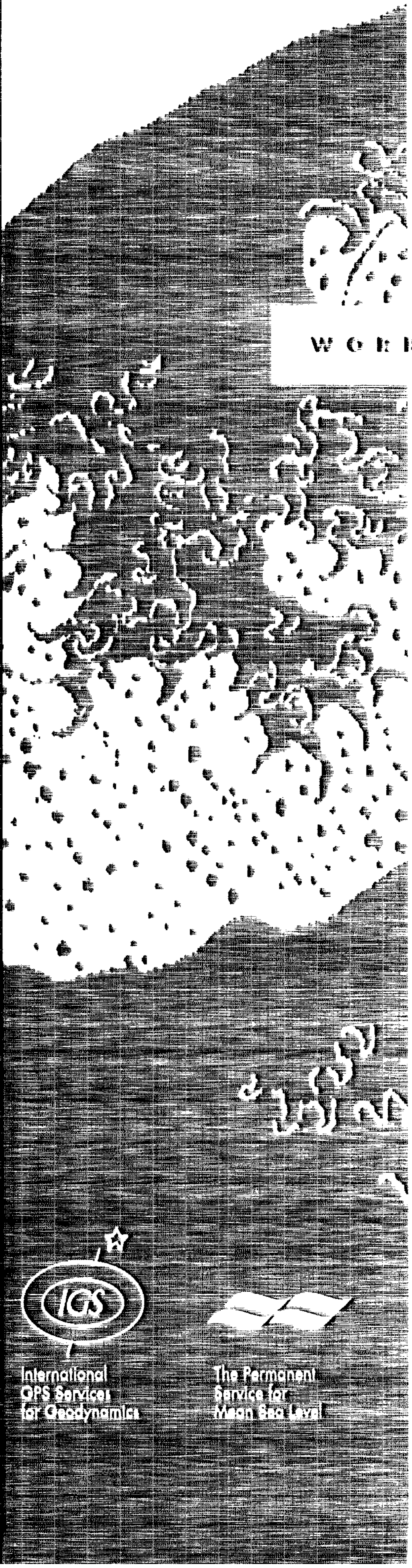

IGS-PSMSL

WORKSHOP ON METHODS FOR MONITORING SEA LEVEL

GPS and Tide Gauge Benchmark Monitoring and GPS Altimeter Calibration

PROCEEDINGS

MARCH 17-18, 1997

PASADENA, CALIFORNIA, U.S.A.

IGS Central Bureau

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California U.S.A.

Edited by

R. E. Neilan
P. A. Van Scoy
P. L. Woodworth

ABSTRACT

These are the proceedings of the first joint workshop between the scientific communities of the Permanent Service for Mean Sea Level (PSMSL) and the International GPS Service (IGS) regarding applications of the Global Positioning System (GPS) to monitoring sea level change. Two applications were highlighted: 1) monitoring and interpretation of tide gauge benchmark motion through collocation measurements of GPS and, 2) collocation of GPS at island and coastal title gauges to calibrate orbiting altimeter missions (e. g., TOPEX/Poseidon, JASON, etc.). The workshop covered the technologies, science and engineering issues, practical experiences, data management, and analysis. Summary recommendations from the final joint session are included.

ACKNOWLEDGMENTS

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Session 4: Practical Experience and Considerations: Projects Past and Planned

Co-chairs: T. Baker (POL), S. Zerbini (Univ. Bologna)

EXECUTIVE SUMMARY

Ruth Neilan
IGS
Phil Woodworth
PSMSL

The "Workshop on Methods for Monitoring Sea level: GPS and Tide Gauge Benchmark Monitoring and GPS Altimeter Calibration" was held at JPL on March 17 and 18, 1997, convened by the Permanent Service for Mean Sea level (PSMSL) and the International GPS Service (IGS). The Sea Level workshop was specifically organized to review the status in measuring changes in sea level as the third in a sequence of workshops over the past ten years. The first was held at Woods Hole Oceanographic Institution, Massachusetts, USA, 1988, and the second at the Institute of Oceanographic Sciences, Surrey, UK, 1993. These first two workshops resulted in the "Carter Reports. " It was the summary recommendations from the Surrey Workshop that was the catalyst for the organization of this workshop at a joint meeting between the GPS and Sea Level communities.

March 1997 IGS Analysis Center Workshop

The Sea Level workshop was preceded by an IGS Analysis Center workshop held March 12-14, and the plan to gain balanced GPS representation at the Sea level workshop was realized with participants from the IGS/ GPS community (see IGS Mail Message #1569 at http://igscb.jpl.nasa.gov). A number of the items discussed at the IGS Analysis Center workshop are of direct interest to participants in the Sea Level workshop, such as site-specific issues, rigorous combination of GPS solutions, and tropospheric studies with GPS.

Sea level Workshop Objectives

The summary recommendations and requirements from the 1993 Surrey Workshop targeted using the structure of the IGS and GPS to measure and understand the position and velocities of global tide gauge stations within the International Terrestrial Reference Frame (ITRF), with emphasis on the vertical velocities and accuracies at selected global locations. The 1997 Pasadena workshop focused on how the techniques of GPS and tide gauges can be applied to:

1) studying the long-term changes in sea level through understanding the deformation of the solid earth, particularly the vertical motions, and how this affects the observations of the tide gauge records and;

2) measuring the drift of the altimeter instruments for sea surface height determination on missions like TOPEX/ Poseidon, and several planned follow-on missions such as JASON, GFO, etc.

3) organizing those people and agencies involved in making such measurements, facilitating cooperation and soliciting sponsorship.

The summary recommendations from the workshop, which follow, clearly identify the next steps that must be taken in order to achieve these objectives.

5th IOC Gloss GE

On March 19-21, following the Sea Level workshop, the Fifth Session of the Intergovernmental Oceanographic Commission (IOC) Group of Experts on the Global Sea level Observing System (GLOSS) was held at JPL, hosted locally by the IGS Central Bureau. The agenda for this meeting included review and sanctioning of the recommendations set forth by the preceding Sea Level Workshop. Among many other issues, the meeting also addressed further formulation of GLOSS recommendations that serve as a guide for establishing activities related to the use of GPS; these recommendations are then sent to the many national oceanographic agencies. This is within the GLOSS Implementation Plan that takes into account new techniques applicable to sea level studies, including here GPS, satellite radar altimetry, absolute gravity, etc. This is promoted through the IOC of UNESCO.

This workshop was the first interdisciplinary workshop between these two scientific services and their communities whose activities are synergistic. Both the PSMSL and the IGS are member services of the Federation of Astronomical and Geophysical Data Analysis Services.

We would like to thank all attendees for their active participation and efforts to formulate the next steps in these activities. Many thanks also are due the session chairs for their interest in and dedication to organizing a successful workshop: Trevor Baker, Geoff Blewitt, Mark Merrifield, Gary Mitchum, Steve Nerem, Carey Nell, Mike Watkins and Susanna Zerbini. Finally, for the local organization details, thanks to Priscilla Van Scoy for her efforts in managing the logistics so very smoothly.

SUMMARY RECOMMENDATIONS
WORKSHOP ON METHODS FOR
MONITORING SEA LEVEL

1) For the purpose of monitoring and understanding long term changes in sea level, including the contribution of land motion to these changes, this group recommends that: Science Working group(s) be formed that interface with the IGS or are components of the IGS, at the Associate Analysis Center level (such as the Regional Network Associate Analysis Centers RNAAC), following all conventions established by the IGS Densification Project. (See this report for details.)

2) For the purpose of monitoring the drift of satellite altimeters it is recommended that: Approximately 10 additional stations be incorporated into the IGS gobal analysis and data flow. In order to realize the above objectives, it is further recommended that:

3) The IGS, in cooperation with the International Earth Rotation Service (IERS), produce vertical velocity estimates to be updated annually in addition to a height time series derived from GPS, expressed in the International Terrestrial Reference Frame (ITRF).

4) A working group on the free exchange of data be formed that includes representation from the GPS and Sea level communities, for the purpose of establishing necessary data links.

5) That science working groups that are established to address these developments ensure their representation under the umbrella of International Association for the Physical Sciences of the Ocean (IAPSO) and the International Association of Geodesy (IAG), including IGS, IERS, IAG Subcommission on Sea Level and Ice Sheets and the IAPSO Commission on Mean Sea Level and Tides.

6) A Technical Working Group be constituted to set up recommended standards and specifications for operating GPS at Tide Gauge sites, in collaboration with the IGS working group on "Site Specifications and Network Operations." This Working Group will consider, document and make recommendations on the following types of tide-gauge and site-specific information:

- making measurements for precise ties (e.g., between the GPS, the tide gauge, the tide gauge bench marks, the local reference networks, etc.)
- data handling of the survey tie information
- site stability aspects
- monumentation techniques
- collocation philosophy and observing methods (continuous measurement rationale)
- absolute gravity measurements for complementary information on vertical crustal movements and mass redistribution
- environmental parameters, meteorological sensors, ancillary measurements, etc.

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- environmental parameters, meteorological sensors, ancillary measurements, etc.

Poster Presentation (cent'd)

J. Kakkuri M. Poutanen J. Zielinski	(5) The Baltic Sea level Project - History, Present and Future
W. Schlueter J. Ihde W. Gurtner J. Adcsm B.G. Hoarson G. Wöppelmann	(6) European Vertical GPS Reference Network (EUVN) - Concept, Status and Plans
D.U. Sanli G. Blewitt	(7) Monitoring Tide Gauges Using Different GPS Strategies and Experiment Designs
M. Miller R. Weldon D. Johnson R. Palmer	(8) Variation in Sea level Change Along the Cascadia Margin: Coastal Hazards, Seismic Hozards and Geodynamics

Session 5: Data Handling
Co-chairs: Carey *Noll, GSFC (IGS Global Data Center),* and Mark *Merrifield, (UH* Sea *Level* Center)

11:10	C. Nell	Flow of GPS Data and Products for the IGS
11:30	M. Merrifield	Sea Level Data Flow
12:00		Discussion
12:30		lunch

Summary Session

Co-chairs: *Philip Woodworth* & *Ruth Neilan*

2:00

- Open Issues
- Development and Discussion of Workshop Summary Recommendations and Actions
- Discuss Potential observing Program/Projects
- Future Plans
- Workshop proceedings Schedule

5:30 Adjourn

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WORKSHOP OBJECTIVES AND SCIENCE QUESTIONS

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1NTRODUCTION TO THE WORKSHOP ON METHODS FOR MONITORING SEA LEVEL: G1'S AND TIDE GAUGE BENCHMARK MONITORING, GPS ALTIMETER CAL1BRATION

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BACKGROUND TO THE MEETING

This is the third major international meeting on geodetic positioning of tide gauge benchmarks during the last decade. The previous two were held at the Woods Hole Oceanographic Institution, USA in 1988 and the Institute of Oceanographic Sciences, Surrey, UK in 1993 and were organised under the auspices of the International Association for the Physical Sciences of the Ocean (l APSO) Commission on Mean Sea Level and Tides. Both meetings were chaired by Dr.Bill Carter from the National Oceanic and Atmospheric Administration (NOAA) and resulted in excellent reports (the 'Carter Reports') which have proved extremely useful for introducing the new geodetic techniques to non-specialists, and as authoritative international sources on which requests for national funding have been based.

This third workshop has been organised by the Permanent Service for Mean Sea Level (PSMSL) and the International GPS Service for Geodynamics (IGS), taking advantage of the fact that other important meetings on sea level and the Global Positioning System (GPS) arc planned to be held at the Jet Propulsion Laboratory (JPL) at around the same time. The intergovernmental Oceanographic Commission (1OC) is co-sponsoring the workshop because of the direct relevance to the development of the Global Sea Level observing System (GLOSS).

In the past few years, GPS has been demonstrated to be capable of providing accurate relative positioning between receivers which are both fixed and moving. The use of receivers at tide gauge benchmarks (Carter et al., 1989; Carter, 1994) and the tracking of TOPEX/POSEIDON (Melbourne et al., 1994) have provided notable examples, The IGS baseline network of receivers for precise GPS orbital information now serves many users, and the IGS itself has become a full member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) alongside the PSMSL. As almost 4 years have elapsed since the 'Surrey Meeting' on tide gauge benchmark fixing, it seems appropriate to review the field once again and to make plans for the future.

The meeting will address a number of questions, some of which arc shown below in italics to get people to start thinking about things, and some of which I have tried to answer in part, primarily from a tide gauge point of view. However, 1 am no GPS expert, so please let me know where I am wrong. Of course, the list of questions is not complete.

Why do Tide Gauge Data Analysts Need GPS?

First, continuous, or frequently repeated, geodetic positioning of tide gauge benchmarks is required in order to refer the gauge data to the same geodetic datum (e.g. reference ellipsoid) as satellite radar altimeter information is already. This opens the possibility of using geodetically-controlled gauges (primarily on islands) to provide an ongoing 'absolute calibration' of altimeters. If many such gauges have GPS receivers (and DORIS at a number of locations, which is logical as the same DORIS receivers will be tracking the satellites), they could be thought of as forming one big 'gauge', which will be insensitive to individual gauge data drop-outs. Even if one confines oneself to 'relative' altimeter calibrations (e.g. that of Mitchum, 1996), in which one attempts to calibrate altimeter heights with respect to a constant, although arbitrary overall, datum, then information on vertical land movements at the gauges obtained from GPS is required in the long term, Altimetry calibration using GPS will form a major topic of the meeting.

Geodetic positioning of gauges is also required in order to determine the absolute ocean currents which may flow between them, in a similar fashion to the application of altimeter data, once precise geoid information is available.

The most obvious application of GPS, the topic which primarily motivated the two 'Carter reports', is to the determination of rates of vertical land movements at gauges in order to provide estimates of 'real', rather than 'land relative', sea level secular trends. In such investigations at present, records of typically 40-60 years or longer are employed to establish reliable trends with a 'statistical' error lower than about 0.5 mm/year. (The error is not really 'statistical' of course, it arises from the interannual variability in the records). Estimates of rates of vertical land movements are then subtracted from the observed trends in order to provide a determination of 'real' sea level change. In most analyses, this subtraction is performed by means of a model of present-day vertical land movements arising from post-glacial rebound (PGR) (IPCC, 1995). This necessitates an intelligent filtering of the tide gauge sites in order to select locations which are 'far field' from areas of maximum rebound (i.e. far from Scandinavia and northern Canada) and which are not subject to other major, unmodelable geological processes. See Douglas (1 991) for an excellent example.

The advent of GPS can radically modify this approach if accurate rates of vertical land movements can be measured in a decade or so by GPS, and real measurements are always better than simply modelling something. Consequently, data can bc used for trend studies from all gauge sites equipped with GPS, including Scandinavia (with its many fine, long gauge records) and even earthquake-prone areas, Therefore, the potential for wider global sampling of reliable long term trends will be much improved.

In the medium term (i.e. approximately the next 10-20 years), the maximum benefit will be derived from the deployment of GPS at sites with existing tide gauge records several decades or longer, rather than at entirely new sites (Carter, 1994). If rates of vertical land movement prove to be essentially linear, they may be applied with confidence to the historical gauge record.

Although GPS will be the main technique used for this work, absolute gravity measurements could provide important parallel data sets in some countries (Carter et al., 1997). GPS, absolute gravity and other such measurements have the advantage that they need not bc employed solely at tide gauge sites. For example, they can be located in in-land areas of maximum rates of PGR uplift, providing a comprehensive testing of the geodynamic models.

What Accuracies are Required?

For altimetry calibration, and for a range of other applications such as absolute surface current determination, height accuracies of order 1-2 cm must be achieved and must bc maintained in the long term. This value is comparable to the accuracy of a TOPEX-class altimetric measurement system, and to the accuracy of geoid-differences in locations where good geoid models are available (e.g. order 1 cm in 300 km for the North Sea, which would include, for example, gauges either side of the 30 km wide Straits of Dover).

The Surrey workshop discussed in some detail accuracies required for long term trend studies, which still seem valid. in brief, as long term tide gauge trends arc known to approximately 0.3 nlnl/year (from half a century or so of data), GPS measurements of land movements (over any required epoch) must strive to achieve similar accuracies. If one aims at this accuracy over 20 years or so, then accuracies in height of 1-2 cm arc again required. (In principle, continuous accuracy of 1 cm for a decade would give 0.3 mm/year).

For reference, the two main requirements for trends identified in the Surrey report were:

* The minimum accuracy for vertical crustal velocities to bc useful for sea level studies is estimated to bc 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.

* Global absolute sea-level monitoring must bc developed around the ITRF (International Terrestrial Reference Frame).

It can bc seen that the first requirement now has a slightly different slant, altimeter calibration using gauges was not such an issue in 1993, but that the requirements are in general the same.

So Does GPS Work Anyway?

This means several things. First, are the receivers technically capable of providing consistent, accurate data in the long term? What are the time-dependent systematic errors e.g. from antenna phase centre variations and the troposphere? Should permanent receivers be a firm recommendation? If funds arc not available for permanent receivers, what experience has been acquired on short deployments? (Session 4 of the workshop will include results from such short-deployment campaigns as well as from continuous measurements).

Then, are there agreed common methods for processing the data to give consistent station coordinates and velocities? In Europe at least, each GPS group seems to have software capable of providing apparently accurate and repeatable station coordinates, but coordinates derived from the same data sets show significant differences between groups, Recently, onc source of difference was traced to something as obvious as inclusion (or not) of the permanent tide in the height reference. The same international Earth Rotation Service (IERS) standards are not being followed by all groups.

Presumably the development of a network of IGS Regional Associate Analysis Centres (AC's) (see below) will lead to common standards. However, if more research is required in any area, can this meeting flag what is needed?

What are the IGS Arrangements for Delivering GPS Data to Users such as Tide Gauge Analysts (e.g. PSMSL)?

The formation of the IGS provides an organisational framework within which G1'S measurements at gauges and elsewhere can be made, with estimates of land movements at gauge sites eventually combined with the tide gauge data in order to provide a decoupling of land and ocean level signals in their records. As I understand things, the IGS plans to have a network of Regional Associate Analysis Centres providing station coordinates and velocities in its area.

First, 'velocities' implies that the Centres will have an archiving and reprocessing function? This is different to the situation at present, in Europe at least, where most work is being performed by university GPS research groups with the uncertainty in long term archiving that implies.

Second, will the IGS Central Bureau play a role in grouping the data sets of the Regional Centres or, if we (PSMSL, for example) want a global data set, do we have to maintain links with N Regional Centres?

'1'bird, if the cost of receivers falls to the extent that there are several hundred gauges with GPS around the world (see the 1997 GLOSS Implementation Plan, for example), will the network of AC's be able to handle them all?

Fourth, if GPS recording is episodic at a gauge (say for a four day period every year), then presumably the AC will produce station coordinates flagged by the epoch. However, if recording is permanent, with what frequency will the AC produce coordinates? Daily?

Fifth, is there a policy on what constitutes a 'station coordinate' or 'velocity'? Presumably they are with full technical and environmental corrections (i.e. ionosphere, wet/dry atmosphere etc.) but do they have geophysical corrections such as atmosphere and ocean tidal loading as well? Presumably these things will be well documented?

Sixth, what software developments do the PSMSL and other sea level centres have to make to accommodate GPS data? For example, if the PSMSL simply stored GPS velocities measured over a particular epoch, which is certainly the primary parameter of interest, that would be very simple to handle. But analysts may want access to time series of GPS heights if, for example, there had been abrupt land movements due to earthquakes at some time. Then there is the messy question of handling the information on local GPS-gauge tics within the data sets (see below). Would the GPS people be responsible for holding that information in their data sets, or the sea level centre?

Then, when can we expect the first GPS data in 'final' form?!

How do Non-Specialist Groups Get into GPS?

imagine that you have operated a tide gauge for many years in, say, the Maldives. You have a good long record and you now want to get into GPS; you have probably read about it all in the Carter reports. However, your country does not have a leading GPS research group. What do you do?

The IOC has published two manuals in the last decade or so on 'how to operate a tide gauge'. Is it possible for a third manual to be written on 'how to operate GPS at a tide gauge'? Do wc have a volunteer to edit it? (Note that a recent IERS Workshop (IERS, 1997) also recommended that this J]}], meeting be asked to prepare technical specifications on these issues and that the specifications be prepared with contributions of several (e.g.IERS) geodetic experts).

Presumably the manual would cover antenna choice and site monumentation (the effective maintenance of tide gauge benchmarks is already stressed heavily in the first two manuals, but special arrangements will be required for GPS), requirements for power supplies and data flow (which AC would the data go to?), and the need for local ties (already stressed as being required annually in the first Carter report). It would have to include advice on receiver manufacturers etc. Does such information already exist at the IGS or elsewhere which could be re-edited for our purposes?

The Problem of Ties

In many countries, tide gauge operations are the responsibility of hydrographic organisations or flood defence people and not the national geodetic or surveying agency. Sometimes the different organisations communicate well, sometimes not. In some places the geodetic people make the regular local ties between gauge and benchmarks, in others the tide gauge people are quite capable of doing the work. However, almost always the ties are typically 10's or 100 m.

However, the situation with gauges and GPS can be seen to be a more difficult one if GPS is operated some distance from the gauges, as is already the case at a number of locations where there are permanent IGS receivers within a few km of a gauge.

In that case, who does the ties? Who pays? Is a special effort needed to make ties at a number of priority gauge sites for altimeter calibration purposes? How should the ties be made, with GPS or conventional levelling? How often? What are the relative accuracies? Does the accuracy of the tie degrade significantly the overall system accuracy which we require for the science? How is the information on ties data banked? There is scope for a sub-committee here!

Recommendations?

The 'Surrey Report' made two main recommendations:

* Recommendation 1: 'l'he President of the Mean Sea Level and Tides 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 Terrestrial Reference Frame. The products should be coordinates and velocities of the tide gauge stations bench reference marks in the ITRF systcm.

* Recommendation 2: The Permanent Service for Mean Sea Level (PSMSL) archiving system would 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.

The fact that this JPL meeting is taking place, and with such an interesting agenda, shows that the two Surrey recommendations are being acted upon. The various papers stemming from the meeting will provide an essential overview of the status of research, thereby providing a guide to work over the next few years. However, can more formal recommendations be made, such as:

Arc there recommendations which can be transmitted to the fifth session of the IOC GLOSS Group of Experts which follows this workshop? The fourth session of the Group

(IOC, 1995), attended by experts from the IGS, gave particular consideration to the role of GPS within GLOSS, and the Group will address the issue again in its fifth session. Advice and recommendations of the workshop will be used by the Group to formulate specific actions to bc addressed by IOC Member States in respect of GLOSS development.

