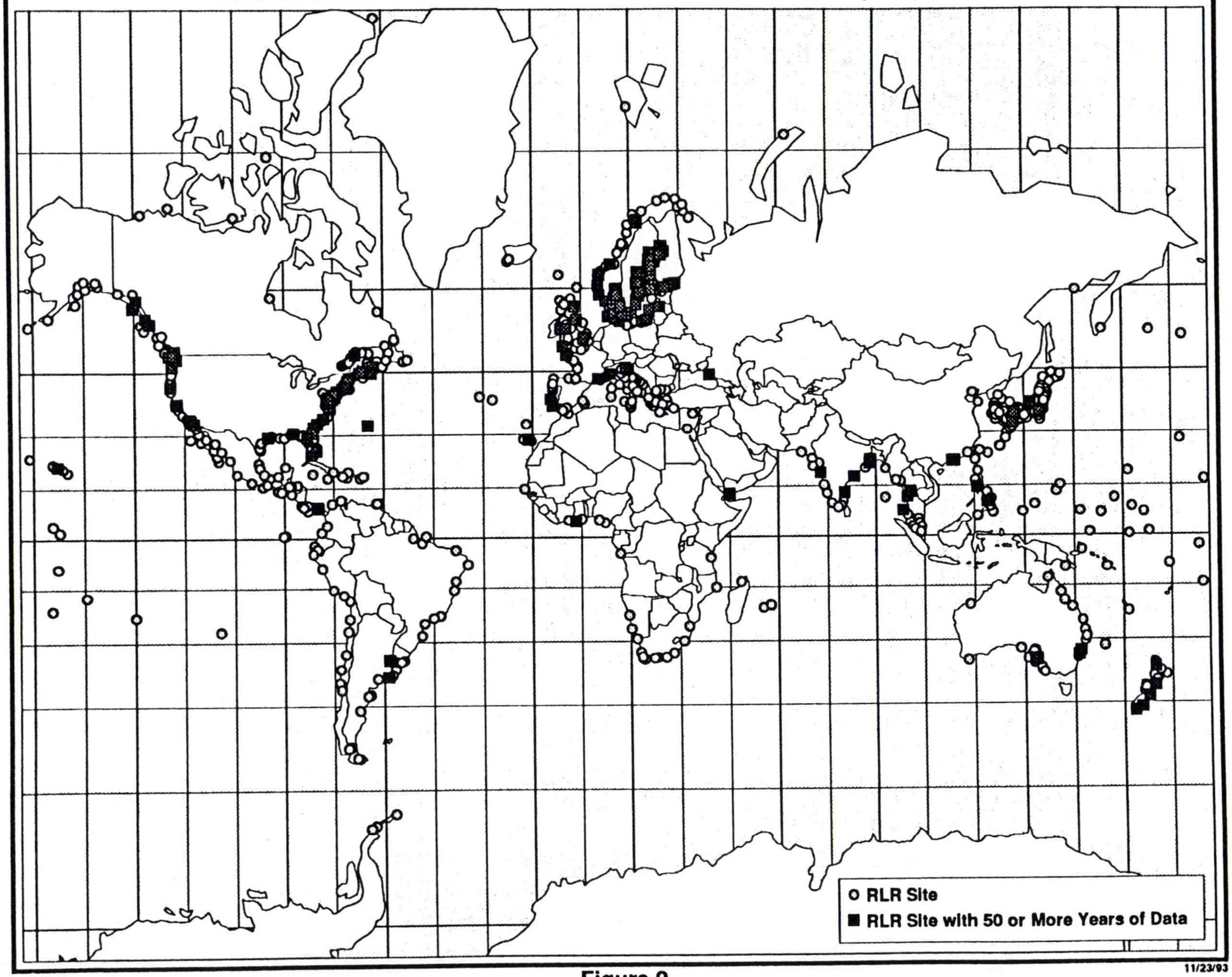


Figure 9

11/23/93

PROXIMITY OF TIDE GAUGE LOCATIONS TO FIXED SLR, VLBI, OR GPS SITES
Revised Local Reference (RLR) Sites