Arc there recommendations to be transmitted to IAPSO or the International Association of Geodesy (JAG)? Note that recommendations of a recent IERS Workshop (IERS, 1997) were broadly consistent with those discussed in the two Carter Reports.

Arc there detailed recommendations (e.g. for the line research should take) which we can identify and act upon at national and regional levels?

All these recommendations will be ncluded n the Proceedings of the Workshop.

POSTSCRIPT (APRIL 1997)

It is extremely encouraging that so many oft ıe questions Ii steal above, and many others, were addressed at the Workshop. In particular, the organisational framework suggested by Geoff Blewitt for GPS data processing, leading to data flow to the PSMSL and other sea level centres, provides a basis around which planning can now take place. In addition, the formation of the Workshop Technical Committee should lead to important practical recommendations for operating GPS near to, or at, gauges, which will benefit everyone.

On behalf of the PSMSL half of the organisation of the Workshop, I would like to thank everyone concerned for the many stimulating sessions, a number of papers from which are included in this volume. In addition, 1 would like to thank the IGS Central Bureau for their hospitality at JPL.

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IGS-PSMSL

THE MEASUREMENTS — AN INTRODUCTION

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Summary of Session 2
The Measurements - An Introduction

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On the assumption that the workshop would include people with a broad range of expertise, and with experience in very different areas that might not overlap, it was decided to start with a review of the three types of measurements that were expected to be discussed at some length during the workshop. These three were GPS measurements, sea level measurements with tide gauges, and sea surface height measurements with satellite altimeters, It was expected that workers in any one of these areas might very well not be familiar with even the basic instrumentation used in one of the others. For example, someone very knowledgeable with GPS instruments might have only a rudimentary understanding of how tide gauges work and would probably have very 1 ittle information at all about the t ypcs of errors to be expected, or even the order of magnitude of these errors.

Based on this assumption about the attendees of the workshop, we scheduled three talks, one each on GPS, tide gauges, and altimetry, that were aimed at people who were not experts in that type of measurement system. The first talk on GPS measurements was given by Mike Watkins, the second talk on tide gauge measurements was given by Gary Mitchum, and the last on altimetry was given by Steve Ncrcm. The main points made in each talk were as follows.

The first talk, by Mike Watkins, was focused on GPS measurements in general, and on the vertical rate estimates in particular. He stated that getting vertical rates to a precision of 1 mm/yr is challenging and noted two important issues for getting good vertical results. First, he emphasized the desirability of maintaining continuity of equipment. By this, hc meant that it is necessary to minimize equipment changes (receiver, antenna, mounting set-up, even nearby multi path sources and sky blockages) for periods of years. Second, he recommended that if one desires to measure the tectonic motion of a site, as opposed to measuring motion of a tide gauge including subsidence and other nontectonic causes, then the monumentation must be of high stability and quality. He reviewed previous studies showing that Wyatt-style tripods or certain types of massive structures have been found to be acceptable for this purpose. Watkins' talk concluded with a discussion of the analysis of the data, and he pointed out that the analysis of the data need not be coupled into the complex orbit determination process, that it can be highly automated, and that it could even take place months after the fact, if necessary.

The second talk by Gary Mitchum introduced tide gauge measurement of sca level, which was carefully distinguished from the open ocean measurements of sea surface height made by satellite altimeters. The important distinction is that sea level is only defined in reference to a benchmark on the adjacent land, and is not known relative to a reference ellipsoid, as is the case for satellite altimetric measurements. Mitchum pointed out the importance and difficulty of maintaining an appropriate set of benchmarks, and of carefully and regular] y checking the heights of the benchmarks with traditional surveying techniques. An overview of tide gauge instruments was made, but most of the emphasis was on float-type gauges in stilling wells, as this is still the most common type of gauge in the global network. Much of the emphasis in the instrumentation part of the talk was on the role of the tide staff, or tide pole, which many people may not recognize as an integral part of the system. It was pointed out that the tide staff is ultimatel y the source of the long-term vertical stability of the measurements, and the importance of doing regular staff observations was described as essential to making high quality sea level measurements.

Mitchum's talk concluded with an assessment of the errors in the tide gauge system. It was estimated that the errors in the benchmark and tide staff surveys, and errors in the tide staff observations themselves, lead to temporal trend errors on a decadal time scale that were of order 0.5 mm/yr, which is negligible relative to decadal trends duc to true ocean signals. In assessing the errors duc to the tide gauges, a set of calculations involving "replicate" measurements from independent tide gauges separated by less than a fcw meters was presented. The result was that daily sca levels derived from traditional float-type gauges have instrument errors of order 0.5 cm, which is an order of magnitude less than the ocean signals at these time scales. Finally, it was shown that these error estimates were completely consi stent with intercomparisons between t idc-gauge sca levels and altimetric sea-surface heights. It was also argued that errors duc to small-scale distortions of the sca surface height field near the land, which is often argued as being responsible for tide gauge/altimeter differences, arc probably not a very serious problem.

The final presentation in this session was given by Steve Nerem, and was focused on satellite altimetry measurements, and on TOPEX/Poseidon (T/P) measurements in particular. Ncrcm emphasized the precision of the data returned from modern altimeters, such as T/P. Specifically, through improvements to the instrument and orbit determination, T/1' has demonstrated a sca-level measurement accuracy of 3-4 cm, which in turn produces a global mean sea level measurement repeatabi lit y of 4 mm for 10-day averages. This is much better than previous missions such as Seasat, Geosat, and ERS-1.

The precision and accuracy of the global mean sca level is of particular importance, as it is this measurement that can be interpreted as variations in the total volume of the ocean, which is the variable that sca level rise estimates from tide gauges arc truly aimed at inferring. Ncrcm emphasized that assessing long-term trends in sca level using the T/P data requires an independent assessment of the instrument performance, which he argued is most easily achieved using the global tide gauge network. 1 Ie pointed **out** that Mitchum [scc the article in these proceedings under session 3] has demonstrated the feasibility of this approach, having determined the drift in the T/P sea surface heights to about 1 mm/year. GPS monitoring of the tide gauge positions would significant] y improve the accuracy of this technique,

Nerem concluded with a brief discussion of future altimetry missions, pointing out that the extension of the T/P sea level time series via follow-on missions, such as Jason, will require intercalibration of the altimeters. This intercalibration can also be accomplished with tide gauges if there is a gap between the missions. Finally, he pointed out that linking together multiple missions to establish a multi-decadal time series of sea level change could allow the detection of a “geographic fingerprint” of climate change in the sea level record.

AN OVERVIEW OF TIDE GAUGE MEASUREMENTS

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ABSTRACT

Sea level (measured by tide gauges) and sea surface height (measured by satellite altimeters) are defined and ditinguished. The instrumentation used to measure sea level is briefly described, with an emphasis on the problem of defining and maintaining a consistent vertical reference point. Rough estimates of the errors involved in sea level measurements are given.

INTRODUCTION : DEFINITIONS AND COORDINATE SYSTEMS

The aim of this paper is to provide a brief introduction to some of the issues involved in measuring sea level with tide gauges. It will not serve as a manual for operating tide gauges, and readers who are already familiar with sea level measurements are not the intended audience. It is mainly intended for people from other disciplines who need to cooperate with tide gauge operators, and who need an introduction to some basic terminology, to understand the principles involved in making sea level measurements that are useful for research purposes, and to obtain a rough idea of the errors to be expected in these measurements. Additional, more detailed, information can be obtained from the publications cited in the References section at the end of this paper. These cites are not exhaustive, but can serve as a starting point for readers interested in further reading.

A good place to begin might be by establishing a distinction between measurements taken by tide gauges, which I will refer to as *sea level*, and those made by satellite altimeters, which I will call *sea surface heights.* Sea level, as I define it, is strictly defined only at the boundary where the ocean meets the land, and it is the height difference between the level of the sea surface and the level of a fixed point on the adjacent land. Obviously this definition has no meaning in the open ocean where an altimeter measures sea surface heights. It is tempting to view sea level as the boundary value of sea surface height, but this can be misleading, as the sea surface height and the sea level have different zero points. In fact, different tide gauges also have different zero points as well.

Typically sea surface heights from an altimeter are defined relative to a reference ellipsoid, and the tide gauge zero points can be placed in the same reference system by the use of appropriate geodetic measurements, GPS for example. While GPS can provide a common reference surface, it should be noted that this is not a very desirable one for an oceanographer attempting to use the sea levels (or sea surface heights) for the purpose of studying ocean dynamics. The reason for this is simply that the dynamical equations in oceanography use a vertical coordinate that is defined as perpendicular to the vector sum of the force of gravity and the centrigufal force due to the Earth's rotation. The appropriate zero point, then, is a geoid, or a equipotential surface for the resultant force. At present the geoid is not known accurately enough to use it as a reference surface for oceanographic applications, but this should be the long-term goal, In the meantime, measurements such as GPS can provide a useful interim reference point. Sea level measurements referenced in this fashion can be used in studies of changes in the ocean volume, but cannot be used to estimate mean surface currents, for example. While this point may seem obvious to some readers, I have found it to be a point of confusion for many non-oceanographers.

Returning to the subject of tide gauges, the vertical reference point is a *benchmark* on the ajacent land. This benchmark on the land is typically connected to a *tide gauge* by traditional surveying techniques, usually by the use of a *tide staff* (also known as a tide pole). These three components of the complete tide gauge system are described in the following section. In the final section the errors to be expected from this system are briefly discussed.

BASIC COMPONENTS OF THE TIDE GAUGE SYSTEM

A benchmark on the land near the tide gauge provides the fundamental zero point for the sea level measurements, and is thus a critical part of the system, a fact that is sometimes overlooked. Several points are important to consider in the placement and maintenance of benchmarks. First, it is essential to place an local array of multiple benchmarks near the tide gauge. Some locations chosen may not be stable, and this can be determined by intercomparison of the surveyed heights of the benchmarks relative to one another. More importantly, though, is the fact that benchmarks can often be lost or destroyed, Tide gauges are usually located in busy ports and harbors, and constant construction and activity is a fact of life in such places. It should be assumed that benchmarks will lost over time and have to replaced with new ones. As long as at least several of the benchmarks in the array are available from one survey to the next, useful results can be obtained. Careful placement of the benchmarks can minimize these sorts of problems, and they should be placed on stable structures that are deemed most likely to remain in place for long periods of time. For example, it has been suggested that a good location for a benchmark is the jail nearest the tide gauge, the idea being that jails are likely to remain useful and necessary for long periods of time.

The benchmarks are ultimately tied to the tide gauge itself via a tide staff, although recently some types of tide gauges are designed to be surveyed into the benchmark array directly. There are also a number of strategies that maintain the tide gauge connection to the benchmarks automatically. But the most common and best understood system remains the one that uses a tide staff, and this paper will focus on that system. Briefly, the tide staff is simply a calibrated rod that is placed near the tide gauge at a location where the instantaneous water level height can be read off directly by a human observer. When the benchmarks are surveyed, the tide staff is placed in the same coordinate system by measuring the height of the staff zero point relative to the benchmarks. The problem then becomes one of referencing the tide gauge observations to the zero point on the tide staff.

In order to relate the tide gauge measurements to the tide staff zero, the human observer directly reads the sea surface height from the staff several times a week, noting the time of these observations, which are actually an average of a number of measurements taken over a few minutes, and the values measured by the tide gauge at those times is also noted. The gauge measurements can then be regressed against the staff measurements in order to calibrate the tide gauge to tide staff zero. This regression typically uses more than one year of observations, which is necessary because the staff measurements are noisy. Experience indicates, however, that the staff measurements are quite independent of one another and that the errors average down quite rapidly. It is important, however, that the regression must be done only on many tide staff observations (I recommend at least a year's worth of at least weekly observations), otherwise the error in determining the tide gauge zero point is too large. These errors will be discussed a bit more in the next section. It should also be noted that the staff to gauge regressions are generally only used to monitor the stability of the gauge time series, and adjustments to the data are only made when a clear drift or shift has occurred.

It is interesting to note that for researchers interested in low frequency variability, the staff measurements can easily be viewed as the more fundamental observations of the sea level. The tide gauge can be viewed as being forced to agree over long time periods with the tide staff, and as simply providing a temporal interpolation between staff readings, thus allowing better measurement and removal of high frequency signals, such as tides and storm surges, that are aliased in the temporally more sparse staff readings. The advantage of using the noisy, but very direct, measurements of sea level provided by the tide staff is that it circumvents the need to assume that the tide gauge itself is free of low frequency drift, which is a sensible assumption to avoid with any mechanical instrument.

Turning finally to the tide gauge itself, this is most simply described as any system that can determine the height from some fixed point in the instrument to the sea surface. Many different devices are available. Some types depend on a pressure measurement, which converts a subsurface pressure measurement to a height from the pressure sensor to the sea surface by measuring or assuming values for water density and air pressure. Another common type of modem gauge determines the distance to the sea surface by measuring the travel time of an acoustic pulse that is reflected from the sea surface. These acoustic gauges return high quality data and are becoming more common, but the most common type of gauge is still a traditional stilling well and float arrangement. In this type of gauge a counterbalanced float follows the sea surface and the height measurement is taken by measuring the length of the wire holding the float. The stilling well is a tube, usually about 30 cm in diameter, that has only a small orifice open to the sea. This limited connection acts to provide a mechanical filtering of high frequency (periods less than tens of seconds) surface gravity waves. Note that stilling wells are not unique to float gauges, but are also used with most acoustic gauges.

In summary, the complete tide gauge system usually consists of a float type gauge in a stilling well that measures the height of the sea surface to a fixed point in the gauge. This measurement is calibrated to the tide staff observations in order to convert that height to a height relative to the zero of the tide staff, and also to insure that the height measurements made by the gauge does not drift. The tide staff zero is in turn calibrated to the benchmarks via periodic surveys that make the measurements relative to the height of the adjacent land. These surveys also serve to monitor the stability of the tide staff.

MEASUREMENT ERRORS

I will conclude with a brief discussion of the errors to be expected in sea level measurements from tide gauges. This discussion is more aimed at introducing some of the sources of error, and providing order of magnitude estimates for them, than it is at doing a detailed error analysis, which is beyond the scope of this paper. There are three sources of error that I will mention. First, there are errors in connecting the benchmarks to the staff during the surveys. Second, there are the errors in the tide staff measurements made by the human observer. Third, there are the instrument errors in the measurements taken with the tide gauge itself. I will also take a brief look at the errors in the overall system by comparing to observations from the TOPEX altimeter. This comparison probably does not quantify the tide gauge errors, as much as it places limits on the errors and serves to verify some of the analysis of the components of the tide gauge system.

Consider first the errors due to surveying the staff and the benchmarks. The errors in these surveys is roughly proportional to the length of the line surveyed and the error (in millimeters) can be estimated as 4(D)%, where D is the distance in kilometers. Typically, the local benchmarks and the staff are within approximately 1 km, so the inferred error should be of order 0.5 cm. A check on this estimate can be made by noting that there is typically an array of benchmarks. When a circuit is made of the benchmarks, which starts and ends at a particular benchmark, the "closure" in the height measurements should also be of 0.5 cm. This is in fact the case.

If the surveys are done annually in order to detect drifts, and the annual surveys are taken to be independent, then the drift error after 10 years of measurement will be less than 0.5 mm/yr. Given that true ocean signals can have trends much larger than this on decadal time scales, this error seems to be sufficiently small. Of course, this assumes that the surveys are being done consistently and carefully, and assuring this is the most important task of the person overseeing the operation of a particular tide gauge.

The observations of the tide staff by the human observer is a frequently criticized part of the overall system. I believe, however, that this concern is probably overstated. The noise associated with an single staff reading is admittedly large, of order 5-10 cm, But the error in the staff to gauge calibration is essentially equivalent to the standard error of the mean staff reading computed over the observations taken in the time period used to do the calibrations, and, as argued above, this should not be done on less than annual time scales. By taking 2 observations a week for a year, one obtains 100 independent observations. The standard error of the mean is then 0,5 - 1 cm, which is comparable to the precision of the annual surveys, and therefore produces a similar long-term drift error of order 0.5 mm/yr on a decadal time scale.

If this analysis is essentially correct, then it should be possible to use the tide staffs alone to observe low frequency (periods greater than 1 year) sea level variations. Figure 1 shows a case where this is indeed the case, The data for this comparison are taken from Yap Island in the western tropical Pacific. This station was chosen because it has not been necessary to adjust the tide gauge with the staff data for over 15 years, meaning that the staff data and the gauge data have been kept completely independent. The tide gauge data in this figure are simple monthly means computed from hourly observations. The staff data are monthly averages obtained after correcting the staff readings with an extremely simple tide model, which consisted of only 4 tidal components that were fit directly to the very sparse staff measurements, This is necessary because the tides are obviously badly aliased in the staff readings, much as they are in altimetry data. The two time series are obviously highly correlated ($r>0.8$) and a spectral analysis (not shown) reveals that at periods longer than about 1 year the coherence exceeds 0.95, the phase is within a few degrees of zero, and the response function (the ratio of the autospectra) is indistinguishable from 1, which means that one could use either series to study interannual variations in sea level, at least at this station. This sort of agreement would not be possible if the staff measurements were much noisier than I have estimated above, or were subject to serious systematic errors.

In order to estimate the errors in the tide gauge instruments themselves, an analysis was done at a number of sites in the University of Hawaii's Pacific island sea level network where redundant instruments were installed in order to increase reliability. At these stations there were two essentially identical instruments installed within a few meters of one another, Differences between these two instruments are therefore interpreted as measuring the precision of the instrumentation, similar to how one might use replicates in a laboratory setting. The result of this comparison is that daily sea level differences between two standard float type gauges typically have a standard deviation of only 0.5-1 cm. Larger errors were certainly found, but were always traceable to errors in the operation of the gauge, and these errors were rather easy to detect during routine quality control of the time series. Again, as was the case for the surveying, the important point is that the only large errors were due to careless operation, and insuring careful maintenance of the instruments is crucial to returning high quality data. If this is done, the errors of measurement are manageable.

From these "replicate" analyses it is difficult to justify errors for the tide gauges that are much larger than 1 cm, and smaller estimates are probably more reasonable. A more

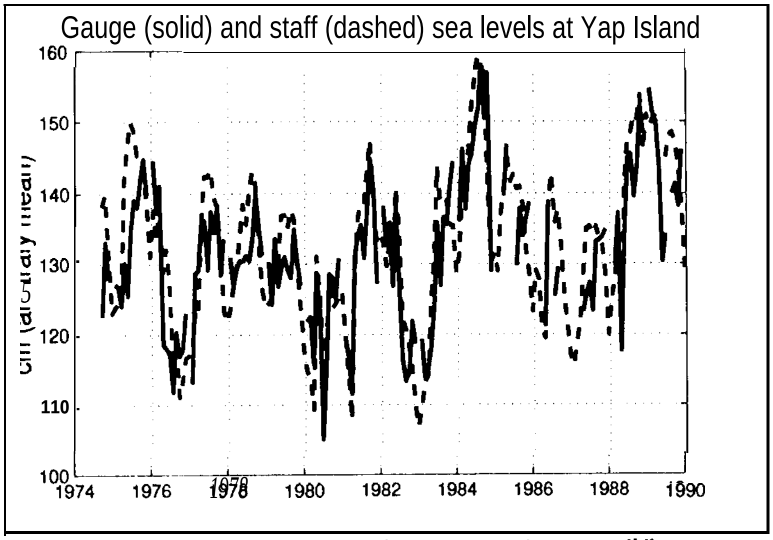

Fig. 1. Comparison of sea level from a tide gauge vs. that from a tide staff.

significant error has nothing to do with the measurement system itself, but with the signals the gauge is measuring. Usually it is desired that the sea levels be interpreted in terms of the surrounding oceanic variability, but the problem is that there can be relatively small-scale signals near the coasts that complicate this interpretation. This error is more difficult to assess, but some progress can be made by noting that comparisons between tide gauge sea levels and TOPEX-derived sea surface 'heights agree to approximately 4 cm on daily time scales (Mitchum, 1994) and to 2 cm on monthly time scales (Cheney et al., 1994). These errors are much larger than can be accounted for with errors in the tide gauge measurement system itself, and must therefore be attributed to either small-scale distortions around the gauges, or to errors in the sea surface height measurements.

It is worth noting that 4 cm is not a very large error even if we are only considering the altimeter alone, meaning that it may not be necessary to attribute any significant error to the tide gauges at all. A more pessimistic estimate (from the tide gauge point of view) might be derived by assuming the tide gauge and altimeter errors are comparable, each being of order 3 cm on daily time scales. Although I will not go into detail here, some recent results (Mitchum, 1997) from an analysis of the covariance structure of the TOPEX, tide gauges differences suggests that the former interpretation is more reasonable; i e., that the majority of the 4 cm mismatch on daily time scales can be accounted for by the errors in the sea surface height measurements.

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The Contribution of Satellite Altimetry to Measuring Long-Term Sea Level Change

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Abstract

This paper assesses the prospect of measuring long-term sea level variations using satellite altimeter data from the TOPEX/POSEIDON (T/P) mission, where global mapping of the geocentric height of the ocean surface is routinely achieved with a point-to-point accuracy of better than 4 cm, The global mean sea level variations measured by T/P every 10 days have an RMS of 4 mm and a rate of change +2.1 ± 1.3 mm/year, after accounting for instrument drift using the global tide gauge network. A likely cause of the observed instrument drift is the microwave radiometer, which provides the water vapor delay correction, but other causes which may contribute as well. Maps of the geographic variability of the observed sea level trends are dominated by the recent ENSO event, and thus any climate change signals cannot currently be isolated. These results suggest that T/P, when combined with tide gauge monitoring of the satellite instruments, is achieving the necessary accuracy to measure global sea level variations caused by climate change, although a longer time series is necessary to average out possible interannual and decadal variations. In addition, GPS monitoring of the tide gauge positions would greatly strengthen the accuracy of the altimeter calibration estimate.

1. Introduction

Traditionally, global sea level change has been estimated from tide gauge measurements collected over the last century. However, two fundamental problems are encountered when using tide gauge measurements for this purpose. First, tide gauges only measure sea level change *relative* to a crustal reference point, which may move secularly at rates comparable to the sea level signals expected from climate change *[Douglas,* 1995]. Direct monitoring of the geocentric location of the tide gauges using precise space geodetic techniques [Carter *et al., 1989]* is clearly warranted, but this has yet to be implemented at a sufficient number of tide gauge sites, Second, several investigators have discussed the difficulty of measuring mean sea level variations with tide gauges because of their limited spatial distribution and "noisy" coastal locations [*Barnett, 1984; Groger and Plag,* 1993]. Nevertheless, tide gauges have been carefully studied for indications of global sea level rise because they offer the only source of historical precise long-term sea level measurements *[Emery and Aubrey*, 1991; *Warrick et al.*, 1993; *Douglas, 1995]. Douglas [1991; 1992]* has argued that by selecting tide gauge records of at least 50 years in length and away from tectonically active areas, even a limited set of poorly distributed tide gauges can give a useful estimate of global sea level rise. However, averaging over such a long time period makes the investigation of shorter terms changes difficult.

The most recent studies of mean sea level rise from tide gauge data [*Peltier and Tushingham*, *1989; Trupin and Wahr*, 1990; *Douglas, 1991; Unal and Ghil, 1995]* have all relied on adopting a model of the post-glacial rebound (PGR) of the crust [*Lambeck, 1990]* using the "ICE" models [*Tushingham and Peltier*, *1991].* After removing crustal rebound trends, they produce estimates of global sea level rise of between +1.75 and 2.4 mm/year. Earlier results computed without the removal of PGR effects generally show smaller rates (see *Douglas* [1995] for a recent review). In addition, the issue of global sea level acceleration is also a topic of interest, since this would corroborate predictions obtained by some climate models *[Houghton et al.,* 1996]. However, the models predict an acceleration of up to 0.2 mm/year^2, which is an order of magnitude greater than has

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1. Introduction

Traditionally, global sea level change has been estimated from tide gauge measurements collected over the last century. However, two fundamental problems are encountered when using tide gauge measurements for this purpose. First, tide gauges only measure sea level change *relative* to a crustal reference point, which may move secularly at rates comparable to the sea level signals expected from climate change *[Douglas,* 1995]. Direct monitoring of the geocentric location of the tide gauges using precise space geodetic techniques [*Carter et al., 1989] is* clearly warranted, but this has yet to be implemented at a sufficient number of tide gauge sites. Second, several investigators have discussed the difficulty of measuring mean sea level variations with tide gauges because of their limited spatial distribution and “noisy” coastal locations [*Barnett*, 1984; *Groger and Plag, 1993].* Nevertheless, tide gauges have been carefully studied for indications of global sea level rise because they offer the only source of historical precise long-term sea level measurements [*Emery and Aubrey, 1991; Warrick et al., 1993; Douglas, 1995]. Douglas [199 1;* 1992] has argued that by selecting tide gauge records of at least 50 years in length and away from tectonically active areas, even a limited set of poorly distributed tide gauges can give a useful estimate of global sea level rise. However, averaging over such a long time period makes the investigation of shorter terms changes difficult.

The most recent studies of mean sea level rise from tide gauge data [*Peltier and Tushingham, 1989; Trupin and Wahr, 1990; Douglas, 1991; Unal and Ghil, 1995]* have all relied on adopting a model of the post-glacial rebound (PGR) of the crust [*Lambeck,* 1990] using the “ICE” models [*Tushingham and Peltier, 1991].* After removing crustal rebound trends, they produce estimates of global sea level rise of between +1.75 and 2.4 mm/year. Earlier results computed without the removal of PGR effects generally show smaller rates (see *Douglas [1995]* for a recent review). In addition, the issue of global sea level acceleration is also a topic of interest, since this would corroborate predictions obtained by some climate models *[Houghton et al., 1996].* However, the models predict an acceleration of up to 0.2 mm/year^2, ‘which is an order of magnitude greater than has been observed in the tide gauge data of the last century [*Woodworth, 1990; Gornitz* and *Solow,* 1991; *Douglas, 1992; Douglas, 1995].*

Clearly, validation of the tide gauge results is needed using an independent global measurement technique. In principle, satellite altimeters should provide improved measurements of global sea level change over shorter averaging periods because of their truly global coverage and direct tie to the Earth's center-of-mass. Satellite altimeters provide a measure of *absolute* sea level relative to a precise reference frame realized through the satellite tracking stations whose origin coincides with the Earth's center-of-mass. However, for altimeter missions such as Seasat, Geosat, and ERS - 1, errors in the satellite altitude and measurement corrections obscured the sea level rise signal *[Wagner and Cheney, 1992].* Many of the limitations of previous altimeter missions have been corrected or improved with the TOPEX/POSEIDON (T/P) mission [*Fu et al.,* 1994]. Consequently, this paper summarizes the current ability of satellite altimetry for precisely measuring long-term sea level variations, identifies current limitations, and suggests future improvements.

2. Results from Previous Altimeter Missions

A number of previous attempts to measure global mean sea level variations from the earlier Seasat and Geosat missions have met with limited success. Results using Seasat's 3-day repeat orbit showed 7 cm variations for estimates of global sea level over a month [*Born et al.*, 1986]. *Tapley et al. [1992]* used two years of Geosat altimeter data to determine 17-day values of variations in mean sea level with an RMS of 2 cm and a rate of O ± 5 mm/year. The largest errors were attributed to the orbit determination, the ionosphere and wet troposphere delay corrections, and unknown drift in the altimeter bias, which was not independently calibrated for Geosat. *Wagner and Cheney [1992]* used a collinear differencing scheme and 2.5 years of Geosat altimeter data to determine a rate of global sea level rise of -12 ± 3 rim/year. When compared to a 17-day Seasat data set, a value of +1 O mm/year was found *[Wagner and Cheney, 1992].* The RMS of the Geosat variations was still a few cm, even after the application of several improved measurement corrections. The ionosphere path delay correction was identified as the single largest error source, but there were many other contributions including errors in the orbit, wet troposphere correction, ocean tide models, altimeter clock drift, and drift in the altimeter electronic calibration. Since the Geosat study of *Wagner and Cheney [1992],* several improvements have been made to the altimeter measurement corrections (ionosphere, tides) and the orbit determination. However, *Nerem* [1995b] and *Guman et al. [1996]* still find the Geosat mean sea level measurements are not of sufficient quality to allow a determination the secular change in mean sea level accurate to the mm/year level,

3. TOPEX/POSEIDON Data Analysis

The T/P mission has brought a reduction to many of the error sources which plagued the measurement of global sea level variations from previous missions. The precision orbits have been improved by nearly an order of magnitude to 3 cm RMS radian y [*Tapley et al., 1994; Nouel et al., 1994; Marshall et al.,* 1995]; an ionosphere correction is produced directly from the dual frequency altimeter; a wet troposphere correction is supported by microwave radiometer measurements of the integrated water column; and the altimeter system calibration is monitored at several verification sites.

The data processing in this paper is identical (with one exception) to that used in *Nerem [1995a;* 1995b] and thus will not be reproduced in detail here. To summarize, global mean sea level variations are computed every 10 days by using equi-area weighted averages of the deviation of sea level from the mission mean. All of the usual altimeter corrections (inverted barometer (IB), ionosphere, wet/dry troposphere, ocean tides, sea state, etc.) have been applied to the data. Unlike previous work where no IB correction was applied *[Nerem,* 1995a; 1995b], here a modified IB correction was applied where the mean correction over each 10-day cycle was forced to be zero *[Nerem et al., 1997]. The* CSR 3.0 ocean tide model was used. Data covering Cycles 9-168 (Cycles 1-8 were omitted, see *Nerem [* 1995b]) from both the TOPEX and POSEIDON altimeters have been used in this study, with no relative bias applied to either data set. The on-board TOPEX altimeter internal calibration estimates (discussed later) have also been applied [*Hayne et al.,* 1994]. In addition, an important correction for an error in the TOPEX oscillator correction algorithm has been applied. The latest improved orbits *[Marshall et al.,* 1995] using the improved JGM-3 gravity model [*Tapley et al., 1996]* have also been employed. While some data editing is performed, *Nerem [* 1995b] and *Minster et al.* [1995] have shown the mean sea level estimates to be very insensitive to this editing. The time series is virtually unaltered when the following data were eliminated: 1) data above ±55° latitude, 2) data in water shallower than 3000 m (as opposed to the nominal 200 m cutoff), and 3) data in areas of high mesoscale variability (RMS > 15 cm).

Figure 1 shows the cycle-by-cycle (10 days) estimates of global mean sea level for Cycles 9-168 computed using the techniques described in *Nerem* [1995 b]. These results have been smoothed using a 60 day boxcar filter. The RMS of the unsoothed mean sea level variations is roughly 4 mm, 2 mm after smoothing. The observed rate of sea level rise is -0,2 mm/yr with a scatter of 0.4 mm/yr. However, after accounting for the correlation of the trend residuals [*Maul and Martin, 1993],* the standard deviation is 0.6 mm/yr. Most of the remaining variability can be described by a least squares fit of seasonal variations in sea level. The robustness of the time series can be tested by dividing the altimeter measurements into groups of ascending and descending passes. The resulting time series are quite similar, and the rates of sea level change are statistically identical.

Figure 2 shows a map of the sea level trends observed around the globe by T/P during Cycles 9-168. These trends were determined via a least squares fit of secular, annual, and semi-annual terms at each location along the T/P groundtrack, and then mapping the trend coefficients using the gridding technique described in *Nerem et al. [1994].* Currently, these trends are dominated by variability from the recent extended ENSO event, as they are also clearly manifested in the satellite observed sea surface temperature results *[Reynolds and Smith, 1994]* of the same time period, as well as in numerical ocean models *[Stammer et al.,* 1996]. However, as the sea level record from satellite altimetry lengthens, the ENSO variations will gradually average out, hopefully allowing the detection of the geographic “fingerprint” of climate change *[Church et al.,* 1991].

Figure 1. Global Mean Sea Level Variations from TOPEX/POSEIDON Altimeter Data

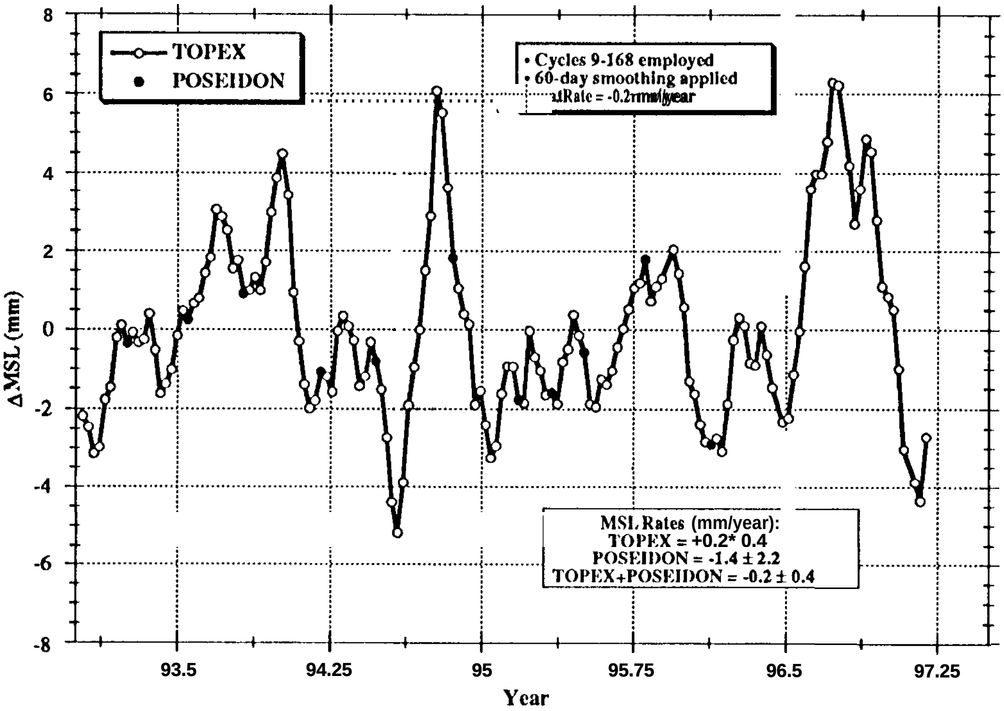
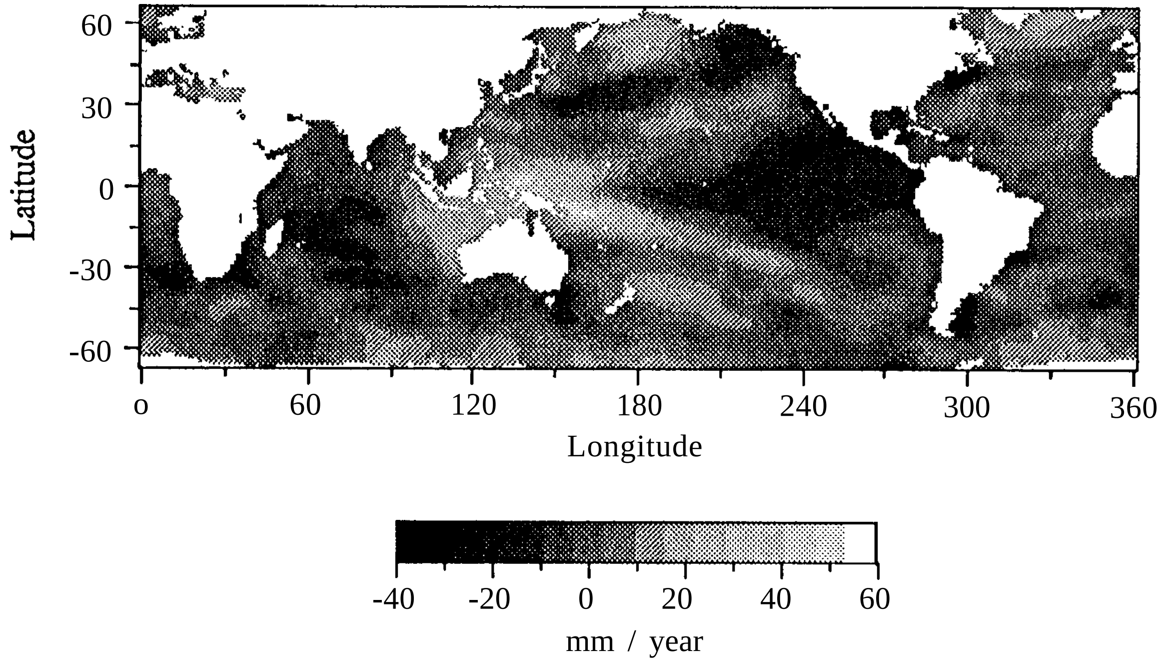


Figure 2. TOPEX/POSEIDON Sea Level Trends



Several investigators have attempted to use Empirical Orthogonal Function (EOFs) techniques to help isolate the cause of the sea level rise signal *[Hendricks et al., 1996]*, however it has been determined that the large sea level changes related to ENSO events are still inseparable from the sea level rise signal, and may even be related [*Trenberth and Hoar,* 1996]. Thus, even these advanced statistical techniques require a longer time series in order to detect climate change effects.

4. **Altimeter Calibration**

It has been demonstrated that the T/P data can provide measurements of mean sea level with a repeatability that is sufficient for determining trends at the level of 1 mm/year or better. However, as discussed previously, the long term accuracy of these measurements is unknown. While a number of possible error sources are evident, including the troposphere delay correction, the EM bias correction, and instrument drift, an analysis of the altimeter data by itself cannot provide the necessary information to assess these potential error sources. Only by employing independent data can the long-term fidelity of the measurements be ascertained. The following is a review of recent results from two altimeter calibration efforts.

Altimeter Calibration at Platform Harvest

The calibration of the T/P altimeter is monitored at the Harvest oil platform off the coast of Southern California *[Christensen et al.,* 1994]. Harvest has been very successful at determining the average bias of the T/P altimeters, which will be important for tying the T/P measurements to future altimeter measurements. However, determining the drift of the bias at the level of 1 mm/year is a daunting task, and one for which the calibration experiments were not designed. "Closure" at Platform Harvest is accomplished by employing SLR tracking from mainland sites, GPS measurements of the SLR-platform distance, and tide gauge measurements using several different instruments attached to the platform, in addition to local environmental measurements. T/P overflights occur at Harvest every 10 days. The latest results encompassing data over Cycles 9-168 [*Haines et al., 1996]* indicate that the TOPEX altimeter instrument drift is -3 ± 2 mm/year. The sign of the drift is such that the altimeter is measuring longer or equivalently, observed sea level is falling. Similar accuracies are being obtained at other regional calibration sites *[White et al.,* 1994; *Morris and Gill, 1994].* While this level of accuracy is useful for diagnosing potential systematic errors in the measurement systems, the current magnitude of the error precludes applying the drift estimates to the T/P sea level record. This is most likely because sea level measured at the platform does not have the same spatial averaging as that provided by the altimeter footprint. However, as discussed by *Christensen et al. [1994],* if another four years of data can be accumulated, sufficient averaging will be obtained and the Harvest calibration measurements will provide an important resource for validating the mean sea level measurements by T/P. In addition, Harvest provides one of the few estimates of the absolute bias of the altimeter, whereas most other techniques can only monitor the change of the bias with time, and not its absolute value.

The wet troposphere correction, which is derived from the microwave radiometer measurements of the integrated water column, is believed to be accurate to the cm level [*Ruf et al.,* 1994], although the spatial and temporal characteristics of these errors are not well known. Monitoring of the fidelity of this correction has also been done at Platform Harvest using water vapor radiometers *[Christensen et al., 1994; Haines et al., 1996].* For the "dry" overflights (water vapor path delay less than 85 mm), the drift of the wet troposphere correction is estimated to be -1.7 ± 0.6 mm/yr. For all overflights, the drift is -1.9 ± 1.2 mm/yr. While this assumes no drift of the ground-based measurements, it raises the possibility that the T/P microwave radiometer could be a significant error source for measurements of mean sea level. It is also important to note that this is one of the few error sources that is common to both the TOPEX and POSEIDON altimeters.

Altimeter Calibration Using Tide Gauge Data

The global tide gauge network can provide an improved estimate of the instrument calibration drift by using many gauges to reduce through averaging the error experienced by a "point" calibration such as Harvest. *Mitchum [1994; 1997]* maintains a near real-time collection of data from more than 70 tide gauges, most of which are located in the Pacific. He has rigorously computed differences in the measured sea level variations between each tide gauge and the neighboring altimeter data averaged over each T/P repeat cycle. If the tide gauges are considered as truth, the drift in the altimeter calibration over Cycles 6-129 was found to be -2.3 mm/year. The error is ± 0.6 mm/year after accounting for the correlation of the TOPEX-tide gauge sea level differences, and ±1.2 mm/year if an allowance (±1 mm/year) is made for possible systematic land motion. This result is statistically consistent with the Harvest results, as well as with a variety of other anal yses employing tide gauges [White *et al.*, 1994; *Chambers et al.*, 1996; *Murphy et al., 1996]*, lake level gauges in the Great Lakes *[Morris and Gill*, 1994; *Chambers et al.*, 1996], and in-the-water measurements (XBTS, TOGA-TAO, etc.) [*Chart et al.*, 1996; *Chambers et al.*, 1996]. The tide gauge results are clearly approaching the accuracy required to calibrate the altimeter at the level necessary for mean sea level studies. As with the Harvest results, this technique will benefit from the averaging provided by a longer time series.

One serious limitation of this calibration technique is that the movement of the land to which the tide gauges are attached, which can be the same order of magnitude as the changes in global mean sea level, is unknown. Currently, this can only be overcome through continuous monitoring of the tide gauge sites using GPS positioning. This would clearly improve the reliability of the altimeter drift estimates from the tide gauges, and several international organizations are now studying this possibility. Another limitation of the tide gauge calibration technique is that it assumes there is no geographical dependence to the instrument behavior. For example, if the sensitivity of the microwave radiometer (which provides the correction for the water vapor delay) is changing with time, then the error would be expected to be larger in the tropics where water vapor is more abundant, Because the tide gauges used in the calibration are not distributed globally, and in fact are concentrated more in the tropics, the calibration drift computed from the tide gauges would be biased. If the observed instrument drift is in fact being caused by the microwave radiometer, then it is estimated that the drift estimate of -2.3 mm/year may be biased high by 20-50% [*Mitchum, 1996]*. This is a large change, but still within the error estimate. There are in fact several pieces of evidence which support this hypothesis including: 1) the drifts in the water vapor comparisons performed at Harvest [*Haines et al.*, 1996], 2) comparisons between T/P and ERS-1 radiometer measurements show a relative drift of 1-2 mm/year *[Chambers et al., 1996]*, and 3) sea level is falling in the tropics relative to the rest of the world, While these pieces of evidence do not alone prove the radiometer measurements are drifting, when taken together they are fairly compelling. Resolving any geographical dependence in the altimeter calibration will require a larger network of tide gauges than used by *Mitchum [1997]* with good global sampling.

Another possibility for the cause of the measurement drift observed by the tide gauges is the internal calibration estimates [*Hayne et al., 1994]* that were applied in the data processing, which if removed, eliminates most of the trend in the TOPEX-tide gauge sea level differences. This is not sufficient evidence to suspect the internal calibration estimates, and thus they have been retained in this analysis. In any case, regardless of the source of the drift, the final sea level measurements can be corrected for the observed instrument drift of -2.3 rim/year. However, issues such as the long-term performance of the microwave radiometer, and the validity of the internal calibration, along with other issues, remain topics of future research.

POSEIDON Altimeter Calibration

Clearly, the application of the aforementioned drift calibration techniques are only applicable to the TOPEX altimeter, as too few POSEIDON altimeter data have been collected to determine a reasonable estimate for its drift rate from the calibrations sites or the tide gauges. However, on-board calibration data for the POSEIDON altimeter are collected [*J. F. Minster,* personal communication, 1995], and applied to the POSEIDON data during the production of the GDRs in France, although the details of this calibration procedure are unknown. In any case, as mentioned earlier, the use of the POSEIDON data in this analysis has very little effect on the final results. As more POSEIDON data are collected, it may become possible to use the two altimeters as consistency checks for studies of mean sea level.