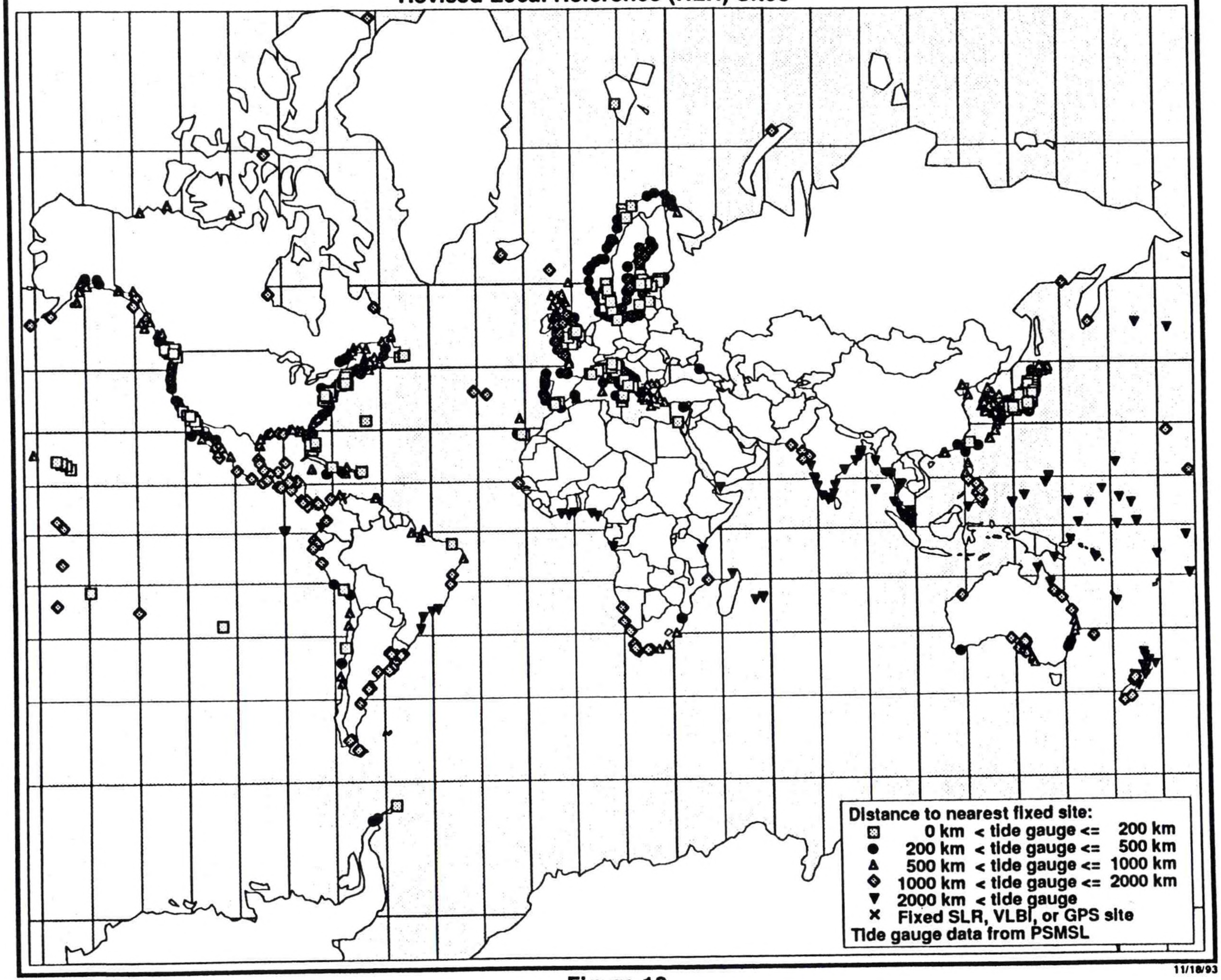
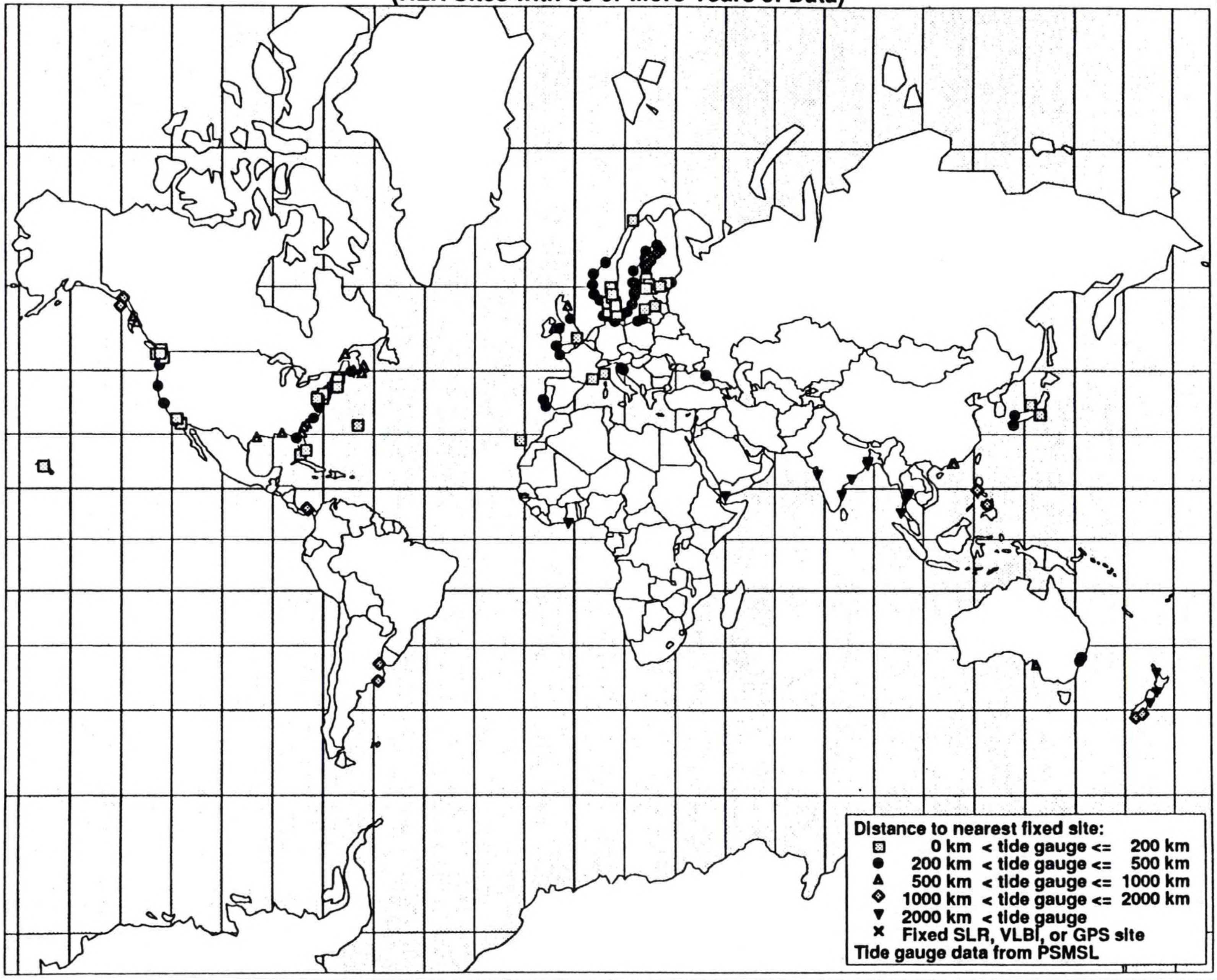


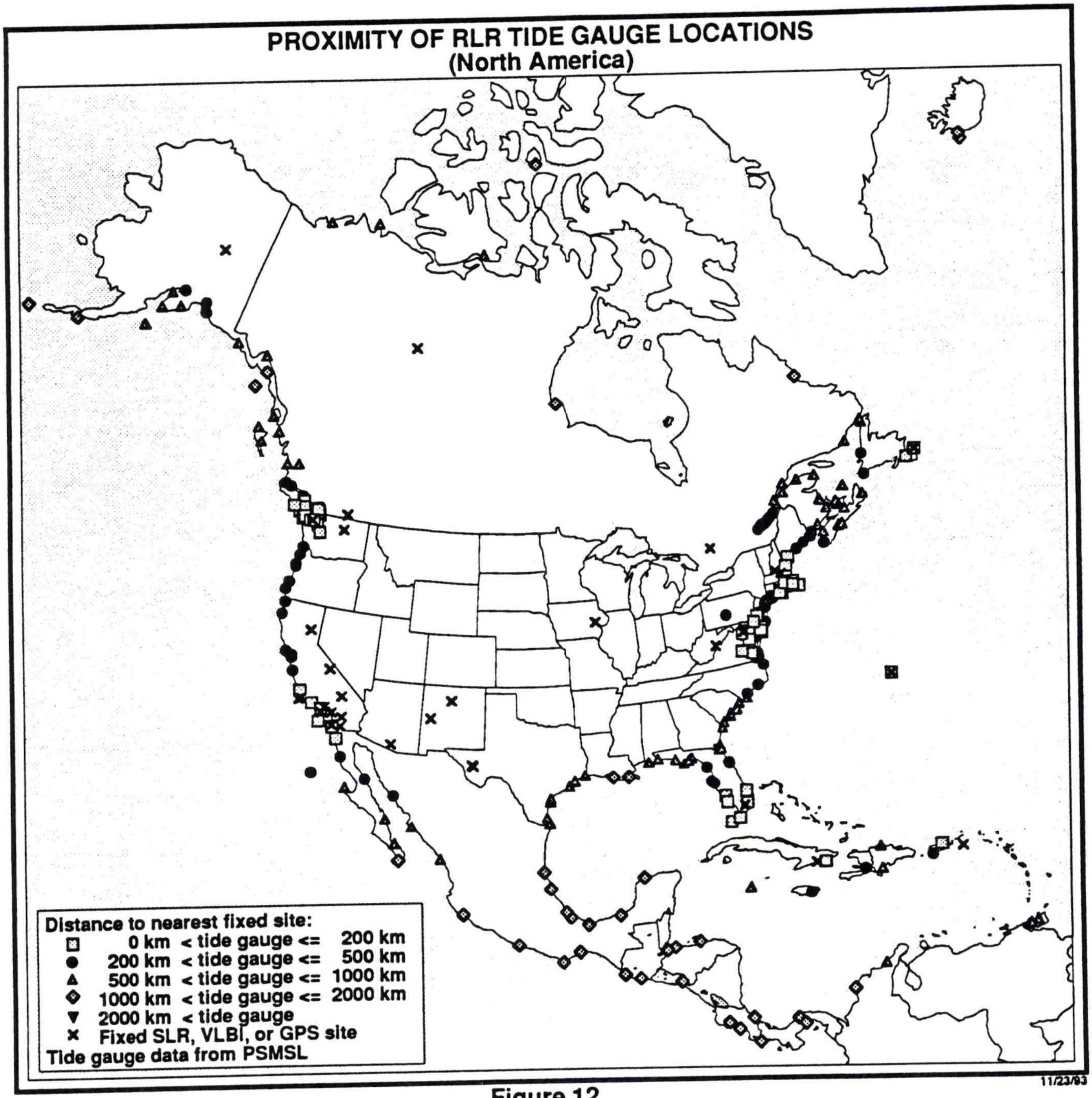
Figure 10

PROXIMITY OF TIDE GAUGE LOCATIONS TO FIXED SLR, VLBI, OR GPS SITES
(RLR Sites with 50 or More Years of Data)



11/23/93

Figure 11



PROXIMITY OF RLR TIDE GAUGE LOCATIONS
(North America)

Figure 12

11/23/93

Figure 13

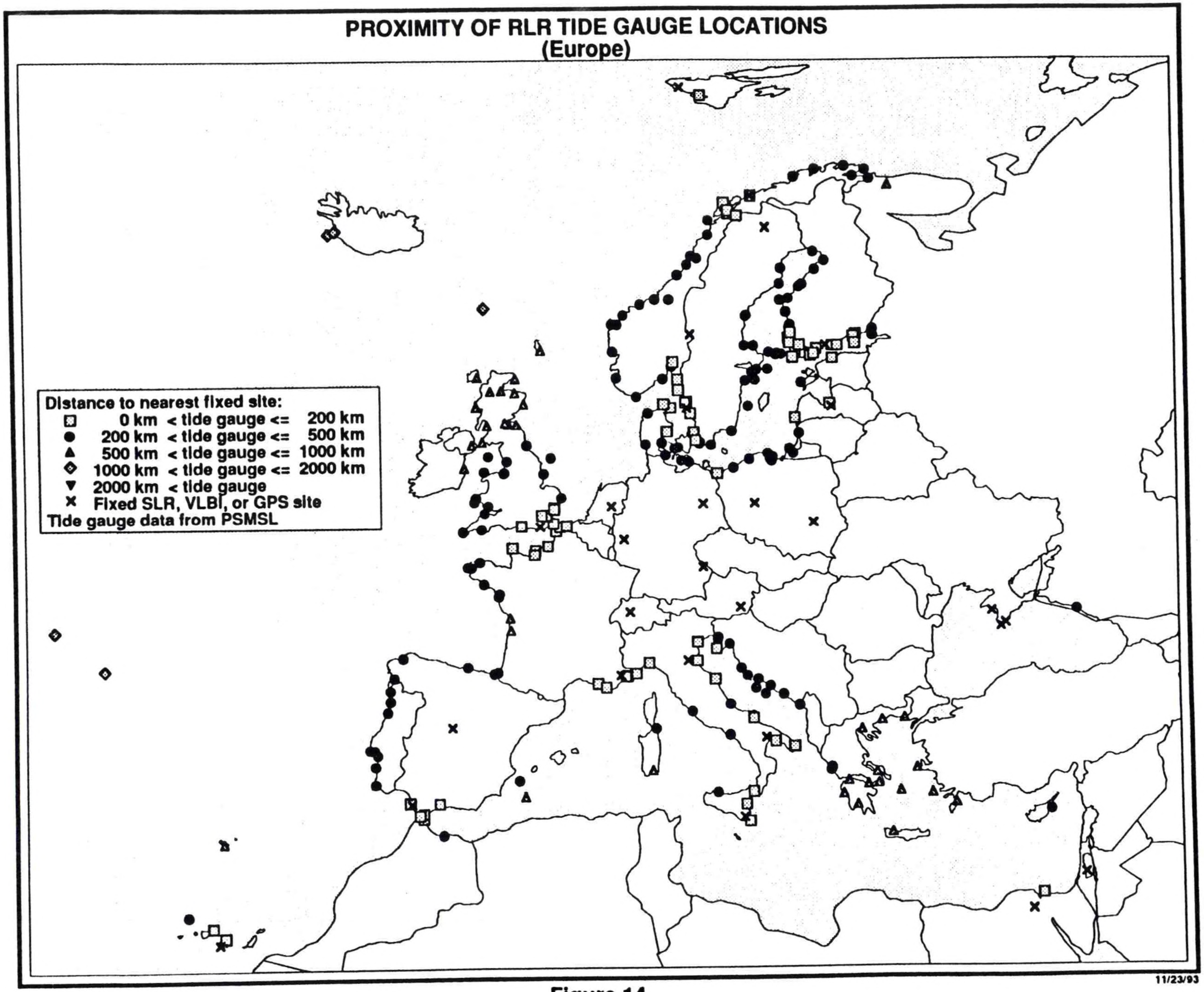

PROXIMITY OF RLR TIDE GAUGE LOCATIONS
(Europe)
Distance to nearest fixed site:
▨ 0 km < tide gauge <= 200 km
● 200 km < tide gauge <= 500 km
▲ 500 km < tide gauge <= 1000 km
◈ 1000 km < tide gauge <= 2000 km
▼ 2000 km < tide gauge
× Fixed SLR, VLBI, or GPS site
Tide gauge data from PSMSL
11/23/93