5. Conclusions

By combining the raw altimeter results shown in Figure 1 with the tide gauge estimates of the instrument behavior from *Mitchum [1997],* a "calibrated" estimate of sea level rise can be developed, along with an error assessment, as shown in Table 2, The calibrated estimate of global mean sea level rise is +2.1 mm/year, with an estimated error of ±1.3 mm/year. This estimate was computed by combining the "calibrated" TOPEX data and the "uncalibrated" POSEIDON data, however the inclusion of the POSEIDON data has no significant affect on the sea level rise estimate. The POSEIDON data alone give an "uncalibrated" rate of sea level rise of -1.4 ± 2.2 mm/year, which also suggest a problem with the water vapor correction, and would be +0.9 mm/year if the TOPEX calibration results were adopted. As noted earlier, both of these estimates might be biased high by 20-50% if the cause of the observed instrument drift is determined to be the microwave radiometer. For similar reasons, the geographic variations of sea level rise shown in Figure 2 are essentially uncalibrated, since the tide gauges cannot currently detect any geographic dependence of the instrument performance. The global sea level rise estimate is in quite good agreement with values obtained from the analysis of the last 50 years of tide gauge data *[Douglas,* 1995]. It is difficult to determine an error estimate directly, since very little is known about the long-term behavior of the measurement corrections, the instrument, etc., and there are virtually no independent measurements available offering similar accuracy. Therefore, the error estimate has been assembled indirectly by combining the formal standard deviation of the observed sea level rise estimate (±0.6 mm/year) with the error estimate of Mitchum's tide gauge calibration (±1.2 rim/year), as shown in Table 1. The calibration errors will be reduced as: 1) a longer time series is collected, 2) GPS is used to monitor the tide gauge locations, and 3) more is learned about the cause of the observed instrument drift.

Table 1. Calibrated Estimate of Mean Sea Level Rise from T/P

	Sea Level Change (mm/year)	**Estimated 1σ Error (mm/year)**
"Raw" Estimate	-0.2	0.6
Instrument Calibration	2.3	1.2
Combined Estimate	2.2	1.3

The importance of maintaining the current network of ocean tide gauges cannot be overstated. Not only do the tide gauges currently provide the best method for monitoring the performance of the instruments on the satellite, but they will also provide a means of linking future satellite altimeter measurements to the T/P time series, especially if there is a gap between the missions. The accuracy of the tide gauge calibration technique could be significantly improved by instrumenting the tide gauges with GPS receivers, thereby allowing the long-term crustal motions to be monitored.

It should be emphasized that due to the short ~4 year time series available for this analysis, it is impossible to isolate any climate change signals which may be embedded in the T/P observations. As an example, Figure 3 shows a time series of global mean sea surface temperature (SST) anomalies from 1982-96 [*Reynolds and Smith,* 1994], which show an increase over the T/I? mission that is likely to be short-lived. Rough calculations indicated that up to half of the observed sea level rise could be due to these interannual SST variations. In this regard, the collection of a longer measurement time series, probably employing multiple altimeter missions, for the purposes of averaging interannual and decadal sea level variations, will provide considerable improvement to these results in the future. With a sufficiently long time series, it should be possible to identify the geographic "fingerprint" of climate change by computing maps similar to that shown in Figure 2. Nevertheless, T/P is the first satellite altimeter mission to demonstrate the necessary measurement repeatability required for climate change studies. The importance of an uninterrupted time series of T/P quality measurements through future altimeter missions cannot be overstated. Towards this end, the planned follow-on mission to T/P, called "Jason", promises to continue the T/P time series well into the next century, as will a number of other planned missions.

Figure **3. Sea Surface Temperature Anomalies: 1982-97**

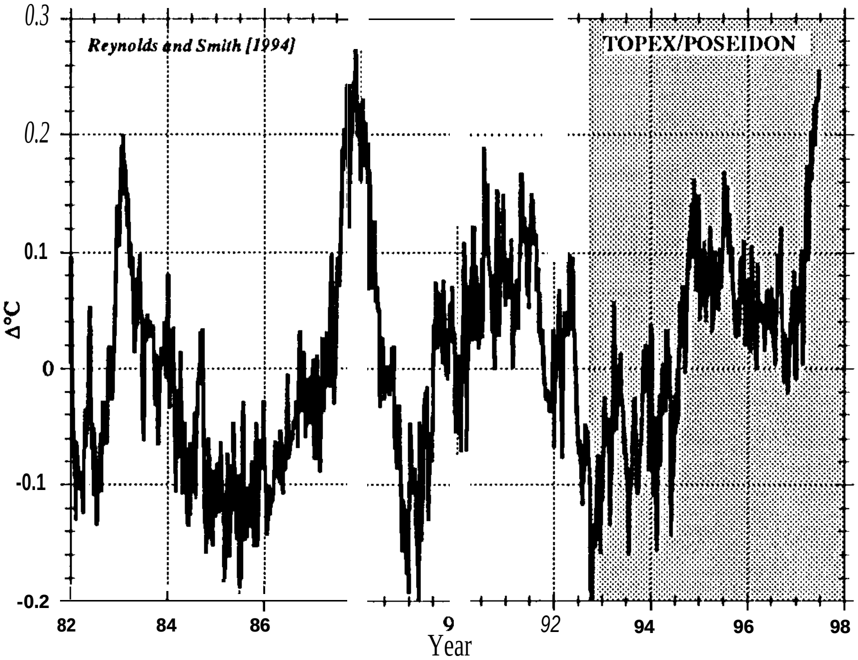


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Figure Captions

Figure 1, Global 10-day mean sea level variations from TOPEX/POSEIDON Cycles 9-168 after applying both the oscillator correction and the internal calibration.

Figure 2. Sea level trends as measured by T/P over Cycles 9-168. The trends were determined via a least squares fit that included annual and semi-annual variations.

Figure 3. Global mean sea surface temperature anomalies over 1982-96 computed from the data of *Reynolds and Smith [1994]*

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IGS-PSMSL

MEASURING LONG-TERM SEA-LEVEL CHANGE

Co-chairs:

Geoff Blewitt

University of Newcastle

Newcastle upon Tyne, U.K.

Steve Nerem

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SUMMARY OF SESSION 3:
MEASURING LONG-TERM SEA LEVEL CHANGE

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INTRODUCTION

This session, co-chaired by Geoff Blewitt and Steve Nerem, addressed the application of tide gauges to measuring long term sea level change, including their use for calibrating satellite altimeter measurements (presented by Gary Mitchum), the need to use GPS for calibrating long tide-gauge records for land movement (presented by Philip Woodworth), and tide gauge benchmark monitoring as part of the IGS Densification Program (presented by Geoff Blewitt). The time set aside for discussion proved to be very fruitful, as it led to a concrete recommendation on how science groups interested in sea level change can make links with the IGS and therefore ensure a universal level of consistency and solution quality.

We note that the titles of the papers published in these proceedings don't necessarily exactly correspond to what was printed in the original workshop agenda. In some cases additional ideas have been included after the workshop. This summary therefore draws mainly from the published papers rather than the material actually presented.

1. Mitchum, G., "A Tide Gauge Network for Altimeter Calibration"

Mitchum developed a strategy for using tide gauge measurements to monitor errors in satellite altimeter measurements, with the goal of reducing the error in altimetric height drift to less than 1mm/yr within 3 years of collecting data. It relies on GPS to monitor tide gauge benchmarks at carefully selected tide gauges. His error models indicate that 30 gauges will be adequate. He suggested that these 30 be a subset of the 157 WOCE stations, which satisfy the criteria that (i) the variance of the difference in altimeter and tide gauge records be small (<150 mm), and (ii) nearby GPS can be used to monitor sub-centimeter motions over a 3 year period. These criteria cut the number of eligible stations down to 106. The 30 selected stations can then be selected to be evenly distributed.

2. Woodworth, P.L., "The Need for GPS to Provide Information on Vertical Land Movements at Tide Gauges with Long Records"

Woodworth emphasizes the use of long tide gauge records to infer global change in sea level. He argues that GPS is needed to monitor land movements at tide gauges, because previous methods attempting to decouple long term land and ocean signals in the tide gauge record have proved to be unsatisfactory. His paper reviews the historical tide gauge data, and looks at the requirements for correcting for trends due to land movement. He supports the previous conclusions of the Carter committee, that we need to measure vertical land movements to an accuracy of ***0.3*** to 0.5 mm/yr in a reasonable period. He then proposes a medium-term strategy for GPS measurements at tide gauges. He suggests making use of tide gauges with at least ***40-60*** years of records, and use GPS at these sites for, say, 20 years, He suggests an appropriate number of GPS sites might be 150-200 where the density depends on geological spatial scales in each region. He questions whether GPS processing centers can handle this magnitude of data flow, and refers to Blewitt's presentation.

3. **Blewitt, G., P. Davies, T. Gregorius, R, Kawar, and U, SanIi, "Sustainable Geodetic Monitoring of the Natural Environment using the IGS"**

Blewitt et al. introduce the concept of "sustainable monitoring," defined as "the production of geodetic data which will be as useful and amenable as possible to future generations." This concept is developed using tide gauge benchmark monitoring as an example. It is suggested that the IGS has developed the infrastructure, methodology, and products to help users practise the principles of sustainable monitoring. Moreover. tide-gauge benchmark monitoring activities can link into the existing infrastructure to the benefit of both communities, as well as for good practical reasons. Blewitt et al. describes the IGS Densification Program, and the role of Associate Analysis Centers in producing a unique, global geodetic solution, The response to Woodworth's question about the ability to handle such data flow is an unequivocal yes, provided the tide gauge community get organized and linked with IGS.

4. **Discussion: Organizational Aspects**

During the ensuing discussion on these ideas, Blewitt illustrated how investigators could link with IGS, using a diagram similar to the one reproduced in Figure 1.

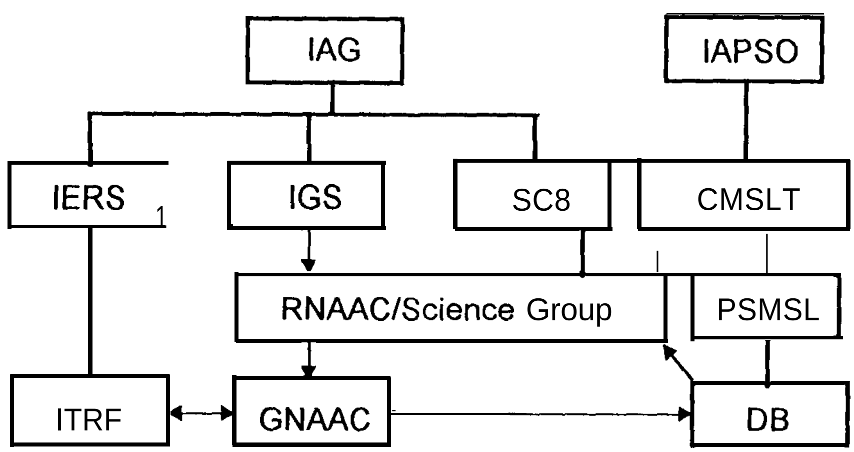

Figure 1: Chart illustrating organizational links and data flow to facilitate the activity of tide-gauge benchmark monitoring (explained in text).

Figure 1 requires some explanation! Simple lines connecting the boxes indicate the organizational hierarchy. Arrows indicate data flow. Starting with the bottom right hand side, we have the goal of this organization, which is the production of a database (DB) of the coordinates and velocities of tide gauge benchmarks available at the Permanent Service for Mean Sea Level (PSMSL), which formally reports to the Commission of Mean Sea Level and Tides (CMSLT), under the umbrella of the International Association for the Physical Sciences of the Oceans (IAPSO). Clearly, coordinates and velocities are a geodetic matter, hence PSMSL are also formally connected to Section V of the International Association of Geodesy (IAG). This link between PSMSL and IAG is not shown for clarity!

The coordinates and velocities are derived from a realization of the IERS Terrestrial Reference Frame (ITRF), produced by the International Earth Rotation Service (IERS). The input to ITRF for the tide gauge benchmarks comes from the Global Network Associate Analysis Centers (GNAAC), who combine GPS permanent network solutions from around the globe, including those produced by the Regional Network Associate Analysis Centers (RNAAC). Both GNAAC and RNAAC are organizational components of the International GPS Service for Geodynamics (IGS), which provides the necessary orbit and station data for an RNAAC to produce consistent products.

The structure described so far is essentially in place (actually, in pilot testing, but it will be official very shortly). What remains to be done, is to include GPS data from tide gauge sites into the dataflow. This can be achieved by setting up special RNAAC'S to perform the necessary analysis. Since IGS is a service organization, and not primarily in the business of scientific investigation, it is logical that each of these RNAAC'S be connected to some science group, which has its own objectives and agenda (in this case, calibration of the tide gauge record).

The diagram shows each RNAAC as a part of a science group which falls under the International Association of Geodesy (IAG) through the Special Commission 8 on Sea Level and Ice Sheet Variations (SC8). Special Commission 8's terms of reference look as if they have been written especially for this task, since they not only mention geodetic observing programs to investigate sea level change, but also interdisciplinary communication among geodesists, geophysicists, and oceanographers, Science groups are also connected to the CMSLT to make the collaboration with oceanographers explicit, and for the practical necessity for expertise on tide gauge selection. It would be natural for science groups to be regional, given that they act as RNAACS.

To complete the loop, the Science Groups access both the tide gauge records and the geodetic records from the PSMSL for scientific interpretation.

These concepts provide the basis for some of the Workshop Recommendations.

A TIDE GAUGE NETWORK FOR ALTIMETER CALIBRATION

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ABSTRACT

Recent work (Mitchum, 1997) has demonstrated the feasibility of using tide gauge measurements to monitor temporal drift in satellite altimeter measurements, and has also shown that the major remaining errors are due to poor spatial distribution in the set of gauges chosen for that work, and to uncertainties in estimating the land motion at the tide gauges. A strategy is developed using GPS and careful gauge selection that should contrain the overall error for the altimetric height drift to be less than 1 mm/yr over three years of data. It is determined that 30 gauges will be required for this task, and a strawman list of gauges is developed, along with guidelines for finalizing the selection.

INTRODUCTION

The purpose of the study described in this paper is to define a relatively small set of tide gauge stations that can be used on an ongoing basis to monitor, and correct if necessary, slow temporal drifts in the sea surface height time series obtained from satellite altimeters. The basic idea is quite simple. Tide gauges have been used for some time as an obvious source of data for validating sea surface heights from satellite altimeters. Studies such as these (e.g., Mitchum, 1994; Cheney et al., 1994) have consistently shown that modern altimeters, such as TOPEX/Poseidon, and tide gauges obtain very comparable measurements. This implies that both datasets can now be considered valid measurements of the same geophysical signal. This further leads to the conclusion that the differences in the two measurements (tide gauges and altimeters) will be dominated by the errors in the two systems.

Given that the tide gauges are the much simpler of the two systems, it is reasonable to consider these measurements as the more direct, and hence the least likely to exhibit low frequency drift. Note carefully that this is not to say that tide gauges are perfect measurements, but only that the gauges are simpler to operate over the long-term. From this point of view, then, low frequency and spatially coherent changes in the altimeter minus tide gauges difference time series should be dominated by drift in the altimeter measurements. Determining these drift errors are crucial to determining sea level rise (SLR) from satellite altimeters (e.g., Nerem, 1995; Nerem et al., 1997) and for studying very low frequency (VLF) height variations.

A recent paper (Mitchum, 1997; hereinafter M97) discusses these issues in more detail, and only a brief summary is given here. Basically, M97 derives a formalism for analyzing the altimeter minus tide gauge differences and shows results of an application to the TOPEX altimeter. The basic result, which was obtained by analysis of a known drift in the TOPEX system, the so-called "algorithm error", is that the method works very well. M97 shows that the existing tide gauges control random errors well, but possible spatial structure in the error and possible land motion at the tide gauges limit the accuracy of the drift estimates. The work of M97 led naturally to a suggestion (B. Douglas, pers. comm.) to use this formalism to determine an "optimal" subset of the tide gauge network to be upgraded and maintained for the purpose of monitoring drift in altimeters, and to address the remaining problems of spatial structure and land movement.

The goal of this exercise is to define a set of tide gauge locations and instrumentation that will reduce the expected error in the drift estimates to order 1 mm/yr over a 3-year averaging period. This error budget includes contributions from land motion and spatial structure in the altimeter drift rate. This error limit will allow useful input to the SLR and VLF problems during the lifetime of a single altimeter mission. And over multiple missions that span more than 10 years, the calibration error will drop to less than 0.2 mm/yr, which might allow the determination of a SLR acceleration estimate. The tide gauge subset will also allow the referencing of separate altimeter missions in the case that the missions are not contemporaneous, and will provide an independent check of the altimeter to altimeter comparison in the case that the missions do overlap.

EXISTING PROBLEMS AND PROPOSED SOLUTIONS

Three issues concerning the drift and the errors that contribute to the error budget for its determination are considered in this study. First, consider a drift that is spatially uniform and errors that are essentially random. This was assumed in the existing calculation by M97, and the formalism in that paper is primarily aimed at handling this type of error. Such random errors were found to be of order 0.6 mm/yr over a 3-year averaging period. Second, suppose the drift has spatial structure; e.g., due to water vapor correction. This signal is assumed to vary primarily in the meridional direction. The distribution of gauges used by M97 was not adequate to address this type of drift signal. Finall y, land motion at the tide gauges contaminates the tide gauge time series and confuses the interpretation of the drift in the difference series as being due to altimeter drift. M97 estimated that this was a source of relatively large errors, which was assigned a magnitude of order 1 mm/yr.

The solutions that are proposed here to these problems are as follows. Taking the case of land motion first, it is proposed that vertical land motion estimates be made at the tide gauge sites by GPS, DORIS, or other available techniques. The emphasis in this study is on the use of GPS, but that is not essential. These land motion measurements must be made either at the tide gauge, or on "nearby" land that is moving at the same rate. Local ties between the GPS receiver and the tide gauge appear to dominate the error budget for the land motion, and should therefore be avoided. If I take a single site uncertainty in the land motion rate estimate to be 10mtn/yr over oneyear, then over3 years the uncertainty becomes 2 mm/yr. It will be shown below that this is adequate for the present purposes.

To address the possibility that the drift rate has spatial structure, it is necessary to improve the distribution of the the tide gauge stations. The drawback to the set of stations used by M97 is that the gauges were primarily in the tropics, and this could lead to a bias in the drift rate estimate if the tropics were behaving differently than the higher latitudes. This is in fact expected if the drift is due to drift in the water vapor estimate from the radiometer, for example. Using a better distribution of stations will allow the inclusion of basis functions for modeling spatial variations in the drift rate, in contrast to the M97estimate that is assumed to be independent of the spatial coordinates. As long as the additional basis functions have no more than a few free parameters, the random error will not inflate significantly, as there are order tens of degrees of freedom. 1 do not, however, want to decide *a priori* the basis functions to use, but rather want to simply span the spatial domain with observations. This will be done by defining 5 latitude bands that split the domain 60N to 60S into equal areas and by distributing the gauges selected evenly among these five bands. The appropriate bands are 60N to 30N, 30N to 10N, 10N to 10S, 10S to 30S, and 30S to 60S. Such a set of gauges, when used to fit at most a few additional basis functions in space, will remove the potential systematic error noted by M97 without significantly increasing the random error through a reduction in the number of degrees of freedom.

The random errors can be treated in a fashion similar to M97. From that work, the standard deviation of a difference series is known to be dominated by the random error and to be of order 50 mm. The TOPEX cycle estimates obtained every 10 days were approximately independent, implying that the trend error over 3 years of data is of order 5 mm/yr at a single site. One can check this scaling estimate by noting that with about 50 sites, M97 obtained a standard deviation based on the random errors of 0.6 mm/yr, as compared to $5/(50)^{1/2} = 0.7$ mm/yr. So this scaling estimate is seen to be somewhat conservative, but reasonably accurate.

So how many stations are required to meet the criterion of an uncertainty of 1 mm/yr with 3 years of data? To address this I will simply propagate the errors. At a single site, combine the errors due to estimating the random error (5 mm/yr) and the error due to estimating the land motion (2 mm/yr) to obtain an error variance of$(52 + 2^2)\,(\text{mm/yr})^2$. Note that this variance is dominated by the random error component. In essence, requiring the land motion estimates to be good to 10 mm/yr over one year is setting these errors to a magnitude where they do not contribute to the overall error budget significantly. But larger errors can be accommodated, if necessary. If I then assume that there will be N sites that can be assumed independent of one another, which is an assumption that is supported by the results of M97, then the variance of the final drift estimate is computed as $(5^2+ 22)/N\ (\text{mm/yr})^2$. In order to get 1 mm/yr, then, N is approximately 30. So I need 6 stations in each of the 5 latitude bins.

This calculation is probably somewhat conservative, but allowing for at least 30 sites provides some redundancy, which is essential due to the fact that instruments will fail occasionally, and it also allows for the possibility that the land motion estimates might not be quite as accurate as I am assuming. Since this is still an area of work that is very much in progress, it only makes sense to be somewhat conservative here.

If this estimate of the number of stations required is accepted, the problem is now to determine which are the best stations to use within a given latitude band, As seen above, the random errors dominate the error budget, and these are proportional to the variance of the altimeter minus tide gauge measurements. So the most important criterion is that the altimeter and the tide gauge data agree well, in the sense that the difference series between the two has small variance. Note carefully that this is not the same as requiring that the correlations between the two series be high. Note also that multiple altimeter passes by a given tide gauge during one cycle can be averaged, reducing the variance of the differences, because only a single series from each site is used. So island stations, which are the ones typically having 3-4 valid passes are preferred to coastal sites, which have other noise sources as well (e.g., coastally trapped wave signals).

Next in order of importance would be existing instrumentation to determine the land motion rate; e.g., GPS or DORIS. For the purposes of this study only GPS is considered, but in the future a similar evaluation of DORIS will be done. This criterion is evaluated by determining whether a GPS receiver is nearby, with near being defined as close enough that the low frequency vertical motions are reasonably expected to be the same as that of the tide gauge. If no GPS receiver exists, then the suitability of a site for the installation and maintenance of one is important. For example, extremely remote sites would be less desirable than ones with regular air service. Finally, real-time access to the data is desirable in order that the GPS data can be used for other purposes, and so that the GPS processing is most likely to be handled by that community.

A third requirement is that the tide gauge site should have a long record already existing. For example, given two essentially equal sites according to the two above criteria, but one having a 30 year record and the other only 3 years of data, one would choose the 30 year site. This allows a better understanding of the sea level signals in the records, allows a consistency check of the land motion signals, and also allows the use of this gauge for estimates of SLR and VLF that are done independently of the data from the altimeters.

SELECTION OF STATIONS, AND CRITERIA FOR CHANGING THE SET

For the initial selection of tide gauge stations, data included in the TOGA and WOCE sea level datasets maintained at the University of Hawaii Sea Level Center were examined. The reason for using this data source was primarily that these stations are available with a reasonable (months to a year) lag time, which is considered to important for this application. These datasets, however, are somewhat weak at high latitudes, which makes it more difficult to obtain the meridional coverage desired. So it was deemed important to consider the present set a "strawman", and to specify criteria that could be used to replace a station in this list with another that might be easier to maintain, or one that was not considered in this initial analysis.

The method for evaluating candidate stations was straightforward, First, characterize each station by computing the standard deviation expected in the altimeter minus tide gauge differences using the TOPEX altimetry data. As discussed above, the multiple time series available from stations with multiple passes are combined to reduce the variance under the assumption that the passes are independent (M97). Consequent] y, there is only one standard deviation estimate for each station.

Specifying the desirability of the site from the point of view of GPS is more difficult. It was decided to simply consider whether a GPS station existed in the vicinity (within 100 km) and to give preference to such stations. Future modifications of the network would need to do a more careful job on this criterion, although it should be remembered that the land motion error is not as important as the altimeter - tide gauge agreement.

There are 5 tables (one for each latitude bin) of tide gauge sites in Appendix A. These tables show the candidate stations in each latitude band, and are further separated into 4 sub-bands. The tables give the standard deviation of the altimeter - tide gauge differences, and the distance to the nearest GPS receiver assuming that one exist within 100 km. GPS locations considered are from the IGS and the CORS networks. Within each latitude band one station was selected from each of the four sub-bands, and then two stations were selected "at large". The selection did not always simply take the station with the smallest standard deviation. In cases where two or more stations had similar values, selections were guided by a desire to favor more accessible sites and sites that I considered more likely to be maintained in the future, and to provide better a spatial distribution in the final set. Some examples of how these choices were made are given below, The stations selected for the strawman are given in bold italics in Appendix A, and are also shown in Figure 1 and Table 1.

Examination of the stations selected from the tables in Appendix A will quickly confirm that the choices were not always made simply by choosing the smallest SIG values from the tables. The reasoning for the exceptions noted in the various choices is as follows. Starting with the 30N to 60N latitude bin (Table A 1), San Diego is chosen over Funchal because the SIG values are almost identical, but San Diego has a GPS receiver. Bermuda is chosen as an at large station because of its unique location, long time series, and the existence of a GPS receiver. Kushiro is chosen as the second at large station to improve the spatial distribution and because it was judged that installing a GPS receiver at a Japanese station would be relatively straightforward.

In the 10N to 30N bin, Johnston Island is selected because it is more accessible than the other stations in that sub-band and has a good SIG value. Also it has a modern acoustic tide gauge and is part of the U.S. national network and is thus likely to maintained over

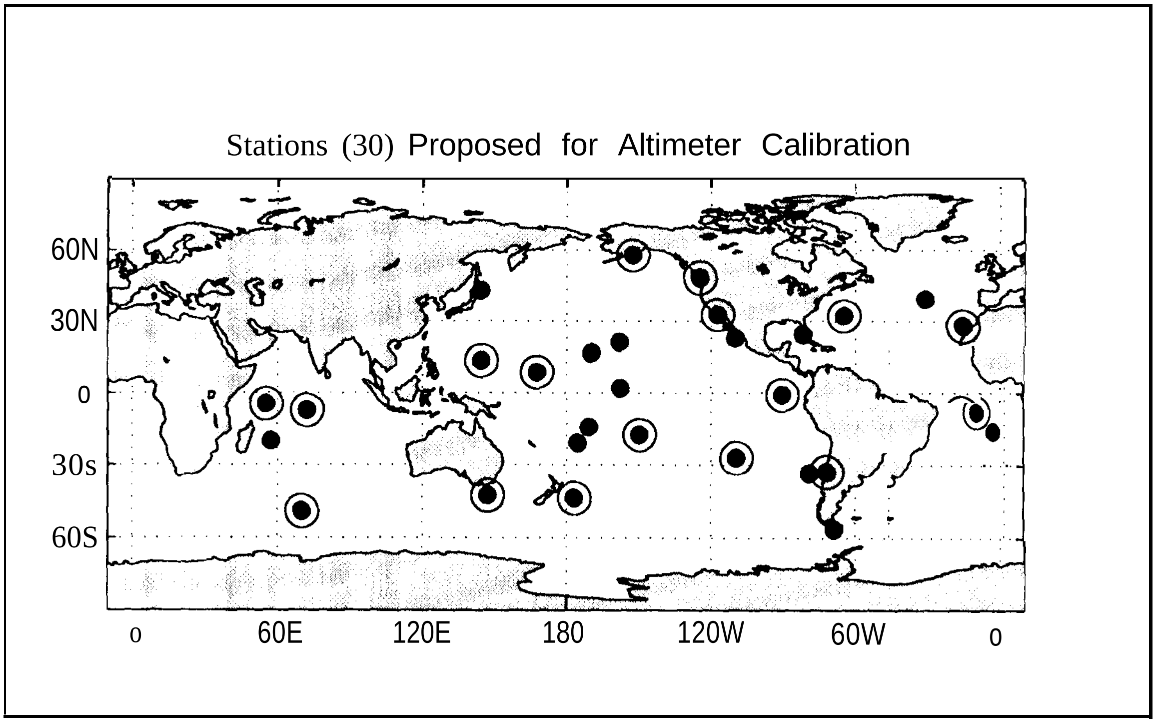

Fig. 1 Stations in the strawman list. Stations with circles have existing GPS receivers. Note that the distribution is equal area, but the plot is not.

the long-term. Las Palmas is chosen over stations with slightly smaller SIG values because of an existing GPS receivers and also because it improves the spatial distribution, The at large stations, Cabo San Lucas and Key West, are chosen for accessibility, length of record, and ease of installing GPS receivers.

in the 10S to 10N band, there are many stations available that have SIG values small enough to satisfy the present requirements, In this latitude band the selections were governed more by a desire to improve zonal separations (hence the selections of Diego Garcia and Point La Rue in the Indian Ocean) and the existence of GPS recievers. In the case of Christmas Island, accessibility was the major consideration, with record length being an advantage as well.

In the two southernmost latitude bands the number of stations available were quite limited, and the choices were made primarily by the SIG values. The only exception to this is the choice of Port Louis as an at large station over a number of alternatives with smaller SIG values. Port Louis is chosen because it improves the zonal distribution of the final station set, and also because it is operated in conjunction with the Meteorological Service of Mauritius. This is an advantage because a GPS receiver installed here could probably return data in real-time and make a useful contribution to the IGS network,

Table 1 : Stations selected for the altimeter calibration set.

See text for further details on how choices were made. The SIG column is an estimate of tide gauge quality, equal to the standard deviation of the difference between altimeter and tide gauge if only 1 pass available, but also takes into account # of passes available. The N LAT, E LON, STATION columns give the position and the common name of the tide gauge. The IGS/CORS columns give the distance (km) to the tide gauge if there is a GPS receiver within 100 km, and is marked with an X otherwise.

SIG	N LAT	E LON	STATION	IGS	CORS
85	-56.51	291.3	Diego Ramirez	x	X
67	-49.35	70.2	Kerguelen	2.7	X
63	-43.95	183.4	Chatham Island	1.1	X
102	-42.88	147.3	Hobart	12.3	X
46	-33.62	281.2	Juan Fernandez	x	X
78	-33.03	288.4	Valparaiso	90.8	X
65	-27.15	250.6	Easter	6.5	X
39	-21.13	184.8	Nuku' alofa	x	X
57	-20.16	57.5	Port Louis	x	X
21	-15.97	354.3	St. Helena	x	X
30	-17.52	210.4	Papeete	4.7	X
42	-14.28	189.3	Pago Pago	x	X
25	-7.90	345.6	Ascension	6.5	X
31	-7.29	72.4	Diego Garcia	3.5	X
37	-4.67	55.5	Point La Rue	5.5	X
40	-0.75	269.7	Santa Cruz	1.5	X
45	1.99	202.5	Christmas	X	X
29	8.73	167.7	Kwajalein	1.3	X
52	13.43	144.6	Guam	29.3	X
50	16.75	190.5	Johnston Island	x	X
35	21.31	202.1	Honolulu	x	X
47	22.88	250.1	Cabo San Lucas	x	X
59	24,55	278.2	Key West	x	X
68	28.15	344.6	Las Palmas	48.2	X
54	32.72	242.8	San Diego	18.1	8.4
58	32.37	295.3	Bermuda	0.1	x
62	39.45	328.9	Flores , Azores	x	x
63	42.97	144.4	Kushiro	x	x
107	48.37	235.4	Neah Bay	83.5	X
95	57.73	207.5	Kodiak Island	x	22.8

Since it is intended that the list of stations given in Table 1 and shown on Figure 1 should be viewed as a strawman, it is appropriate to conclude with a brief discussion of how this strawman should be evolved to a working list. The most important consideration when considering changes to this list should be the standard deviation of the difference series, with meridional distribution second, availability of land motion estimates being third, and zonal distribution fourth. For example, given a station in the list and a possible alternative at the same latitude, one should certainly accept an alternative with a smaller standard deviation, particularly if the zonal separation improved. As a specific example, I would like to consider replacing Valparaiso with Tristan de Cunha in the central Atlantic once 1 have data from Tristan de Cunha to evaluate. Note that it is important that one should compute standard deviations of the difference series for any two stations to be compared from the same altimeter dataset.

As another example, one might want to choose a different site for the sake of GPS installation. In this case, it would be necessary to compare the candidate site to other sites in the same latitude band and show that any potential degradation in the standard deviation is not large. It is not trivial to say how large is large, however, but this could be computed. It must be remembered in this case that the most important contribution to the final error budget comes from the random error, and not from the land motion error. Therefore it would be difficult to modify the list based on GPS availability or desirability unless the altimeter, tide gauges differences were equally small or smaller. A case in point that is presently under consideration is the replacement of Hobart in Australia with Burnie, which is nearby, also has a GPS receiver, and is preferred by the operators of these gauges. As long as the standard deviation of the differences at Burnie is comparable to or smaller than that at Hobart, this change should be made.

Acknowledgements The work was supported by NASA and JPL. The suggestion to extend the results from my earlier work came from Bruce Douglas. I also acknowledge a number of valuable discussions of this problem with Philip Woodworth and Steve Nerem.

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Appendix A : Tables describing all stations considered in this study.

Table Al. Stations between 30Nand60N. As in Table 1.

SIG	N LAT	E LON	STATION	IGS	CORS
51	32.64	343.1	Funchal	x	X
54	32.72	242.8	San Diego	18.1	8.4
58	32.37	295.3	Bermuda	0.1	X
126	34.92	139.8	Mera	x	X
62	39.45	328.9	Flores, Azores	x	X
63	42.97	144.4	Kushiro	x	
79	37.81	237.5	Fort Point	x	6X6
132	39.07	141.7	Ofunato	x	x
145	41.74	235.8	Crescent City	x	x
107	48.37	235.4	Neah Bay	83.5	x
140	51.86	183.4	Adak Island	X	x
95	57.73	207.5	Kodiak Island	X	22.8
122	53.90	193.5	Dutch Harbor	X	x

Table A2. Stations between 10N and 30N. As in Table 1.

SIG	N LAT	E LON	STATION	IGS	CORS
52	13.43	144.6	Guam	29.3	x
41	15.23	145.7	Saipan	x	x
46	17.97	293.0	Magueyes Island	x	x
50	16.75	190.5	Johnston Island	x	x
52	19.05	255.7	Manzanillo	x	x
52	19.73	204.9	Hilo	41.4	x
59	18.23	248.9	Socorro	x	x
62	19.28	166.6	Wake Island	x	x
35	21.31	202.1	Honolulu	x	x
37	21.43	202.2	Mokuoloe	x	x
44	23.87	193.7	French Fr Shoal		X
46	21.97	200.6	Nawiliwili	37?0	19.4
47	22.88	250.1	Cabo San Lucas	x	X
47	21.90	200.4	Port Allen	26.0	19.4
48	20.90	203.5	Kahului	x	23.4
59	24.55	278.2	Key West		X
68	20.03	204.2	Kawaihae	47X1	23.4
42	26.71	281.0	Settlement Point	x	X
48	28.22	182.6	Midway Island	x	X
65	27.10	142.2	Chichijima	x	X
68	28.15	344.6	Las Palmas	48.2	X
102	28.48	343.8	Tenerife	99.3	X

Table A3. Stations between 10S and 10N. As in Table 1.

SIG	N LAT	E LON	STATION	IGS	CORS
25	-7.90	345.6	*Ascension*	6.5	x
30	-9.01	201.9	Penrhyn	x	x
31	-7.29	72.39	*Diego Garcia*	3.4	x
33	-8.93	219.9	Nuku Hiva	x	x
34	-8.53	179.2	Funafuti	x	x
34	-9.43	160.0	Honiara	x	x
36	-6.93	279.3	Lobos de Afuera	x	x
49	-6.73	147.0	Lae	x	x
53	-6.16	39.2	Zanzibar	x	x
27	-2.81	188.3	Kanton	x	x
32	-0.69	73.2	Gan	x	x
34	-4.20	152.2	Rabaul	x	x
36	-0.53	166.9	Nauru	x	x
37	-4.67	55.53	*Point La Rue*	5.4	x
40	-0.44	269.7	Baltra	34.3	x
40	-0.75	269.7	*Santa Cruz*	*1.5*	x
41	-2.59	150.8	Kavieng	x	x
60	-4.07	39.7	Mombasa	x	x
65	-2.01	147.3	Manus	x	x
66	-4.58	278.7	Talara	x	x
30	1.36	172.9	Betio	x	x
36	4.18	73.5	Hulhule	x	x
36	0.35	6.8	Sao Tome	x	x
37	4.19	73.5	Male ,Hulule	x	x
42	1.10	154.8	Kapingamarangi	x	x
45	1.99	202.5	*Christmas*	x	x
97	1.46	103.8	Johor Baharu	x	x
106	1.93	104.1	Sedili	x	x
108	4.23	117.9	Tawau	x	x
118	3.98	103.4	Kuantan	x	x
132	1.33	103.4	Kukup	x	x
28	7.11	171.4	Majuro	x	x
29	8.73	167.7	*Kwajalein*	1.3	x
30	9.51	138.1	Yap	x	x
33	6.99	158.2	Pohnpei	x	x
42	7.33	134.5	Malakal	x	x
42	6.77	73.2	Hanimaadhoo	x	x
61	5.98	116.1	Kota Kinabalu	x	x
78	7.83	98.4	Ko Taphao Noi	x	x
84	9.40	275.8	Quepos	x	x
128	5.42	100.3	Penang	x	x
132	5.27	103.2	Cendering	x	x

Table A4. Stations between 30S and 10S. As in Table 1.

SIG	N LAT	E LON	STATION	IGS	CORS
42	-27.07	289.2	Caldera	X	x
47	-26.28	279.9	San Felix	X	x
65	-27.15	250.6	Easter	6.5	x
39	-21.13	184.8	Nuku ‘alofa	x	x
39	-23.12	225.0	Rikitea	x	x
57	-20.16	57.5	Port Louis	x	x
60	-21.20	200.2	Rarotonga	x	x
81	-22.30	166.4	Noumea	x	x
116	-24.88	113.6	Carnarvon	x	x
118	-20.32	118.6	Port Hedland	x	x
21	-15.97	354.3	St. Helena	X	x
30	-17.52	210.4	Papeet e	4.7	x
48	-18.13	178.4	Suva	X	x
55	-19.67	63.4	Rodrigues	X	x
103	-19.25	146.8	Townsville	X	x
42	-14.28	189.3	Pago Pago	X	x
46	-10.17	150.5	Alotau	X	x
53	-12.78	45.3	Dzaoudi	X	x
63	-12.05	282.9	Callao	X	x
69	-12.12	96.9	Cocos Island	10.7	x

Table A5. Stations between 60Sand30S. As in Table 1.

SIG	N LAT	E LON	STATION	IGS	CORS
85	-56.51	291.3	Diego Ramirez	X	x
67	-49.35	70.2	Kerguelen	2.7	x
63	-43.95	183.4	Chatham Island	1.1	X
102	-42.88	147.3	Hobart	12.3	X
112	-42.55	147.9	Spring Bay	49.4	x
46	-33.62	281.2	Juan Fernandez	X	X
78	-33.03	288.4	Valparaiso	90.8	X
130	-31.53	159.1	Lord Howe	x	x

THE NEED FOR GPS TO PROVIDE INFORMATION ON VERTICAL LAND MOVEMENTS AT TIDE GAUGES WITH LONG RECORDS

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INTRODUCTION

The need for GPS to provide information on vertical land movements at tide gauges with long records was the main scientific requirement discussed in the two 'Carter reports' (Carter et al., 1989; Carter, 1994), The tide gauge community has for many years applied ingenious anal ysis techniques in order to infer a decoupling of the long term land and ocean signals in the gauge records. However, none of these methods areas satisfactory as actuall y being able to measure the vertical movements directly.

'I-his presentation briefly reviews the historical tide gauge data set, and in particular its spatial coverage, and recaps on the 'Carter requirement for GLOSS'. This leads into a proposal for a 'medium term strategy' for Global Positioning System (GPS) measurements at tide gauges.

THE PSMSL DATA SET

The Permanent Service for Mean Sea Level (PSMSL) is, like the International GPS Service for Geodynamics (IGS), a member of the Federation of Astronomical and Geophysical Data Analysis Service (FAGS) and operates under the auspices of the International Council of Scientific Unions (ICSU). The data bank holds approximately 43000 station-years of monthly and annual values of Mean Sea level (MSL) from over 1750 stations worldwide. Where possible, records at each site are placed into a Revised Local Reference (RLR) data set, wherein MSL values at a station arc referred to the same reference height (i.e. the 'RLR' datum which is defined in terms of the height of the tide gauge benchmark or TGBM). Only RLR records can be used for time series analysis, although all MSL stations-years (called 'Metric' data in PSMSL terminology) can be used for studies of seasonal cycles.

If one inspects the geographical distribution of PSMSL data (Woodworth, 1991), then it appears at first as if copious amounts of information are available from virtually every point on the world coastline. However, a closer inspection shows that many records are quite short. A requirement that records be more than 20 years long loses most stations in Africa and at many ocean islands. A requirement for 60 years or more results in only stations in northern Europe, North America and Japan surviving, along with odd ones in the southern hemisphere such as Sydney or Buenos Aires.

Therefore, it is important to keep in mind that the 'global' sea level data set is not only just a coastal set, but is also primarily just a northern hemisphere one. Consequently, the interest of sea level analysts in the provision of ongoing precise altimetry is a very real one!

Most recent researchers of the long records in the PSMSL data set have obtained values for the twentieth-century trend in global sea level of approximate] y 18 cm/century (+/- 7 cm/century). For reviews, see the Second Scientific Assessment of the intergovernmental Panel on Climate Change (Warrick et al., 1995) and Douglas (1995). This is, perhaps, a reassuring result, although it has to be kept in mind that all authors have used the same (PSMSL) data source. However, they differ in their methods for estimating vertical land movements at each site. Peltier and Tushingham (1989, 1991), Trupin and Wahr (1 990) and Douglas (1 991) used versions of Peltier's geodynarnic models of post-glacial rebound (PGR). Of course, PGR is not the only geological contribution to vertical land movements, but it is the only one for which wc possess detailed understanding (i.e. for which we have a model capable of being employed on a global basis) (Peltier and Tushingham, 1989; Lambeck, 1990). Douglas in particular went to great lengths to reject tide gauge records from stations which he considered to be outside of the areas for which PGR is the dominant geological process, and at which, therefore, he could not make a reasonable attempt to estimate the vertical movements.

Gornitz and Lebedeff (1 987) and the European regional analysis of Sherman and Wood worth (1992) took a different approach, using directly in their analyses those sets of geological information of different ages obtained from around the gauge sites, in order to extrapolate the Holocene sea level curves into the present day when they can be considered as primarily reflecting very long timescale geological change. This procedure, in principle, extrapolates all the vertical land movement signal (other than, of course, rapid changes such as due to earthquakes), whether mostly PGR or not. However, it appears to result in systematically lower values for the determined twentieth-century sea level trend; for a fuller discussion, see Warrick et al. (1995).

Whatever the details of the analysis, it is clear that most long tide gauge records from around the world show evidence for increasing levels (Woodworth, 1991). It is interesting, however, that some of the longest, and highest quality, records are from Scandinavia (e.g. Stockholm, the longest continuous record in the world, Ekman (1988)). These have not so far been employed by most analysts in global studies as the 'near field' accuracy of the PGR models has not been adequate to perform a meaningful subtraction from the tide gauge records, unlike the 'far field' situation exploited by Douglas and others.

Stockholm makes the case for GPS monitoring of tide gauge benchmarks almost by itsel f. 1 f one cannot model PGR there adequate] y, one has to measure it. Moreover, by measuring in the interior of Scandinavia (as several GPS groups now are), one assumes that in time that the PGR models will be even further developed. From Scandinavia and PGR, one can extend the argument to, say, Japan and tectonics. In general, we should not be forced to reject any good tide gauge records from studies of trends, as Douglas and other authors had to do, if we can directly measure the land movements,

SOME QUESTIONS ABOUT TIDE GAUGE RECORDS

There arc some reasonable questions which GPS people might ask of tide gauge specialists.

How Good are the Historical Tide Gauge Records in General?

The short answer to this question is that data from pairs or groups of gauges are in general very good. There arc various tests which can be used when one has several samples of essentially the same data, and problems can usually be flagged even if they cannot be fixed, For example, 'buddy checking' (i.e. the differencing of two time series and inspection of the residual differences) is a very simple but powerful technique (IOC, 1993).

When one has a single record from an isolated station (e.g. in West Africa) or from a long, complicated coastline (e.g. the Canadian Arctic), the answer to the question of data quality could well be 'we don't know', unless perhaps one has recourse to ancillary information. For example, sea level data from Antarctic stations usually obey the 'inverse barometer (l B)' relationship to air pressure very well. Therefore, if a new Antarctic time series is made available which does not obey the IB rule, one can be immediately suspicious. However, even if such a time series does appear to be 'IB-like', that is not necessarily a guide to its quality over longer timescales.

One of the largest factors leading to poor long term data quality is changes in technology, in swapping one sort of gauge for a 'better' one. It is no accident that some of the best time series come from countries which have persevered with older, stilling well techniques and have not incurred the systematic errors which technology changes imply. Whenever changes in technology are absolutely necessary, there should be an overlap period of many years in order to understand the systematic differences (IOC, 1993).