Figure 14

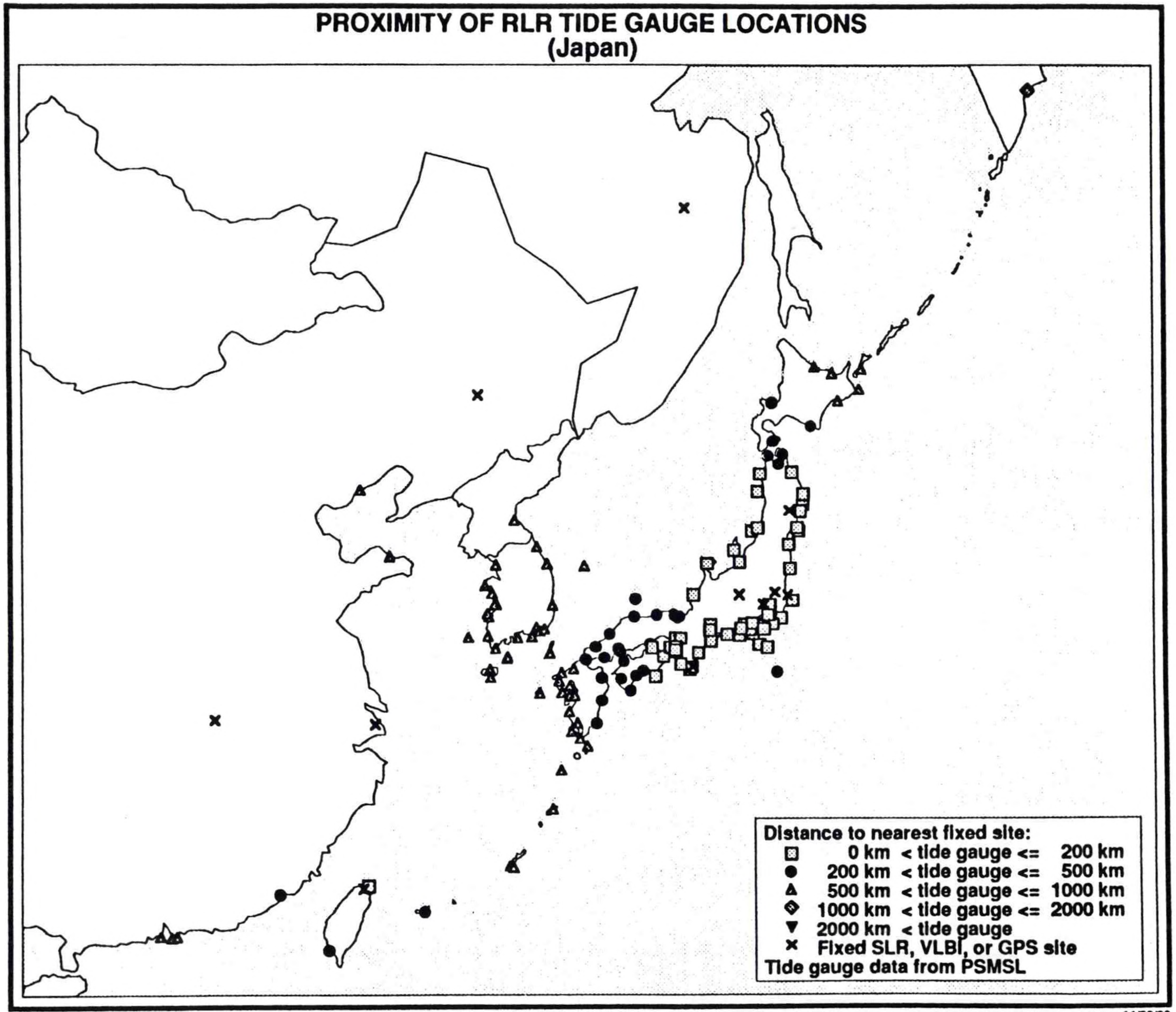

PROXIMITY OF RLR TIDE GAUGE LOCATIONS
(Japan)

Figure 15

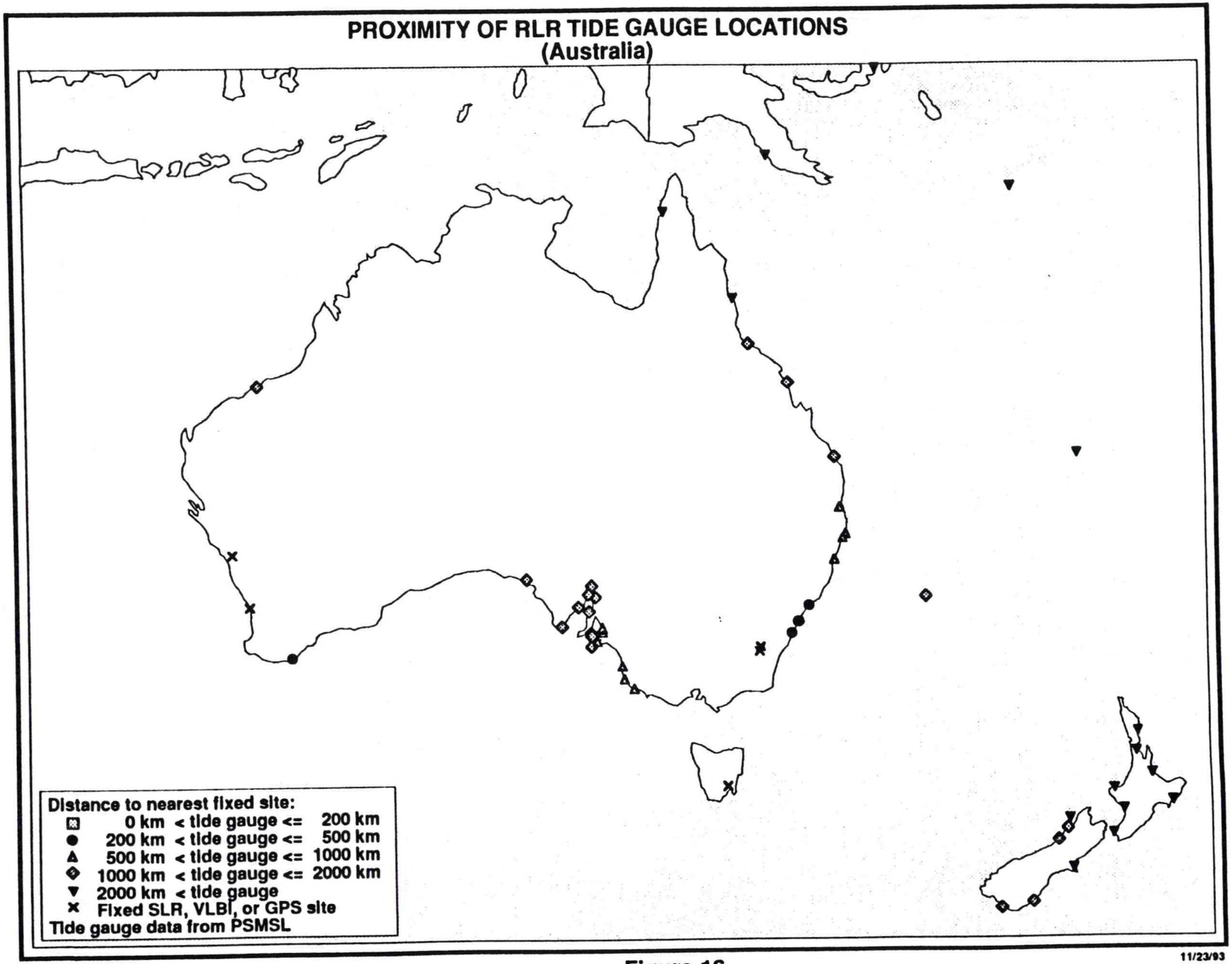

PROXIMITY OF RLR TIDE GAUGE LOCATIONS
(Australia)
Distance to nearest fixed site:
⊠ 0 km < tide gauge <= 200 km
● 200 km < tide gauge <= 500 km
▲ 500 km < tide gauge <= 1000 km
◆ 1000 km < tide gauge <= 2000 km
▼ 2000 km < tide gauge
× Fixed SLR, VLBI, or GPS site
Tide gauge data from PSMSL
11/23/93