The more reliable long term records also tend to originate from countries which have historically paid close attention to the geodetic control of the sea level time series, in terms of repeat levelling between sets of local benchmarks, in addition to good quality control of data from gauges themselves. An extensive local network of benchmarks (at least six), and good practice in repeat levelling (at least annual) is recommended for present day operations (Carter, 1989; IOC, 1985,1994) to guard against the possibility of unexpected very local land movements (e.g. submergence of the gauge itself, perhaps on the end of a pier) propagating into the long term record.

What is the Error on an Observed Tide Gauge Trend?

This is difficult to answer in a straightforward way. First, it is clear that if one fits a simple straight line to a tide gauge time series of annual mean values, then the computed standard error on the trend will be an underestimate of the 'real error' because of serial correlations in the data (i.e. interannual and interdecadal variability) (Pugh and Maul, 1997). The serial correlation will vary from site to site. However, its effect can be clearly demonstrated by computing trends from both annual and monthly MSL values; the two will give similar trends but the standard errors for the latter will be smaller by up to sqrt(1 2). (It will be sqrt(12) smaller if the seasonal cycle dominates the monthly mean power spectrum).

One can make an empirical 'error estimate' for a trend of a medium length ('n' years) record if one has in the same region another, but much longer, ('N' years) tide gauge record. Then one can compute trends over several sub-sets of length n inside of the N years of the longer record, thereby determining the variability (e.g. Figure 1 taken from Sherman and Woodworth, 1992). Of course, this essentially samples the energy in the low frequency part of the sea level spectrum, and implicit] y assumes that any underlying real trend is constant, which is not necessarily the case.

A further technique is to compare sea level trends from tide gauges to those inferred from other data sources e.g. geological or archaeological information. The trend-differences in such comparisons, of course, contain contributions from both data sources, but at least one can estimate an upper limit for the standard errors of the tide gauge trends (e.g. Figure 4 of Sherman and Woodworth, 1992). Variations in long term tide gauge 'relative trends' (i.e. trends in MSL-difference) in data-rich areas (e.g. Scandinavia) indicate standard errors of a few 1/1 O's mm/year, not only after comparison to data from other sources, but also after inspection for continuity in relative trend between neighboring records (Ekman, 1988; Emery and Aubrey, 1991).

Overall, one has a rule of thumb that a tide gauge record typically 60 years long will have a standard error on its trend lower than 0.5 mm/year, and perhaps much better than that depending on the location, which explains why in Carter (1994) it is stated that 'The minimum accuracy for vertical crustal velocities to be useful for sea level studies is estimated to bc . ..0.3 to 0.5 mm per year over intervals of a few decades'.

What is tile Error on a Trend Corrected for Land Movements at Present?

This brings up issues such as the systematic differences between trends computed using Gornitz and Lebedeff and the PGR-model approaches, discussed above, and the subject of parameter values to be used within PGR models. The latter topic is currently being discussed intensively (Mitrovica and Davis, 1995; Peltier, 1996). Clearly, GPS measurements will be welcome to resolve some of these differences.

What would Tide Gauge People have done if GPS had not been Invented?

If GPS had not been invented, tide gauge analysts would obviously have continued to study sca level variations. The subject would have developed through improvements in geodynamic models and their application to studies of linear trends, and through monitoring of any 'accelerations' at sites with the longest records. Various indices can be computed which attempt to represent ‘accelerations’ (or anomalous departures from predicted levels) using the assumption that geological change at many sites is essentially linear with time. For example, Sherman and Woodworth (1992) present a ‘sea level index’ for the North Sea area indicating an apparent fall in real sea levels in recent decades. One might argue that the world has lived happily, more or less, with a 1-2.5 mm/year linear trend in global sea level during the last century (Warrick et al., 1995), and that we could live with that in the future, if there were to be no large accelerations.

So Why do We Need to Know the Trends if only the Accelerations Matter?

The point here is that wc need to know if our representation of the physics etc. of the climate system is essentially correct within the General Circulation Models (GCM's) used to model sea level changes. In other words, we need to have confidence that the observed 1-2.5 mm/year in global sea level change over the past century is consistent with the various climate forcings. Given that confidence, one can then make more reliable predictions for the future. Therefore, wc need to be able to measure trends as well as accelerations, and so we need GPS.

An example of the ‘need to know more’ is given by the fact that wc do not expect long term sea level changes (whether ‘trends’ or ‘accelerations’) to be the same everywhere because of changes in the ocean circulation. In Table 11 of Douglas (1991), one sees a remarkable uniformity in trends observed at most locations over the past century (although the uncertainties could also accommodate a difference of a factor of two between the trends of the European Atlantic and eastern North American coasts). However, this need not be the case with regard to future changes. For example, Figure 7.15 of Warrick et al. (1995) indicates possible large spatial variations in future sea level changes over typically 70 years (in just the one GCM run, of course). The eastern coast of North America shows larger than average rise while the area to the north of the Ross Sea shows constant sea level or even a fall, features which are also indicated in GCM runs by other authors. This ‘climate fingerprint’, if real, can only be isolated if we can measure the real sea level trends, both by coastal tide gauges and by altimetry in the deep ocean.

How Many Gauges should be Monitored by GPS in this Way?

The short answer to this is ‘as many as possible’. 1 and movements should be monitored by GPS at as many places as considered necessary in order to construct an accurate regional picture of the magnitudes and spatial scales of vertical change (e.g. from short scale ground water extraction effects through to large scale PGR). This implies measurements not only at (or near) gauges but also inland.

A MEDIUM TERM GLOBAL STRATEGY

A possible ‘global strategy’ for making GPS measurements at tide gauges has been investigated recently as part of the discussions for a new GLOSS Implementation Plan (IOC, 1997). GLOSS, the 'Global Sea Level Observing System', is a programme coordinated by the Intergovernmental Oceanographic Commission for the establishment of a global core net work of tide gauges, and for the development of a gauge network suitable for contributing to altimeter calibration studies, ocean circulation monitoring, and climate change research. The first main point of the strategy is to make the maximum use of available information from the historical tide gauge data set.

The Plan suggests that criteria for priority long term sea level monitoring sites in the medium term would be:

(i) sites with long records of, say, 60 or more years of RLR data, whether formally GLOSS or not;

and (ii) sites with acceptably long records of, say, 40 years or more which are in the GLOSS core net work and which, therefore, may also be of interest for other oceanographic purposes and which, on average, are likely to be well maintained.

The second main point, or assumption, is that GPS will be able to be used for, say, 20 years at sites which prove to have 'linear geological trends' with a standard error on the GPS-derived vertical land movement trend less than that of the tide gauge trend (i.e. consistent with the Carter requirement for GLOSS shown above). Of course, by this time the 40 year records will have become 60 years. Then, if linear, the GPS trends can be used to hindcast the vertical land movements within the historical records.

Figure 2 shows the locations of a set of sites which are included in these categories which the Plan designates GLOSS-LTT (Long Term Trends). Clearly, the list can be made more geographically-representative by the selection of sites with shorter records from regions with lower recording density. Suggested GLOSS sites with medium length records (i.e. typically 20-30 years) from Brazil, Africa, western Indian Ocean and Antarctica are also included in Figure 2.

Conversely, the list could be pruned and optimised in data-rich areas if it could be demonstrated (as it probably can if the areas are small enough) that 'real' sea level change was coherent between stations, that differential relative sea level change was determined by vertical land movements, and that GPS would provide the future land movement information. This ideal situation pertains primarily in Scandinavia and the east coast of the USA, areas for which most of the long record sites are likely to remain in operation, and for which there are regional study groups fully capable of making any optimisation (e.g. Baker et al., 1997).

The list could, in principle, be optimised further by using circulation models, as outlined above, as a guide to areas where larger rates of rise of sea level might be expected in future. For example, the North Atlantic has been suggested as one region where greater than average rates of rise might be anticipated (Mikolajewicz et al., 1990; Warrick et al., 1995). However, in practice, such models are still at the early stage of development for reliable regional forecasting,

What happens at those sites at which it is clear that the geology is not 'linear' (e.g. Japan)? At these locations, recording has in effect to start again with GPS measurements taken in parallel to the tide gauge data, The benefits of such investment in terms of obtaining more spatially- representative trends will clearly take longer to be realised, although with geophysical insight it is feasible that studies may provide acceptable limits to real sea level trends over reasonable periods.

']'he GLOSS Implementation Plan (IOC, 1997) also recommends the maintenance of gauges at a number of tide gauge sites for the purpose of monitoring aspects of the ocean circulation. This subset of GLOSS is designated GLOSS-OC and numbers several 10's of stations (the list is currently being refined and discussed). Geocentric fixing of the coordinates of the tide gauge benchmarks will be required for these stations as well, with a view towards the future availability of adequately precise geoid information, which will enable orthometric sea surface heights to be computed at the sites, and hence elements of the ocean surface circulation inferred.

LONGER TERM STRATEGY

In the longer term (i.e. > 20 years), one has to work towards greater geographical representativeness of the long term trend measurements, a requirement inherent in the original motivation for the GLOSS core network, Within that wider set, it is difficult to define 'higher priority' sites. For example, one might choose to nominate island sites for their open ocean character (and much publicised potential threat to low-lying island states); high latitude and polar sites for their range of PGR-related signals; the North Atlantic sites mentioned above; or further sites along continental coastlines near to areas of human or environmental concern. As many nations will contribute to GLOSS and GPS developments through national resources, it is not unrealistic to expect a network evolving to form the basis of a more representative data set for trends in coming decades.

One has only to consider the major technical advances in GPS, altimetry and other areas over the past few years, to appreciate the difficulty of projecting a 'long term strategy' 20 or more years ahead. Clearly, the field has to be reviewed at regular intervals, but that should not stop us investing in GPS measurements right now. If the tide gauge operators of a century or more ago had not made their measurements, for admittedly a range of different reasons, we would not have had an historical sea level data set to study now.

CONCLIJS1ONS

- We need GPS (and related techniques such as DORIS and absolute gravity) at gauge sites to determine vertical land movements, and thereby absolute sea level trends, unambiguously.

- ‘l’he ‘Carter requirement for GLOSS’, expressed as the need to measure vertical land movements to an accuracy of 0.3 to 0.5 mm/year in a reasonable period, remains valid,

- A possible medium-term strategy is to make maximum use of the historical tide gauge data set with records at least 40-60 years long, and measure GPS for, say, 20 years (i.e. a period to be determined which depends on the errors in estimating a geological trend from the GPS data).

- Use could be made of GPS at perhaps 150-200 sites worldwide (the GLOSS-LTT set), although this set could be thinned out in northern Europe, North America and Japan by discussions within regional working groups which have a full appreciation of geological spatial scales.

- A longer-term strategy depends on the eventual availability of other longer records worldwide (e.g. through GLOSS) and the long term development of precise altimetry and other technologies.

- One question is whether GPS (IGS) processing centres can handle the magnitude of data flow implied above. The presentation by Geoff Blewitt at this Workshop indicates a possible organisational framework in which planning for this activity can take place.

TECHNICAL POSTSCRIPT

The PSMSL data referred to above can be obtained via ftp or on cd-rem. For information, consult:

http: //www.pol . ac .uk/psmsl/sea_level.html .

The same web page contains links to several other sea level centres.

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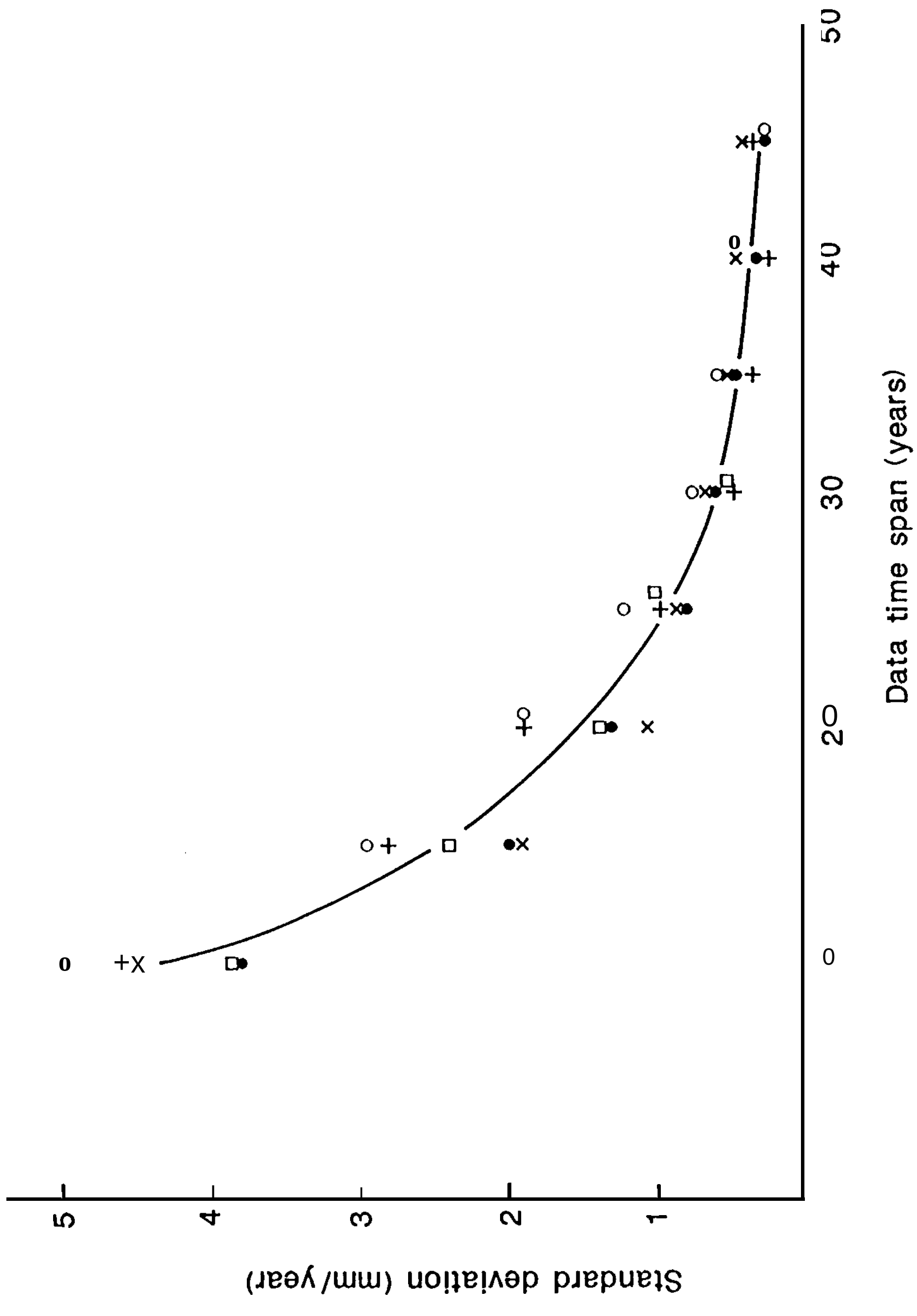

Fig.1. Standard deviations of trends computed over a given data time span, but with arbitrary start date, compared to the trend obtained from the entire twentieth-century using the PSMSL records for Newlyn (dots), Aberdeen II (vertical/horizontal crosses), Hoek van Holland (diagonal crosses), Esbjerg (small open circles) and Bergen (small open boxes). The gaps in the Bergen record preclude very long data time spans. The regional average standard deviation, defined by the average of those shown, is given by the solid line. From Sherman and Woodworth (1992).

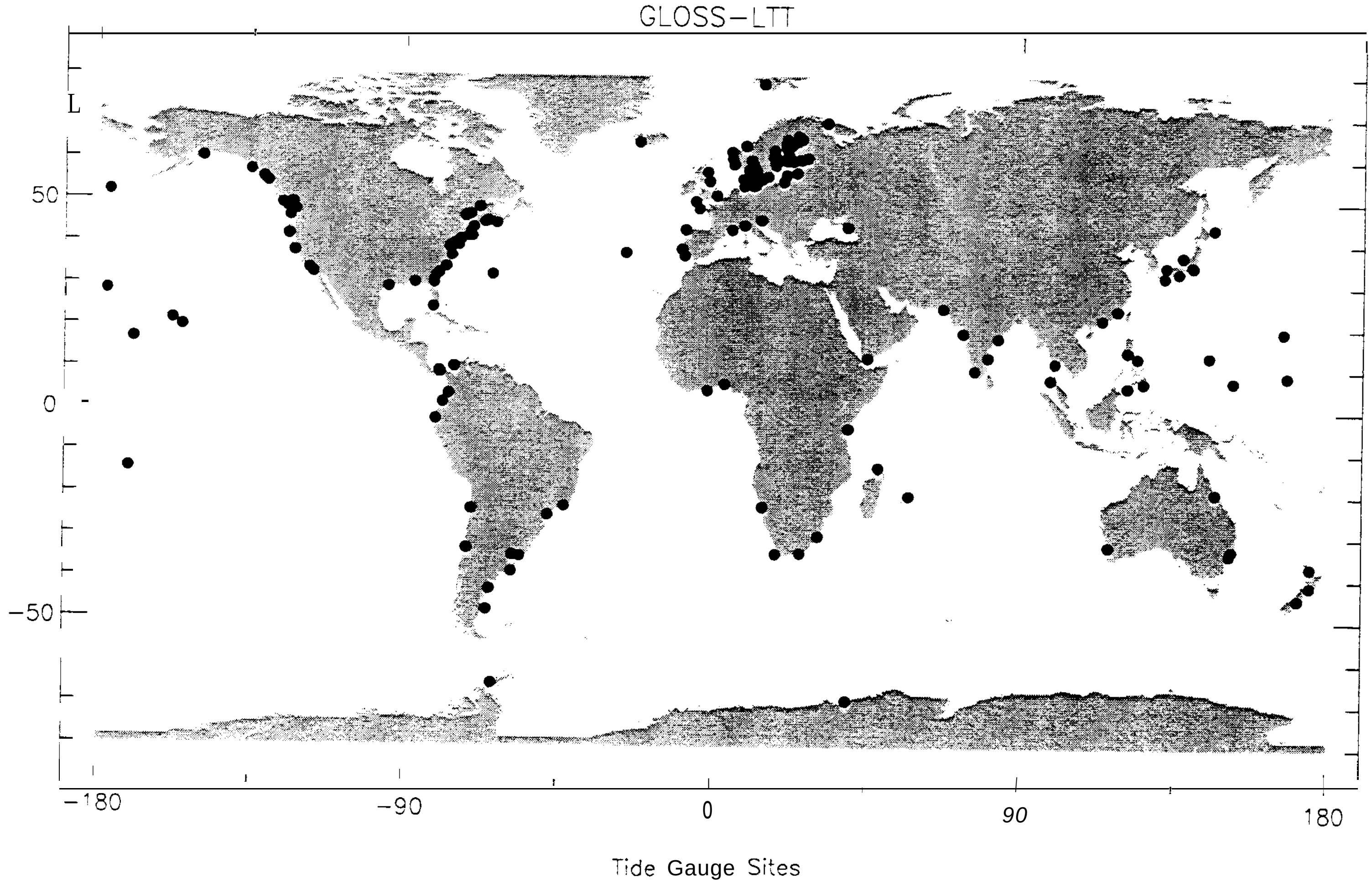

Fig.2. Distribution of tide gauge stations within the GLOSS-LTT set (IOC 1997).

SUSTAINABLE GEODETIC MONITORING OF THE NATURAL ENVIRONMENT USING THE IGS

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ABSTRACT

We introduce the concept of "sustainable geodetic monitoring, " defined in terms of the usefulness and amenability of today's geodetic data to future generations. Tide-gauge benchmark monitoring is a good example of an activity which should be viewed in the broader context of sustainable monitoring of the natural environment. The International GPS Service for Geodynamics (IGS) has the developed the infrastructure, methodology, and products which help Global Positioning System (GPS) users to practise the principles of sustainable monitoring. We propose that any science group committed to long-term geodetic activities such as tide gauge benchmark monitoring participate in the IGS as a "Regional Network Associate Anal ysis Center. " This arrangement would be mutually beneficial for practical reasons too: (1) it is in line with stated IGS objectives, and (2) science groups will benefit from IGS support and "active" reference frame control, through access to data from the global network, precise orbits, and timely information on data quality and the latest developments. Examples of our current research illustrate issues related to sustainable monitoring, particular y on IGS development and operations, SINEX format development, benchmark design, atmospheric effects on geodesy, and tide gauge benchmark monitoring in the North East of England.

INTRODUCTION

As has been pointed out by several observers, geodetic data has the unusual quality that the older' it gets, the more valuable it becomes. This refers to the usefulness of geodetic data from the past in helping today's investigators determine long-term geophysical signals. Translating this idea in time, we therefore introduce the concept of "sustainable geodetic monitoring," which we define as:

"the production of geodetic data which will be as useful and amenable as possible to future generations"

Although current funding mechanisms may favour short term objectives, the space geodetic community, now two decades old, is coming to recognize long term needs.

“Observations made in the next few decades will provide the data needed for informed forecasts relevant in the next century, when the world’s population is likely to reach a maximum” [*Bilham*, *1991]*. Clearly, sustainable monitoring must be an integral part of project planning today, if space geodesy is to realize its full potential towards this goal.

The concept of sustainable monitoring is particularly relevant for the problem of global change in absolute sea level, which requires us to determine the long-term change in the height of the tide gauges. It has been proposed that tide gauge benchmark monitoring be organized so that individual investigators determine the coordinates and velocities of the benchmark using GPS, and report it to, say the Permanent Service for Mean Sea Level for future reference *[Carter,* 1994]. Such an approach must recognize and address problems concerning benchmark stability, compatibility between instruments and observation models implemented in the various software packages, the reference system, and environmental effects on estimated heights. Solving such problems today is a prerequisite to sustainable monitoring.

Tide-gauge benchmark monitoring should be viewed in the broader context of sustainable geodetic monitoring of the natural environment. This is because the height of a tide gauge is affected by a wide variety of environmental effects, including coastal subsidence, solid Earth tides, ocean loading (tidal and non-tidal), atmospheric pressure loading, tectonics and the earthquake cycle, postglacial rebound, current variation in ice sheet loading, sedimentary loading, denudation, pole tides, volcanic activity, and the effect of global mass redistribution on the geocenter. To make the problem even more complicated, we show that estimated height may appear to vary because of systematic error which is correlated with environmental conditions.