Figure 16

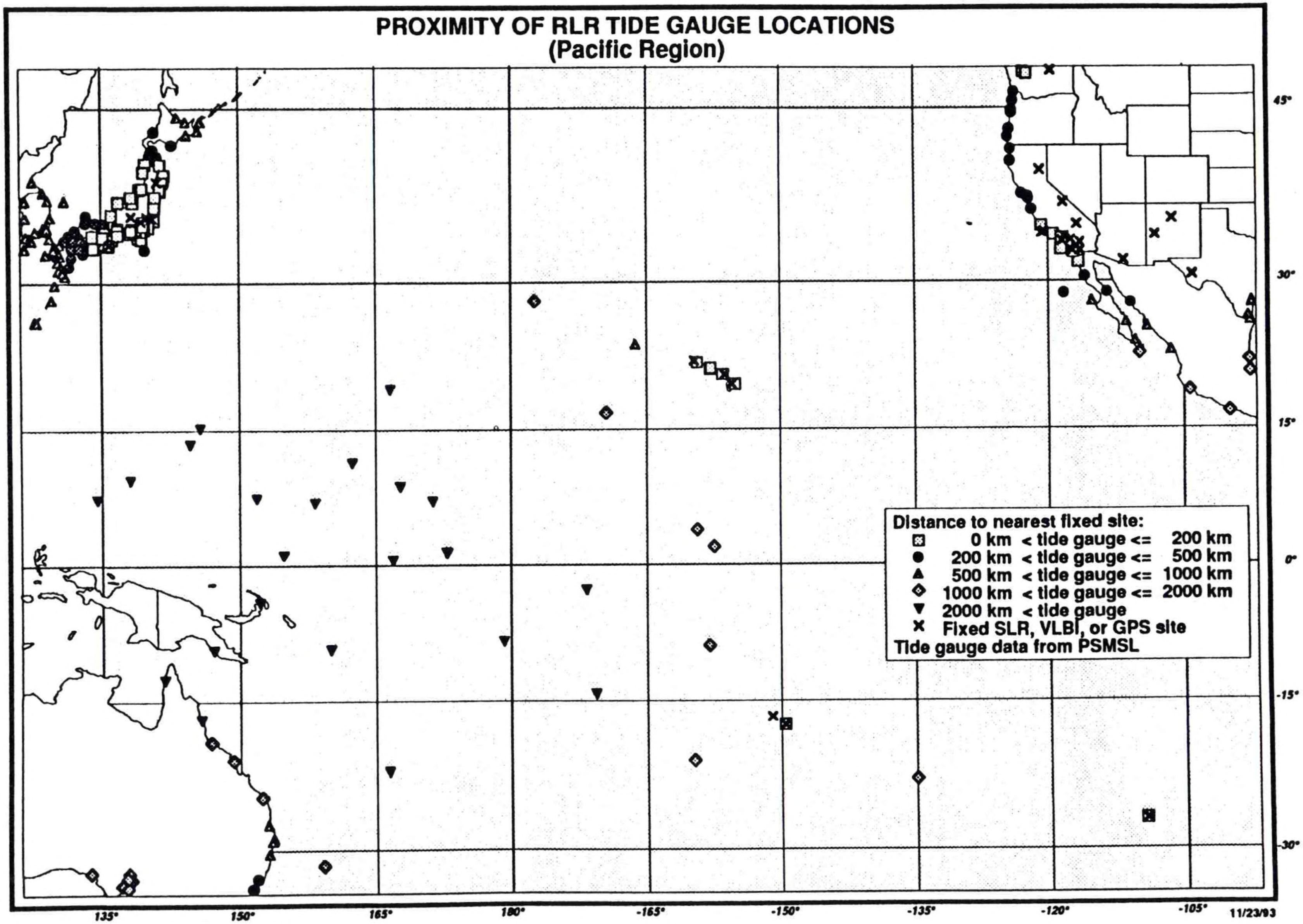

PROXIMITY OF RLR TIDE GAUGE LOCATIONS
(Pacific Region)
Distance to nearest fixed site:
⊠ 0 km < tide gauge <= 200 km
● 200 km < tide gauge <= 500 km
▲ 500 km < tide gauge <= 1000 km
◇ 1000 km < tide gauge <= 2000 km
▼ 2000 km < tide gauge
× Fixed SLR, VLBI, or GPS site
Tide gauge data from PSMSL
45°
30°
15°
0°
-15°
-30°
135°
150°
165°
180°
-165°
-150°
-135°
-120°
-105°
11/23/93

Figure 17

11/23/93

Figure 18

REGIONAL PROJECTS

SEA LEVEL FLUCTUATIONS: GEOPHYSICAL INTERPRETATION AND ENVIRONMENTAL IMPACT (SELF) PROJECT

S. Zerbini, Coordinator of the Project, University of Bologna, Department of Physics/Viale Berti Pichat 8, 40127 Bologna, ITALY

Global warming is supposed to induce volummetric changes in the ocean, due to melting of the ice caps and glaciers of the world and to thermal expansion. In the past century, relative sea level is estimated to have risen more than 10 cm. Relative sea level is being determined at many tide gauges around the work, although measurements of sea level variations are affected by several factors acting at different spatial and temporal scales. Tide gauge readings are influenced, for example, by tectonic activity, by motion due to post glacial-rebound, by variations in the ground water content, by surface loading and other causes. The different data sets can hardly be compared with each other because tide gauge coordinates are referred to local reference systems. By using the Global Positioning System (GPS), it is now possible to connect tide gauges on the well defined global reference system established through the Satellite Laser Ranging (SLR) and/or Very Long Baseline Interferometry (VLBI) techniques. The SELF (**SE**a Level **F**luctuations: geophysical interpretation and environmental impact) project is being developed in the framework of the Commission of the European Communities Programme on Climatology and Natural Hazards (ENVIRONMENT) and involves four Member States (Germany, Greece, Italy, United Kingdom) and Switzerland. Several institutions in the different Countries are working together to connect, on the global reference frame, an ensemble of selected tide gauges in the Mediterranean area in order to estimate sea level changes. The work has the following objectives: to select, in the Mediterranean region, fiducial reference stations belonging to the International Earth Rotation Service (IERS) network and well established tide gauges (**Figure 1** shows the SELF network); to provide GPS links between the SLR/VLBI fiducial stations and the tide gauges; to improve GPS measurement procedures by using Water Vapor Radiometers (WVR) to reduce vertical uncertainties to 1 cm for baselines greater than 100 km; to perform measurements of abs-g both at fiducial sites and tide gauges in order to contribute to achieving a vertical reference accurate to centimeter level and to provide an independent check on the occurrence of vertical crustal movements; to perform, in selected areas of the Mediterranean basin, observations of geologic sea level markers of the Quaternary in order to provide a valuable framework for a better understanding of the interactions among local eustatic-tectonic-sedimentary components in the migration of coastlines; to collect, analyze and interpret tide gauge data; to develop realistic models for tidal loading and tectonics in the Mediterranean region in order to quantify their effects in the observational data and to separate their contribution from purely eustatic sea level variations; to define corrections for the Earth's surface deformation due to exogenic causes by using the existing data and the knowledge about the viscoelastic behavior of the Earth, and to study long-term variability of relative sea level. **Figure 2** describes the coordination of research activities among the participating countries. The outcome of the SELF project should provide the necessary base to successfully approach the measurement of sea level fluctuations and to reliably assess the factors causing sea level changes. The assessment of sea level rise would be important in the timely implementation of proper defenses and in the capability of making reliable forecasts which would mitigate the effects of major disasters. Until now, all the GPS links between the tide gauges and the fiducial stations have been performed as regards the Mediterranean area and the Black Sea area. The abs-g measurements have been performed in all the sites in Italy and Greece; the Spanish and Black Sea sites will be measured in the next months. As regards the analysis of the tide gauge data, mixed quality data are available for the Mediterranean Sea. Although trend values can easily be assigned, the analysis indicates that records at least 40 years long should be used if errors less than 0.5 mm/yr are required. The analyses of the monthly sea level data reveal an unexpectedly large variability of the coastal seasonal tidal constituent which is spatially highly coherent. This variability on decadal time scales most likely is associated with changes in the regional atmospheric circulation. As regards the geologic work, in selected areas of the Aeolian Archipelago (South Eastern Thyrrenian Sea, Italy), local late Quaternary sea level data have been collected by performing geomorphological observations on raised marine conglomeratic levels, absolute age determinations of in situ collected bioconstructions, high resolution seismo acoustic profiles and sea bottom cores.

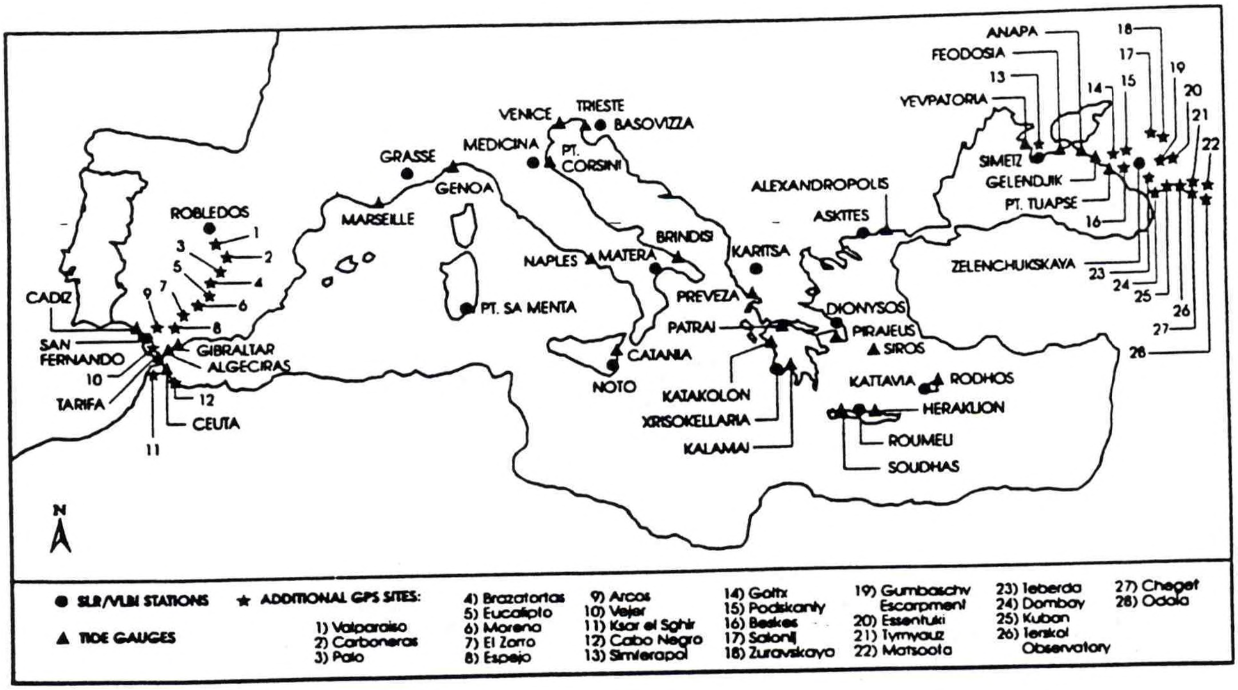


Fig. 1 Tide gauges and fiducial reference stations in the SELF project.

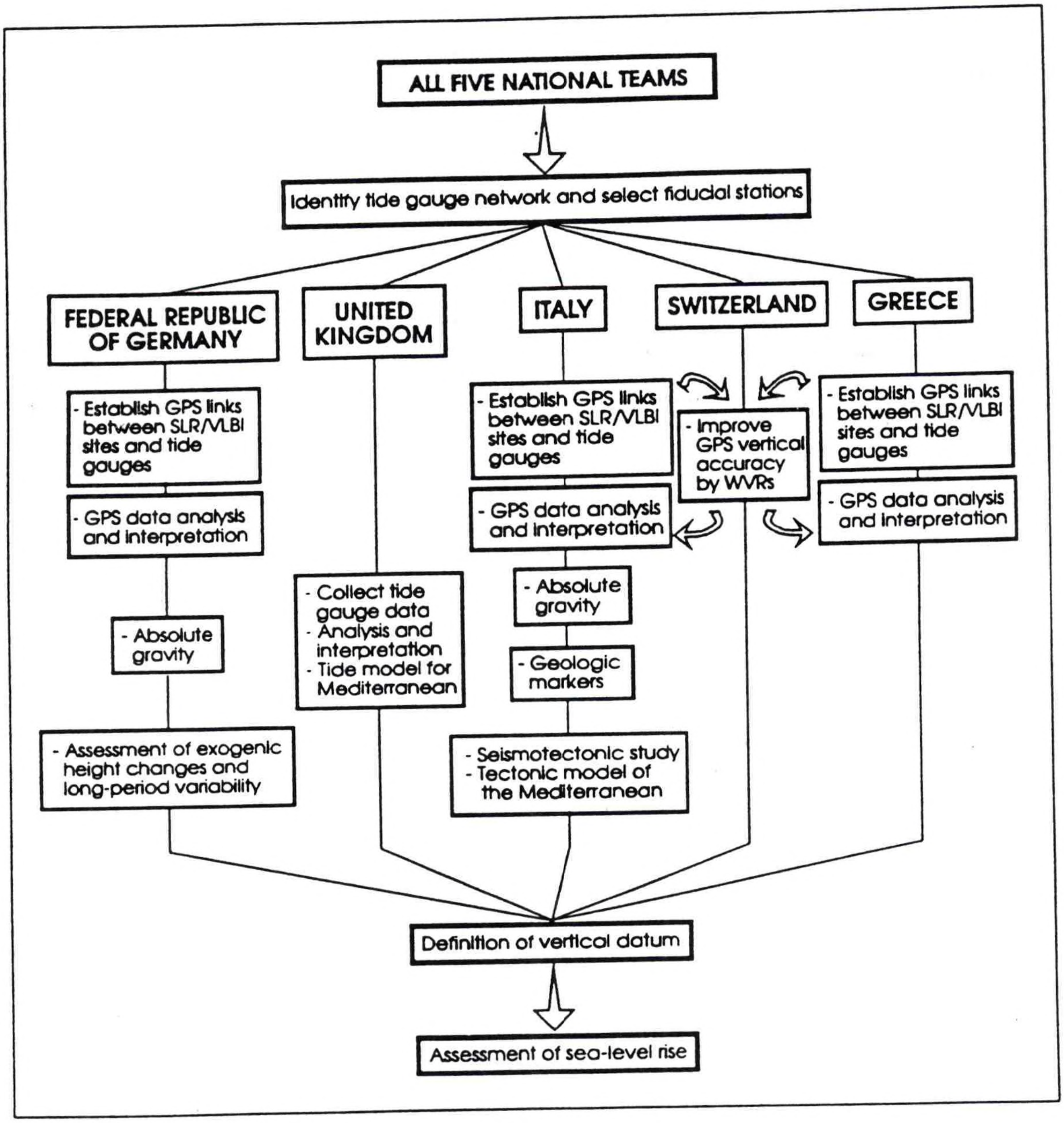


Fig. 2 Block diagram describing distribution of tasks among groups.

THE DETERMINATION OF TIDE GAUGE HEIGHTS IN THE UNITED KINGDOM BY GPS

V. Ashkenazi, R. M. Bingley and A. H. Dodson, Institute of Engineering Surveying and Space Geodescy, University of Nottingham, University Park, Nottingham NG7 2RD England; T. F. Baker, Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead L43 7RA England

In 1990, the United Kingdom Ministry of Agriculture Fisheries and Food gave a Research Contract to the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham to carry out a feasibility study, in collaboration with the Proudman Oceanographic Laboratory (POL), on the determination of tide gauge heights in the UK by GPS. Over the last three years, three independent 5-day GPS campaigns have been carried out by the IESSG and POL, in collaboration with the Military Survey and Ordinance Survey of Great Britain, in the Summers of 1991, 1992 and 1993. By repeating the measurements at such short time intervals, the project aimed to establish the current (absolute) accuracy to which the heights of tide gauge bench marks (TGBMs) could be determined in a global reference framework. The results of the three campaigns will be used as the 'first epoch' measurement for future monitoring of vertical land movement at these tide gauge sites along the South and East coasts of Great Britain.