Reference systems account for some of the height variation, and therefore a reported height or height velocitiy implicitly incorporates (today’s) geophysical models. The current situation is that most groups now abide by much, if not all of the conventions defined by the International Earth Rotation Service (IERS), defining the IERS Terrestrial Reference System (ITRS) [*McCarthy*, 1996]. However, some effects are either too random to be predicted, or currently too difficult to model adequately. This is often because of lack of information or because of the complexity of processing the available information (e. g., global data sets on atmospheric pressure and sea surface height). Apart from the need for met iculous documentation of analysis standards, this raises the more genera] issue that sustainable geodetic monitoring may necessarily have to include the collection of auxiliary data on environmental conditions.

REQUIREMENTS FOR SUSTAINABLE MONITORING

The definition of sustainable geodetic monitoring therefore leads to the following two important requirements (which are stated here in terms more generally applicable than to tide-gauge benchmark monitoring):

Requirement 1: *The data must be useful to future generations, in the sense that they represent relevant aspects of reality so as to enable the future production of good results.*

We have to, of course, guess the needs of future generations, and have some idea of what they would consider "good results." Sampling must be sufficient to characterize all relevant environmental signals. We propose continuous temporal sampling wherever possible, and spatial sampling at a density inversely proportional to the expected coherence length of geodetic signals. The best way to achieve this at present is through the global permanent GPS network, densified appropriately in regions of high geodynamic activity. This also allows for the detection and correction of anomolies due to change of equipment, thus producing a more relevant representation of reality (i.e., the height of a benchmark, and not of an antenna phase center).

Requirement 2: *The data must be amenable to future generations, in the sense that the inherent information content can easily be extracted and used appropriately, without need for interaction with the originator.*

The best way to achieve this is, again, through continuous monitoring of permanent GPS networks, since this allows for the use of existing infrastructure to exchange, process, and archive data in a standard way. These standards also must address the reference system, so that, for example, the definition of "height" is clear] y understood, and can be used by future generations.

We suggest that both these requirements can be met by active participation in the International GPS Service for Geodynamics (IGS) [*IGS*, 1997; *Zumberge et al., 1994].* In this paper we propose a way for science groups, that are committed to sustainable natural environmental monitoring programs such as tide-gauge benchmark monitoring, to draw from the expert ise and fine products from the IGS, while at the same time helping the IGS to achieve its objectives. The primary objective of the IGS is "to provide a service to support, through GPS data products, geodetic and geophysical research activities" [*Mueller*, 1993; *IGS* 1997]. Towards this goal, the stated scientific objectives of IGS include "realization of global accessibility to and the improvement of the IERS Terrestrial Reference Frame (ITRF)," and "monitoring variations in the liquid earth (**sea-level,** ice-sheets, etc.)" [emphasis ours].

To illustrate relevant geodetic issues, the second half of this paper briefly presents research activities at Newcastle towards the IGS Densification Program [*Zumberge and Liu,* 1995], and on height determination for natural environment monitoring. This section also illustrates how this relationship can work both ways, with examples of how non-geodetic monitoring of the natural environment (in this case, meteorology) can help improve height determination.

IGS DENSIFICATION PROGRAM

After several years of planning [*Mueller and Beutler,* 1992], the International GPS Service for Geodynamics (IGS) was officially established in 1993 by the International Association of Geodesy. Ever since an initial pilot phase beginning June 1992, the IGS has been coordinating the operations and analysis a global network of GPS stations. 'l'he IGS officially commenced operations in January 1994, by which time approximately 40 to 50 IGS stations had become operational.

The expanding global network of high precision GPS receivers (Figure 1) was seen to present an opportunity to produce a reference frame which is (i) dense, (ii) of a reasonably homogeneous quality, (iii) of few-millimeter accuracy on a global scale, (iv) readily accessible to GPS users, and (v) ideal for monitoring variations in the Earth's shape, and for providing kinematic boundary conditions for regional and local geodetic studies [*Blewitt et al.* 1993, 1995]. The challenge was to be able to analyze cohesive] y the data from an ever increasing number of receivers, such that near-optimal solutions could be produced. Although ideally all data should be analyzed simultaneously to produce a single solution, in practise this is computationally prohibitive.

This led to the "distributed processing approach, " which, at the algorithm level, partitions the problem into manageable segments [Figure 1], and, at the organizational level, delegates responsibility to analysis centers who would naturally have an interest in the quality of the solutions. Another characteristic of this approach is a level of redundancy, such that a meaningful quality assessment can be made by other, independent groups. Distributed processing was developed as a method which could be carried out as a natural extension to the existing operations of the IGS.

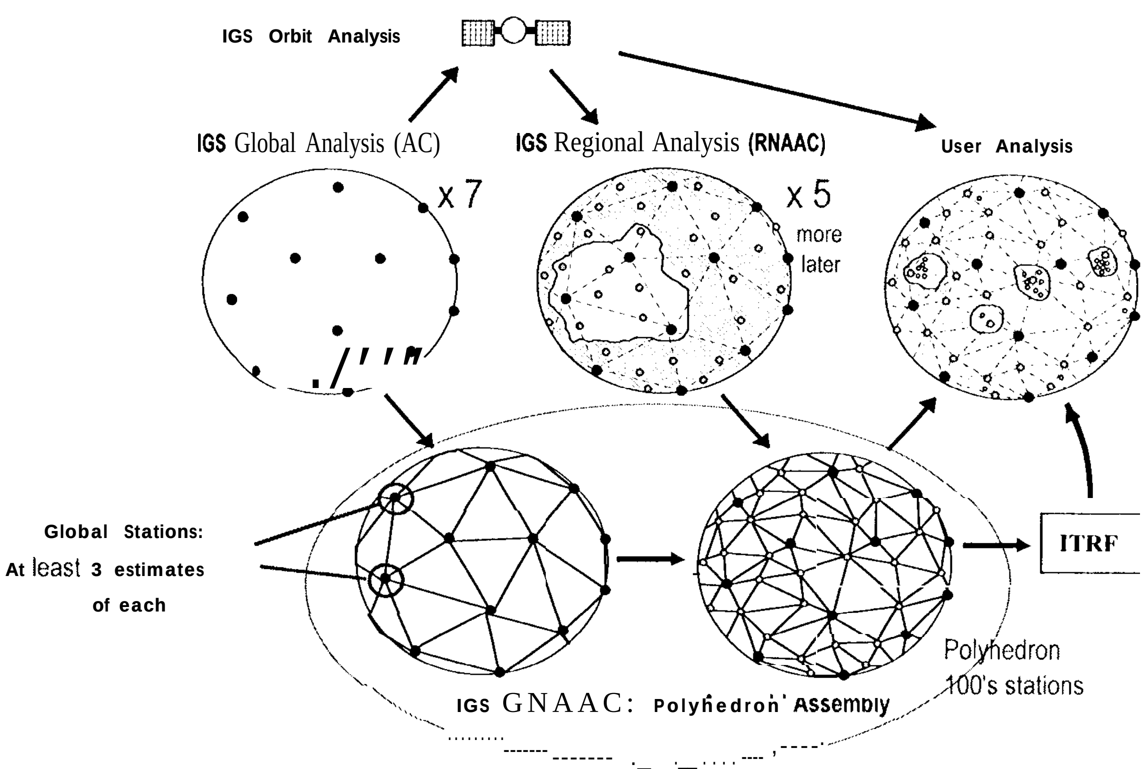

Figure 1: Schematic explanation of the distributed processing approach. Our proposal is for science groups to operate as RNAACS. The GNAACS would then take care of reference frame consistency, and input into ITRF.

Following a planning workshop at JPL in December 1994 [*IGS*, 1995], a pilot program was initiated in September 1995 to test these ideas. Global Network Associate Analysis

Centers (GNAACs) were set up at Newcastle University, MIT, and JPL. A format was developed for the exchange of coordinate solutions, covariance matrices, and site information (SINEX format) [*SINEX Working Group, 1996]*. Initially these GNAAC'S combined solutions for global network station coordinates provided every week by the seven Analysis Centers, producing a single unified SINEX file. Approximately one year later, Regional Network Analysis Centers (RNAACs) began submitting regional GPS solutions, computed using weekly published IGS orbit solutions. These regional solutions were then assimilated into the unified global solution by the GNAACS, what is known as the "IGS polyhedron solution. "

Although currently undergoing final review, the pilot program has been viewed broadly as a success, demonstrating few-millimeter repeatability in weekly solutions for geocentric coordinates of not only the global stations, but also the regional stations. However the actual process of densification (new GPS stations) is still less than adequate in many parts of the globe. This is where tide-gauge benchmark monitoring could help. Additional GPS stations installed at island tide-gauge sites will undoubtedly be greatly welcomed by IGS, especially as oceanic regions of the globe are systematically undersampled (which is the primary reason for the lack of stations in the ocean-rich southern hemisphere). Furthermore, the IGS Densification Program provides a natural way for science groups to participate in IGS. It is important that not too much additional burden be placed on existing IGS components (in particular, the IGS Analysis Centers); therefore participation as an RNAAC would be a natural way to extend the IGS community for the benefit of all involved.

Newcastle's IGS Global Network Associate Analysis Center

Blewitt et al. [1994] discuss the following components of the GNAAC activities (previously called "Type Two Analysis" during the planning stages): (i) detection of inter-agency information discrepancies (e. g. in antenna heights); (ii) monitoring of solution consistencies (inter-agency, and with respect to ITRF); (iii) weekly publication of a combined global solution; (iv) weekly publication of an IGS polyhedron solution (global plus regional networks); (v) periodic publication of kinematic solutions (e.g., stat ion height velocity, plate tectonic Euler vectors, etc.), with submission to the International Earth Rotation Service (IERS) with the goal of improving the ITRF.

Now almost two years since the inception of the IGS Densification Pilot Program, the Newcastle GNAAC is continuously achieving all these objectives *[Davies and Blewitt, 1996, 1997]*. Taking the most recent submission at the time of writing, coordinate solutions for 132 stations are presented, of which approximately 50% are global stations (defined as being analyzed by at least 3 Analysis Centers), and 50% are regional. A total of 54 regional station solutions derive from 3 RNAACS which cover South America, Europe, and Japan.

We have developed combination procedures *[Davies and Blewitt*, 1996, 1997] which aim to (1) minimize bias from datum assumptions, (2) minimise bias from unrealistic covariance matrices; (3) utilize the inherent redundancy of overlapping networks to remove outliers objectively. The first is achieved by applying a loosening transformation to each input covariance matrix [*Blewitt*, 1997], which can be interpreted as the inverse of reference frame projection [*Blewitt,* 1992]. The second is achieved by variance component estimation [*Grafarend and Schaffin*, 1979, *Rao and Kleffe,* 1988; *Ziqiang,* 1989; *Sahin et al.* 1992]. The third is achieved by applying reliability analysis theory [*Kosters and Kok 1989; Baarda 1967* and 1968].

Figure 2 shows that our weekly, long-term repeatability in station height has a best case value of 3 mm, median of 7 mm, and worst case of 19 mm. This is to be compared with the best Analysis Center solutions (best case 4 mm, median 9 mm, worst case >30 mm). We conclude that GNAAC analysis not only provides a consistent unique solution, but also a more reliable solution (in the statistical sense of the word). The IGS Densification Program methodology should not be viewed as compromising solution quality, but rather as a preferred alternative to unilateral analysis,

TOWARDS IMPROVED HEIGHT DETERMINATION

In this section, we present examples of our ongoing research into improving height determination. We include examples from four different areas: (i) benchmarking, (ii) modelling real crustal height variation; (iii) modelling systematic errors that can otherwise appear as height variation; (iv) assessing processing strategies which lead to different height estimates.

Benchmarking

In Western Europe, Neolithic civilizations from 3500 to 4000 years ago have left us striking reminders of their existence: megalithic monuments built of standing stones, which were often transported from distant quarries. The very existence of these monuments is a testiment to their long-term stability. The standing stone, or "menhir", is typically 1-10 tonnes, a few meters long, and tapers towards the top to ensure a low center of mass.

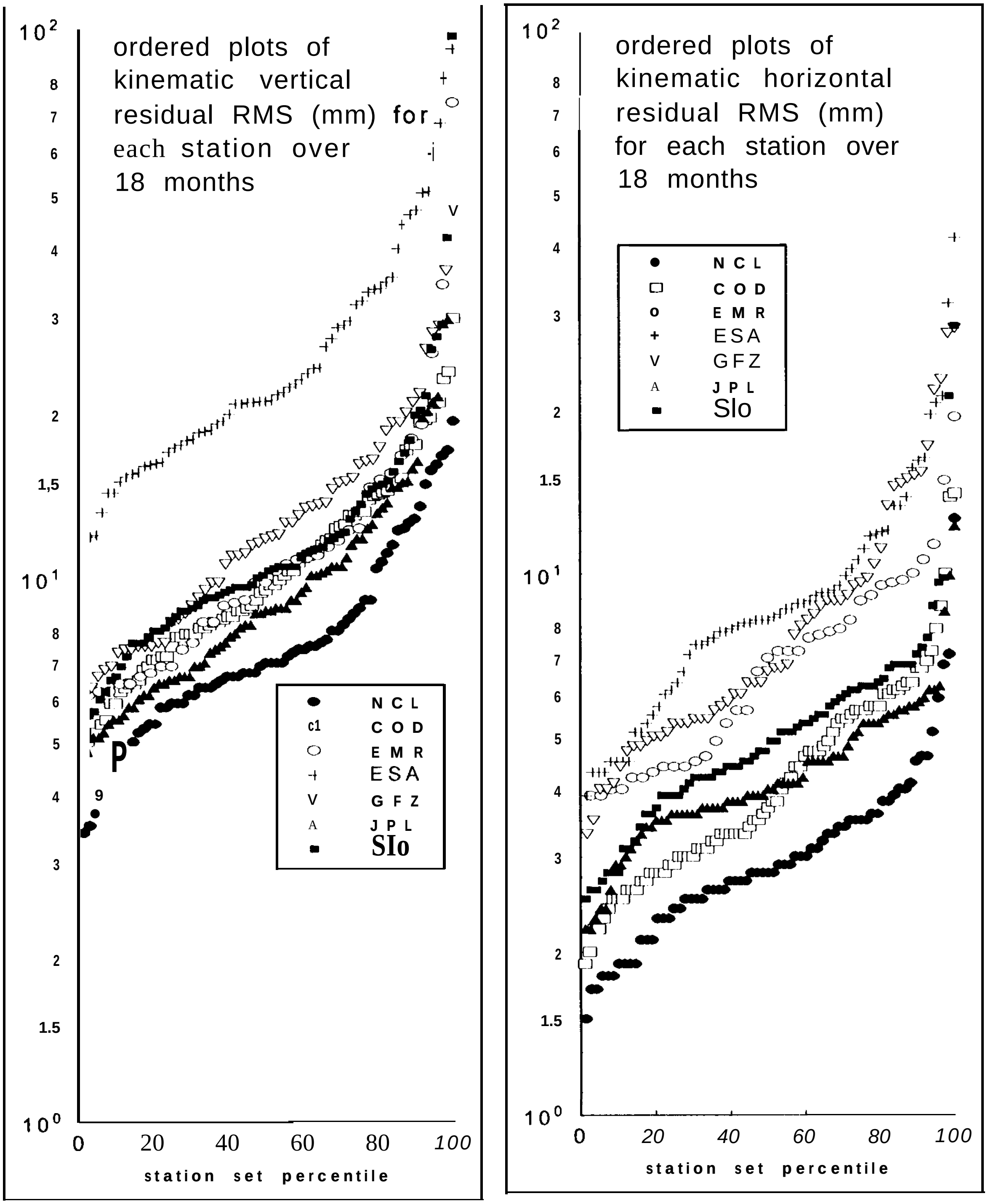

Figure 2: Ordered plots of station coordinate repeatability over 18 months for IGS Analysis Center solutions, and GNAAC solution (labelled NCL)

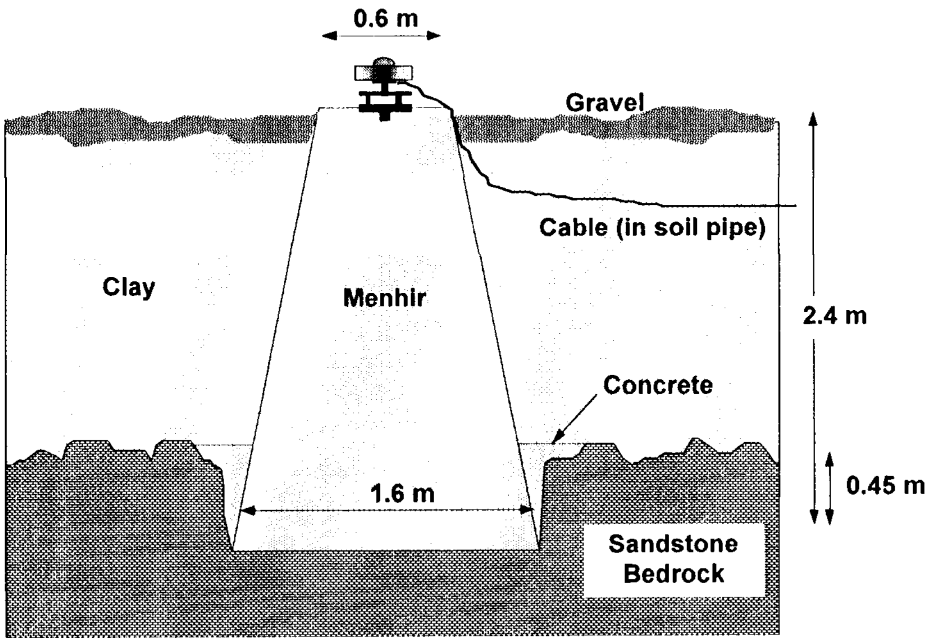

Figure 3: Neolithic menhirs (Late Stone Age standing stones) inspired our design of this geodetic monument, installed at station MORP near Newcastle

Inspired by this design, we have built such a monument in the North East of England (Figure 3), where it is difficult to find rock outcrops at sites which we believe would not be endangered by future development, and yet have the necessary electrical power, communications, and security to support a permanent GPS station. To satisfy the longevity and infrastructure requirements, we selected a site on a farm owned by the University. In effect, we have extended the underlying bedrock at 2-3 meters depth, to the surface using a single quarried rock (brought from 200 km away, by more conventional means!), upon which a GPS antenna is placed. Our worry about more conventional concrete pillars is deformation due to curing (months), long-term shrinkage (>10 **years). Moreover, the** very long term durability of concrete is uncertain.

Our permanent GPS station monument at Morpeth (MORP) consists of a menhir which weighs 4.5 tonnes, stands 2.4 meters high, and tapers from a 1.5 meter base to a 0.6 metre top. On top, epoxied into a rnasoned cavity, a forced-centering Ordnance Survey benchmark ensures reproducible antenna mounting. It is less visually striking than our ancient monuments, as the top is flush with the ground so as to reduce multipath effects. The primary purpose of MORP is to provide a stable height reference for the monitoring of offshore oil production structures, which move with the sea-floor as the oil reservoirs change shape. However, we have been careful to design MORP so that it can be used for decades, if not **centuries to come, as a reference point for monitoring change in sea-level, especially for tide gauges in the North East of England.**

Our objectives are consistent with sustainable monitoring, in that (1) the benchmark motion should faithfully represent crustal kinematics (i.e., the benchmark is "useful"), and that (2) the monument will survive for scientists centuries from now (i e., the benchmark will be "amenable"). Further emphasizing requirements for sustainability, we believe there is a pressing need for a database of permanent geodetic monuments which may be used in the distant future, including physical descriptions which could be used to assist in classifying monuments in terms of their potential stability. This type of activity will be critical for the reliable determination of secular signals of <1 mm/yr, which may require decades of geodetic monitoring. Indeed, the IGS has begun to include this type of information in its station log sheets, available on line from the IGS Central Bureau.

Atmospheric Loading Analysis

The effect of atmospheric crustal loading on GPS station height was studied extensively by *Van Dam et al. [1994]*. Given the general trend towards higher precision, it is timely to reassess these effects. As a preliminary assessment, pressure readings were obtained from the IGS station at Wettzell, Germany, and were compared with the height estimates from the Newcastle GNAAC results. We found that if we applied a loading coefficient of -0.5 mm/mbar to the pressure data, the resulting "modelled" height variation correlated with the GPS time series at the level of 0.69, which is too statistically significant to be considered coincidental. The value of -0.5 mm/mbar is a typical magnitude one would expect to derive by (i) using gridded global pressure to compute height displacement by a Green's function approach, then (ii) regressing these modelled heights to local pressure [e.g., *Blewitt et al., 1995,* Figure 1].

These preliminary findings therefore present some hope that we are now approaching the point where even small crustal height signals, such as those due to loading effects, can be detected, adequately modelled, and removed from the time series. Only through such studies can we hope to have sufficient confidence in the true level of errors in our estimates, and to provide time series which we can be confident in explaining.

Weather Front Analysis

Unfortunately, height is also the most sensitive component to systematic effects, due largely to errors in modelling the effect of tropospheric refractivity on the signal delay. Unlike longitude and latitude, the signal always comes from the positive hemisphere for height; therefore, any systematic shortening or lengthening of the delay will tend to map more into height than the horizontal components. High precision GPS software packages account for tropospheric refractivity by estimating a zenith delay parameter, which through a "mapping function" accounts for the slant depth at arbitrary zenith angles. To account for spatial variations, there have been attempts to model gradient parameters, thus allowing for azimuthal variation in delay. To account for temporal variations, stochastic estimation techniques have been used, ranging in sophistication from Kalman filtering (and equivalent approaches) to simply estimating a new bias approximately every hour [*Blewitt,* 1993].

However, none of the above approaches can adequately account for weather fronts, a meteorological phenomenon which sharply divides air and water vapor of different temperatures, and hence different refractivity. Weather fronts move over a fixed point on the Earth over a period of about two hours, during which time we can expect the integrated refractivity (proportional to the delay) to undergo rapid variation. As an indication of how problematic fronts can be, *Elgered et al. [1990]* concluded that none of the correlations with various ground-based meteorological parameters could be used to make reliable predictions of changes in delay.