For each GPS campaign, eighteen Trimble 4000 GPS receivers were deployed at regional stations in the UK, and the data from five CIGNET/IGS Rogue GPS receivers in Europe (Tromso, Onsala, Wettzell, Herstmonceux and Madrid) were obtained. The regional network (**Figure 1**) included nine 'tide gauge GPS stations' located, mainly on the South and East coast, within 1 km of a 'Class A' tide gauge with a long, continuous mean sea level record. During each campaign, the eighteen Trimble 4000 GPS receivers recorded simultaneous observations for approximately 10 hours each day. The data for each day was processed by using the GPS Analysis Software (GAS), developed at the IESSG, in conjunction with the fiducial GPS technique. Precise spirit levelling links were used to connect the tide gauge GPS stations to the corresponding TGBMs and, hence, determine the ellipsoidal heights of the TGBMs.

The data sets obtained from the three campaigns are of very high quality, with day-to-day height repeatabilities of better than 10 mm on baselines up to 350 km. Using the 1991 data set, tests have been carried out in Nottingham to assess the effect of the global reference framework on the (absolute) accuracy of the fiducial GPS technique. In these tests, sub-sets of fiducial stations have been held fixed to coordinate values obtained from three different global reference frameworks.

These were:

(i) Combined VLBI and SLR (ITRF91 with the Nuvel-1 plate motion model).
(ii) Pure VLBI (GSFC solution at epoch 1992.0).
(iii) Pure GPS (JPL IGS Epoch '92 solution at epoch 1992.6).

Throughout the test, consistency was maintained by keeping the same models for antenna phase center variations, tropospheric delay, earth body tides and the M2 ocean tide loading.

The results of the tests indicate that a pure GPS global reference framework is clearly the most consistent, due to the removal of local offsets from GPS to VLBI/SLR, the elimination of plate motion models and the use of a single space geodetic technique. The results, both in terms of the 'recovery' of the coordinates of fiducial stations not held fixed and a comparison of TGBM heights obtained by fixing different sub-sets of fiducial stations, illustrated that accuracies of the order of 10 mm could be achieved in a global reference framework.

The TGBM ellipsoidal heights determined using the 1991 data set have since been combined with a gravimetric geoid and tide gauge records in order to determine mean sea level at the nine UK tide gauges. Prior to the advent and use of GPS, the TGBMs were connected via the National 3rd Geodetic Levelling Network. It was then apparent that mean sea level computed using levelling and the tide gauge records resulted in a North-South slope of approximately 5 cm per degree of latitude. This disagrees with a series of oceanographic levelling techniques, which suggest that the sea slope is nil, with an uncertainty of 6 cm. This *anomaly* between precise spirit levelling and oceanography, often referred to as the 'British Sea Slope Anomaly', has now been resolved. As can be seen in **Figure 2**, mean sea level computed using GPS and a high precision gravimetric geoid suggests a slope of 0 +/- 5 cm, which is in agreement with oceanographic levelling.

Following the successful completion of the first three GPS campaigns, a new project will begin in 1994 to densify the original regional network of nine TGBMs to sixteen. These sixteen TGBMs are divided into six CORE stations (Newlyn, Portsmouth, Sheerness, North Shields, Portpatrick and Aberdeen) which will be occupied annually from 1994 to 1996, five EAST stations (Newhaven, Dover, Lowestoft, Immingham and Lerwick) which will be occupied in 1995, and five WEST stations (Avonmouth, Holyhead, Heysham, Millport and Stornoway) which will be occupied in 1994 and 1996. This network has been designed to enable advances in the fiducial GPS technique to be monitored while providing a 'first epoch' height data set for a further seven TGBMs.

A second project, with similar aims, but on a much larger scale, has recently been initiated along the Atlantic Coast of Europe.

This European Commission funded project involves collaboration between eight organizations, namely the IESSG and POL, the four National Survey Organizations of Great Britain, France, Portugal and Spain, and the Universities of Newcastle-Upon-Tyne and Madrid. A fiducial GPS network, incorporating GPS stations at sixteen primary tide gauges (**Figure 3**) from Lerwick to Marseille, was observed in November 1993, and the observations will be repeated in March 1994. In this project 'local stability networks' have also been set up at each tide gauge site to monitor any local movement within 5 km of the TGBM.

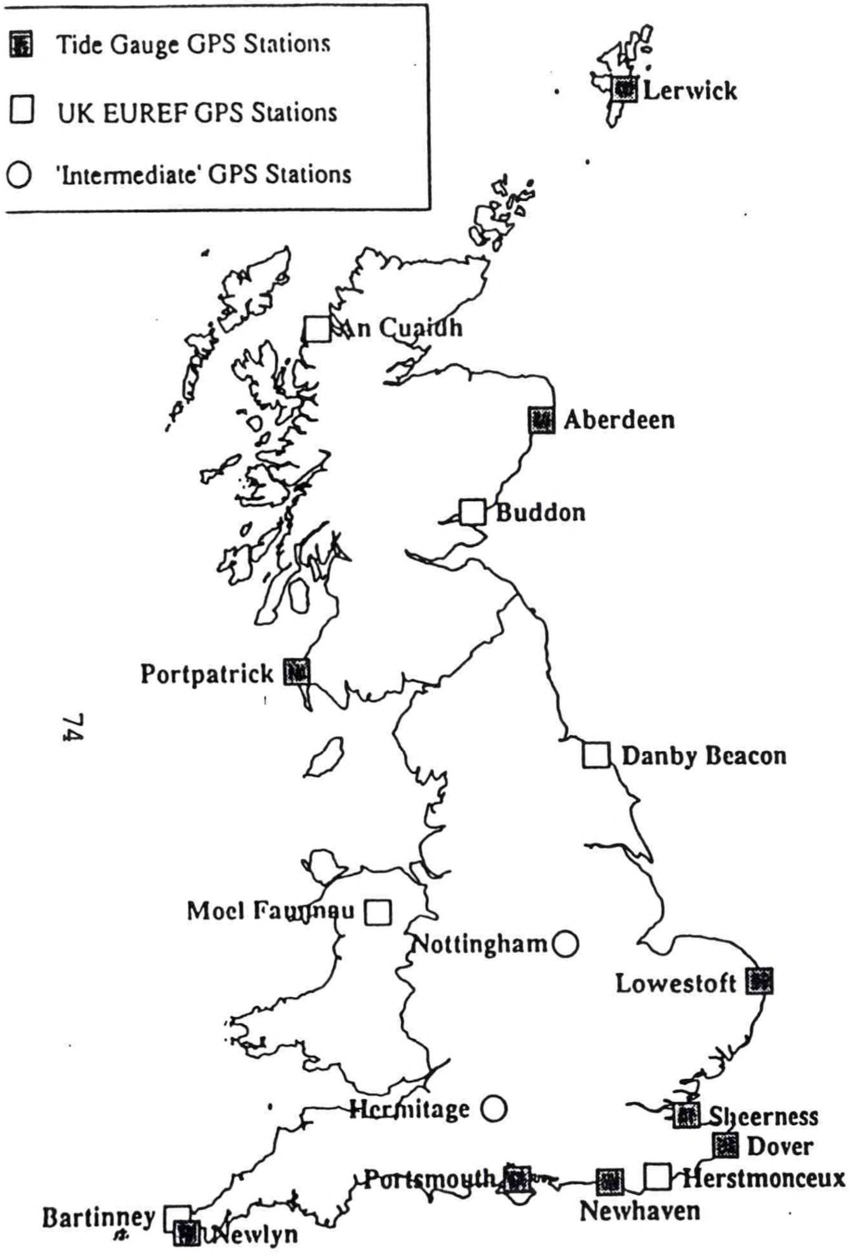


Figure 1 The UK Tide Gauge GPS Network (1991 - 1993)

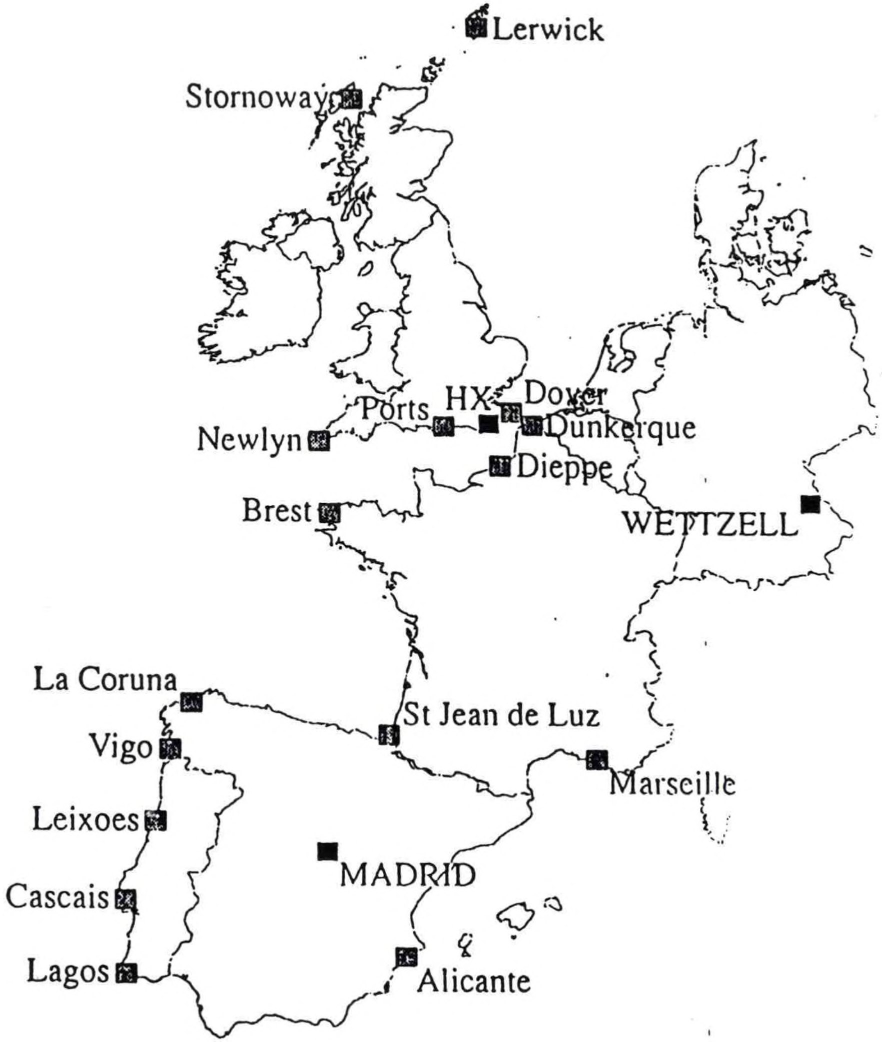


Figure 3 The Atlantic Coast Tide Gauge GPS Network (1993 - 1994)

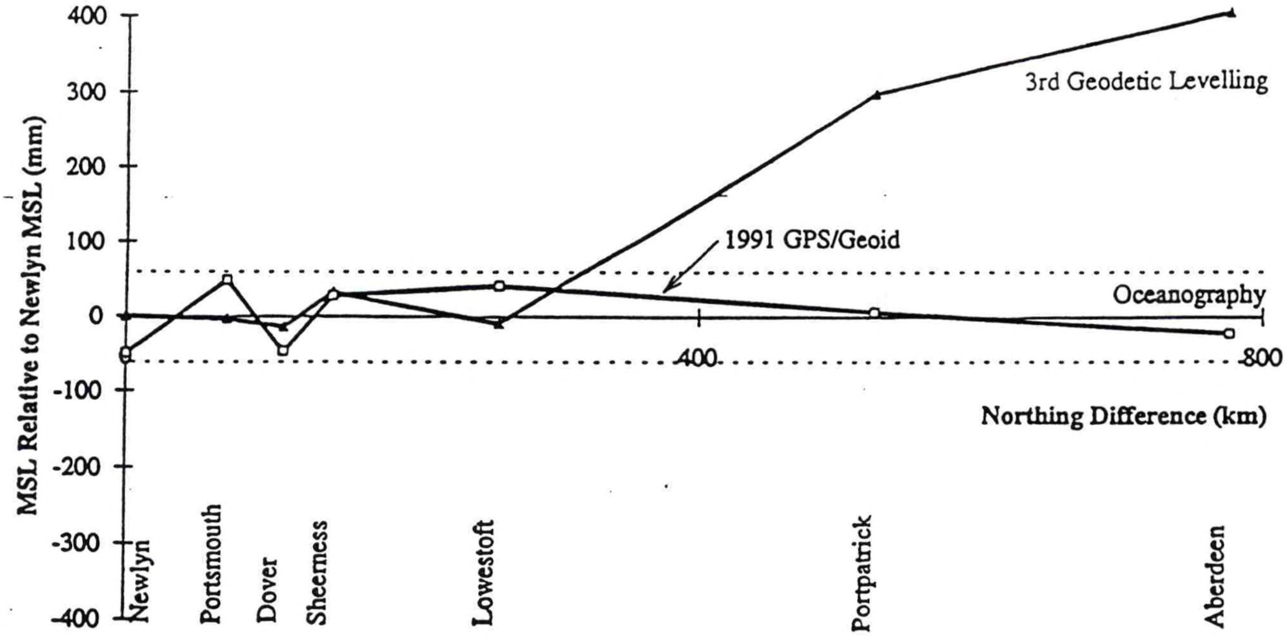


Figure 2 The Resolution of the 'British Sea Slope Anomaly'

A - WORKSHOP PROGRAM

TIDE GAUGE BENCH MARK FIXING

Monday, December 13

Welcoming Remarks - David Pugh (5 minutes)

PSMSL Comments - Philip Woodworth (10 minutes)

Opening Remarks - Bill Carter (10 minutes)

GPS Technology - Geoff Blewitt (60 minutes)

Break

VLBI Technology - Tom Clark (60 minutes)
(no paper submitted)

Lunch

SLR Technology - John Degnan/John Bosworth (60 minutes)

Break

Absolute Gravimetry - Tony Lambert (30 minutes)

Tuesday, December 14

Cryogenic Gravimetry - Bernd Richter (30 minutes)

Implementation of Global Networks - John Bosworth (60 minutes)

A Global Ventical Reference Frame - Dick Reyner

Break

The ITRF - Claude Boucher (60 minutes)

Combining international efforts to develop a global vertical reference frame - Dick Rapp (30 minutes)

Lunch

Cartwright (15 minutes)

International reports on global sea level - geodetic projects (210 minutes)

15 minutes or less presentations by Geoff Lennon, John Manning, S. Zerbini, Vidal Ashkenazi, C. LeProvost, B. Engen, A. Lambert, C. Boucher

Wednesday, December 15

The PSMSL Geodetic Data Base - Phil Woodworth (60 minutes)

Break

Discussions of conclusions and recommendations.

Lunch

IAG Special Study Group 5.149 - E. Groten (60 minutes)

Ad Hoc Committee - SSG Discussions

Joint Dinner and Free time.

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