At Herstmonceaux, England, fronts pass by the station on every other day, statistically. The times of passing fronts were noted using meteorological maps from the UK Meteorological Office. If we only look at days with known fronts, the height repeatability y is 11.7 mm. If we only look at days without fronts, the repeatability improves to 7.7 mm, indicating that the variance contributed by the inhomogeneity in refractivity from fronts is $(8.8\ \text{mm})^2$, which is of the same order of magnitude as the total height variance in the absence of fronts. We therefore conclude that, when they are present, fronts can be the dominant source of height error.

As a first step towards our goal of developing more sophisticated front modelling techniques, we have assessed a method of using only GPS data to determine the presence of a front, and the affect of such detected fronts on the variance of estimated heights. To simplify the analysis, we have applied the precise point positioning technique developed by *Zumberge et al. [1997],* as implemented by the GIPSY OASIS 11 software. This technique requires carrier phase and pseudorange data from a single receiver, holding satellite orbit and clock parameters fixed to positions previously determined by JPL as part of their IGS global network analysis. The parameters are therefore all local to the station: three station coordinates, one station clock bias at every, epoch, a carrier phase bias to each satellite observed, and a zenith tropospheric bias at every epoch. The zenith tropospheric bias is stochastically estimated as random walk process, with a level of process noise set by the user.

Our new technique is to produce these stochastic GPS estimates of tropospheric delay and search for any steep gradients that are sustained over a sufficient period to be indicative of a front. We find the majority of fronts are accompanied by a gradient of a few centimeters per hour, sustained over one to two hours [Figure 4], which is consistent with the findings of *Elgered et al. [1990],* who instead measured sky brightness temperatures using a water vapor radiometer during the passage of fronts. If we objectively eliminate days with high tropospheric gradients, we find that the height repeatability of the remaining days is 8.1 mm, almost as good as the set known to have no fronts.

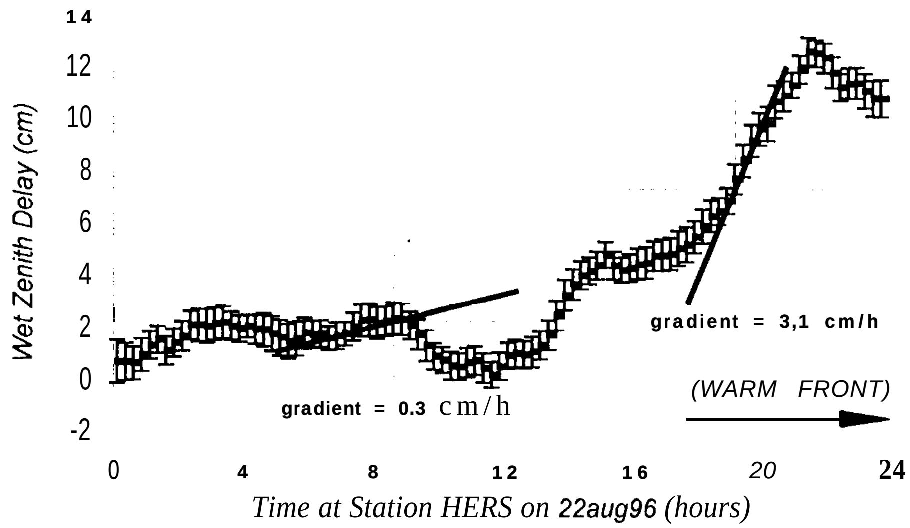

Figure *4:* Onset of a warm front at station HERS can be detected by the steep gradient in stochastically estimated tropospheric delay

To summarize, we have discovered that weather fronts can be a major source of height error. Tropospheric estimates determined using the GIPSY OASIS II software's random walk model can be used to search for gradients, which can then be used to detect the presence of a front. This technique would therefore appear to be directly applicable to any station which suffers from frequent fronts, without requiring any additional meteorological instrumental ion.

Local versus Global Positioning

Given the great variety of possible GPS data processing strategies, not to mention different soft ware packages, we should attempt to determine the best possible strategy. Determining what is "best" is not easy, given that we have no ground truth. We therefore resort to the usual technique of attempting to minimize long term repeatability y, on the assumption that observed height variation can only get worse if a less optimal strategy is employed. This assumption, of course, is statistical, since there is always the element of chance that non-optimal strategy will just happen to produce the "best" results for the specific data set under investigation, However, we use this approach as a useful guide to the truth.

One this assumption, we are systematically testing various strategies, using data collected at permanent GPS stations which are assumed to be stably attached to bedrock, and suffer no local effects (such as coastal subsidence). Another paper in these proceedings [*Sanli and Blewitt,* 1997] presents results from our new station MORP. As described earlier, this station has been installed specifically with height stability in mind, and is being used as a reference point to monitor GPS stations at two local tide gauges, within a 30 km radius.

San/i and Blewitt [1997] use precise satellite orbit and clock solutions from the Jet Propulsion Laboratory to perform precise point positioning of single receivers [*Zumberge et al., 1997].* This approach produces a height time series with a variance not significantly different than applying traditional GPS relative positioning (equivalent to double differencing). This was an unexpected result, considering that reference frame error cancels almost exactly in relative position estimates over 30 km, whereas it would map 1:1 into single receiver point positions. We therefore conclude that the stability of the reference frame imposed by precise satellite ephemerides is certainly no worse than local (non-spatially correlated) error sources, such as multipath in the station's environment. This is further confirmation of the stability provided by GPS global network solutions, and points to possible new procedures in IGS to allow for precise point positioning using IGS products. It also reduces any *geodetic* requirement that might suggest that tide gauge benchmarks be within a certain distance of a fiducial point (on the other hand, there may be geophysical requirements; for example, it might be useful to assess whether any detected height signal is local or regional).

CONCLUSIONS

Sustained monitoring requires data to be both useful and amenable to future generations. The IGS provides the infrastructure and procedures to meet the requirements for sustained monitoring of the natural environment. As well as for the philosophical reasons proposed here, the tide-gauge science community should exploit the IGS for the following practical reasons: (i) it is likely to lead to geodetic solutions at least as good as any other approach; (ii) it saves in labour costs, much of the work being already by other components of IGS to solve for satellite orbits, operate the global stations, distribute and archive data and solutions, and set standards for anal ysis and operations; (iii) it ensures reference frame consistency, as the GNAAC methodology enforces it; (iv) it ensures that the data and solutions are formatted and archived in a consistent way, with cross checking done for inconsistencies; (v) it ensures that the data and solutions will be retrievable and understandable in the long-term, which is crucial for the problem of global change in absolute sea level.

Analyses that use IGS products are also of such high quality and are so relatively easy to produce that research into precise positioning is continuing to progress, thus broadening the range of geophysical signals we can investigate. We have identified and illustrated three areas in which contributions can still be made. These types of activities should continue to be encouraged as part of an overall strategy towards sustainable monitoring of the natural environment, by improving the usefulness of today's solutions for tomorrow's scientists.

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PRACTICAL EXPERIENCE AND CONSIDERATIONS: PROJECTS PAST AND PLANNED

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PRACTICAL EXPERIENCE AND CONSIDERATIONS: PROJECTS PAST AND PLANNED
SESSION SUMMARY

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INTRODUCTION

The two previous workshops on using advanced geodetic techniques to fix tide gauge benchmarks (TGBMs) were held at Woods Hole, USA in 1988 and Surrey, UK in 1993. The reports from these workshops generated a lot of interest in absolute sea level measurements and many new projects using GPS and absolute gravity measurements, in conjunction with sea level measurements, were started in various countries during the last few years. The purposes of this session,which consisted of 4 oral and 9 poster presentations, were to review the progress that has been made in the different GPS projects and to gain from the practical experiences when designing new projects.

The report of the first workshop recommended that episodic campaign type GPS measurements should be made at, or near, tide gauges. The second workshop concentrated more on continuous GPS measurements, which had then started to produce impressive results for the horizontal components and also for the more difficult vertical component. In the following brief session summary, we first review the work on episodic GPS campaigns and then the work on continuous GPS, including proposals to try and combine the two approaches, For various technical reasons, it is often not possible to make the GPS measurements directly at the tide gauge. The distance from the tide gauge is usually only a few hundred metres, but in some cases it can be several kilometres. The accuracy of these ties is an important technical issue that needs to be addressed and some preliminary results presented in this session are outlined in the next section. There was also a presentation on progress and potential developments with GPS measurements of sea levels and waves on buoys, which are outlined in the final section.

EPISODIC CAMPAIGNS

Ashkenazi et al. presented results from GPS campaign measurements at 16 UK tide gauges taken during the UKGAUGE 1 and 11 and the European Union EUROGAUGE projects. For the Newlyn tide gauge the repeatability of the vertical component between 7 campaigns over a 5 year period is better than 15 mm. Analysis of the data from the continuous IGS station at Kootwijk for the same periods as the campaigns and comparison with the ITRF values showed than an accuracy of 15 mm or better could be achieved for campaign type measurements. Whilst a much longer series of campaigns would be required for an accurate determination of secular land movements, this variability is much less than the 50-100 mm interannual and decadal variabilities in mean sea levels (see papers by Sanli and Blewitt, Summerson et al. and Kakkuri et al.), which necessitates the use of several decades of mean sea level data when determining reliable secular sea level trends.

An accuracy of 10 to 15 mm is sufficient for vertical datum work, where the errors due to spirit levelling and, in particular, geoid errors dominate. A GPS campaign is therefore being used to define a European Vertical GPS Reference Network (EUVN). Adam et al. described the plans for the EUVN97 campaign from 21-29 May, 1997. Altogether, GPS measurements will be made at 190 sites covering the European area, including 50 tide gauges.

Zerbini described the results of the SELF I and SELF II projects, which were funded under the European Union Environment and Climate Programme. These projects involve 9 countries working together on sea levels in the Mediterranean and Black Sea. The emphasis is on multi-disciplinary aspects of sea levels involving tide gauge data, satellite altimetry, air-borne laser altimetry, modelling, geological measurements as well as GPS, water vapour radiometer and absolute gravity measurements. The episodic GPS and absolute gravity campaign measurements made at the tide gauges in the SELF I project will be repeated in SELF II. The complementary nature of GPS and gravity observations is being utilised in a special experiment at Medicina, where continuous GPS measurements are being made together with continuous superconducting gravimeter and episodic absolute gravity measurements.

Kakkuri et al, reported on the results of the Baltic Sea Level Project. This involved 2 campaigns and 35 tide gauges in the countries surrounding the Baltic Sea. A third campaign will be observed as part of the EUVN campaign in May 1997. The goals are to unify the vertical datums of these countries at the ±10 mm level and to determine sea surface topography. The data from the second campaign were analysed by 6 different computing centres. Although the Bernese software was used by all the groups the RMS of the height components computed by the different groups was 23 mm, which may reflect problems with modelling the phase center variations. The sea sulfate topography of the Baltic Sea was found from the GPS measurements by using a gravimetric geoid model of the area. The sea surface was found to be 400 mm higher in the north and east compared to the south, which is consistent with oceanographic work.

CONTINUOUS/PERMANENT GPS

Johansson et al. reported the results from 3 years of continuous GPS observations in the BIFROST project. The aims of the project are to determine the vertical deformation rates to an accuracy of 0.1 mm/yr from 10 years of GPS observations and to use these vertical rates, together with the horizontal deformations, to test models of post glacial rebound in Fennoscandia. Data from about 40 continuously operating GPS stations are processed automatically. Connections to tide gauges are made with campaign type GPS measurements every 1 or 2 years. The variability of the daily solutions for the continuous GPS measurements are of the order of ± 10 to 15 mm in the vertical compared to ±5 mm for the horizontal. The data show 10 to 20 mm offsets in the vertical positions corresponding to known changes in antenna mounts or radomes. There are also seasonal variations which are mainly due to snow and ice deposition on the antenna or radome. The linear vertical rates from 3 years of data are estimated to within ±0.7 mm/year and the spatial distribution is in general agreement with that found from models and from long term tide gauge and levelling observations. However, systematic errors remain, in particular, concerning the use of a consistent reference frame and geocentre.

Nerem et al. reported on the results from continuous GPS measurements around Chesapeake Bay, USA (BAYONET). The impact of sea level rise is very significant in this area due to the extensive wetlands and the fragile ecosystems. Chesapeake Bay is in the area of subsidence due to the collapse of the peripheral bulge surrounding the main post glacial rebound area. There is also possible local subsidence due to extensive groundwater extraction, Thus, the project will contribute to climate related sea level changes, the monitoring of local subsidence and the testing of post glacial rebound models and, in particular, the lower mantle viscosity, 5 continuous GPS receivers have been installed at sites around the bay, which have NOAA acoustic tide gauges. Data are also available from several other continuous GPS receivers in the area. The daily repeatabilities are about 10 mm in the vertical and less than 4 mm in the horizontal, Atmospheric pressure loading can account for some of the variability in the vertical, but the main cause is due to residual errors in modelling water vapour in the troposphere. The preliminary results suggest that at least 3 years of data are required in order to determine the vertical rate to an accuracy of 1 mm/year or better. The results from 3 of the sites suggest subsidence of a few mm/year with respect to the IGS site at Goddard. The network will be extended northwards along the east coast of the USA to provide an important test of the rebound models in this area. Tide gauges with at least 50 years of mean sea level data will be given the highest priority, so that the decadal sea level variations have less influence on the estimated secular trends in mean sea levels.

The USA Continuously Operating Reference Station (CORS) network of 100 to 200 GPS stations was described by Schenewerk et al. The network is coordinated by the National Geodetic Survey and involves several Federal Agencies, including the U.S. Coast Guard. Several of these GPS stations are within 5 ktn of tide gauges and so can be used for sea level work,

Summerson et al. described the results from continuous GPS measurements installed near tide gauges in the hostile environment of Antarctica (Mawson, Davis and Casey) and the sub-Antarctic (Macquarie Island). The inter-disciplinary nature of GPS and sea level work was emphasised in presentations by Pavlis et al. on plans for a continuous GPS array in Crete to monitor subduction and sea level changes and by Miller et al. on plans for monitoring the tectonic motions in the Cascadia subduction zone and the associated sea level and seismic hazards. In order to decouple any local movements of the tide gauge pier from the more geophysically interesting vertical crustal movements, Miller et al. propose installing the prime dual frequency GPS station on bedrock and a single frequency GPS receiver on the tide gauge.

In the SELF 11 project, the special experiment with continuous GPS at Medicina, Italy, and at the tide gauge of Porto Corsini (50 km from Medicina) will be used to assess the various error sources in continuous GPS measurements. Water vapour radiometer measurements together with the continuous gravity, absolute gravity and VLBI measurements at Medicina will provide important data sets for this assessment. Ashkenazi et al. described the plans for the UKGAUGE 111 project which will start in 1997. Continuous GPS measurements will be made at 5 UK tide gauges. These will include the tide gauges with the longest mean sea level records and also tide gauges in the S.E. of England, which are important for flood defence. In addition, they propose to develop a roving GPS measurement system in which a dedicated GPS receiver/antenna will make episodic GPS measurements for a few days each year at other UK tide gauges, in order to densify the network.

TIES FROM A PERMANENT GPS SITE TO THE TIDE GAUGE

Whilst there was general agreement that the GPS measurements should be as close to the tide gauge as possible, a compromise often has to be made because of problems such as multipath or site security. In addition, permanent GPS stations are often set up at sites on bedrock with the main purpose of testing geophysical models (e.g. BIFROST and the Cascadia margin projects described above). The accuracy and the frequency of the ties to the tide gauge benchmark, then become important issues.

Turner et al. reported on the installation of modern acoustic tide gauges on 11 islands in the South Pacific. The tide gauges are connected by precise spirit levelling to an array of up to 7 local deep benchmarks and also to an array of benchmarks 10 km inland. They observed local movements of a few mm over 3 years. At Macquarie Island, in the Southern Ocean, the permanent GPS site is just under 1 km from the tide gauge. Summerson et al. have repeated the tie in each of 3 years and found differences of 4 mm using GPS, but agreements to better than 1 Jnm using first order spirit levelling. In the Chesapeake Bay project, the distances involved are usually a few hundred metres and first order levelling connections are made by NOAA, roughly every year.

Sanli and Blewitt described experiments to find the optimum strategy for connecting a permanent GPS site situated on bedrock near Morpeth in Northeast England to the tide gauges at North Shields and Blyth, which are at distances of 28 km and 16 km, respectively. GPS measurements are being made every 2 weeks at the tide gauges in order to see if similar precision can be achieved to what would be found by having permanent GPS receivers at each tide gauge. Tests show how the precision improves as the data window is increased from 3 hours to 24 hours,

GPS ON BUOYS

Parke et al. reviewed the developments of GPS measurements on buoys and the various future applications in oceanographic and geodetic experiments. Differential GPS measurements with respect to a permanent GPS site on the coast provide absolute sea levels. These can be used for calibrating satellite altimeters, calibrating aircraft altimeter measurements and also in regional oceanographic experiments in order to give absolute sea levels with a finer resolution in space and time than can be obtained with satellite altimetry. They also demonstrated that GPS on buoys can be used for measuring wave heights and directional wave spectra. So far, GPS on buoy measurements have been made over relatively short baselines. The accuracy needs to be demonstrated over longer baselines, where errors due to the troposphere become important, and **a cruise is** planned later in 1997, across the Gulf of Mexico, in order to look at this problem.

The SELF II project

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The SELF II project (Sea Level Fluctuations in the Mediterranean: interactions with climate processes and vertical crustal movements) has been funded by the Commission of the European Union in the framework of the Environment and Climate Programme. It involves six Member States (England, France, Germany, Greece, Italy, Spain) and Switzerland, Bulgaria and Russia, Bulgaria and Russia have been included in the SELF II project within the Cooperation between the European Commission and the Third Countries and international Organizations. The SELF II project started officially on February 1", 1996.

The partners in SELF II are:

1. Italy, University of Bologna, Dept. of Physics, Prof. S. Zerbini,
   coordinator of the project;
2. Fed. Rep. of Germany, lfAG Frankfurt, Dr. Ing. B. Richter;
3. Fed. Rep. of Germany, Univ. of Kiel, Inst. of Geophysics, Dr. H.-P. Plag;
   Associated partners to Kiel are:
   Fed. Rep. of Germany, Univ. of Tübingen, Inst. of Informatic, Prof. A. Zen;
   Fed. Rep. of Germany, Univ. of Hamburg, Inst. für Meereskunde, Prof. J. Sündermann;
4. Greece, NTU Athens, Prof. G. Veis;
5. Switzerland, 1;'1'11 Zürich, inst. of Geodesy and Photogrammetry, Prof. H.-G. Kahle;
6. United Kingdom, Birkenhead, Proudman Ocean. Lab., Prof. T. Baker;
7. France, Toulouse, CNES/CNRS, Dr. A. Cazenave;
8. Spain, Univ. of Cadiz, Dept. of Applied Physics, Prof. L. Tejedor;
9. Russia, Moscow State Univ. of Geodesy and Cartography, Dr. V. Lobasov;
10. Bulgaria, Sofia, Bulgarian Academy of Sciences, Dr. V. Kotzev.

They are working together to achieve the stated objectives of the project which arc the following:

a) to improve the long-term monitoring of sea-level variability by applying the most advanced geodetic techniques, including satellite altimetry and airborne laser;

b) to study past sea-levels in the Mediterranean in order to further our understanding of the current processes;

C) to study the effects of the atmosphere/ocean interaction and crusts] movements on coastal sea levels in order to provide a basis for hazard assessment.

The SELF II network is displayed in Figure

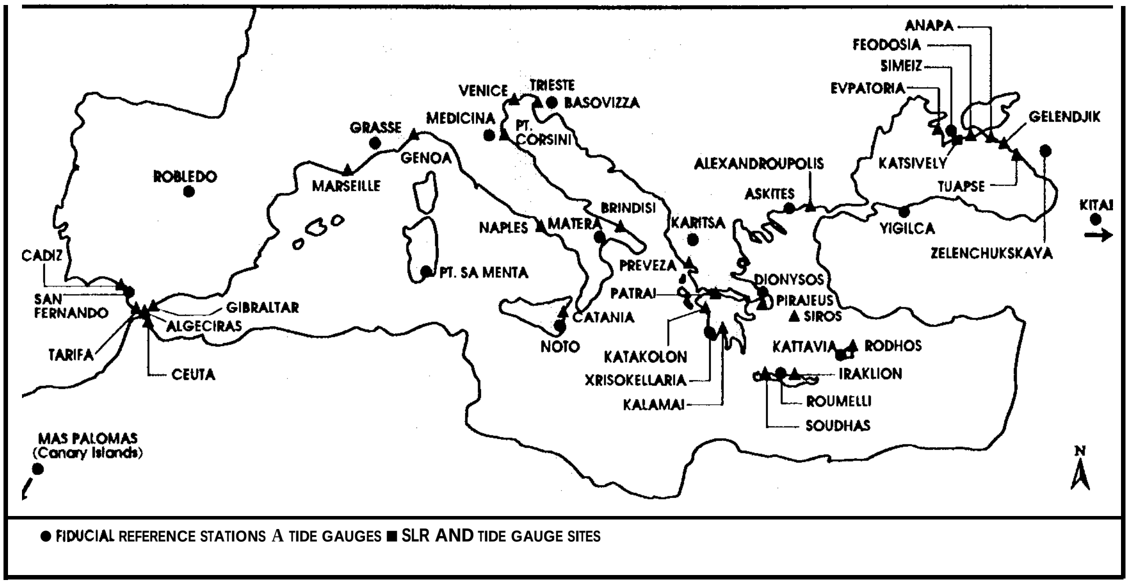

Figure 1. The SELF network.

SELF 11, a continuation of the SELF project (Zerbini et al., 1996), aims at the realization of a broadly based and highly interdisciplinary research work which will use the determination of absolute sea level and of its variations in a comprehensive way for the study of the present interactions, as well as of those of the recent past, among the ocean, the atmosphere and the Earth's crust and to develop appropriate models to assess future aspects.

Measurable objectives of the project are:

a) a first assessment of rates of vertical movements of the tide gauge benchmarks and estimates of their accuracy;
b) optimize the GPS and gravity observation strategies for a cost-effective determination of height changes through two specially designed experiments;
c) to assess the time variability of gravity related to environmental effects;
d) acquire additional tide gauge data from the appropriate National Authorities and quality control the data;
e) a detailed assessment of the quality and usefulness of the available tide gauge and sea level related data;
f) data collection, for selected areas of the Mediterranean coast, of geomorphological and sedimentological indicators of former sea levels and related palaeoenvironmental and palaeoclimatic conditions;
g) compute the temporal (seasonal and interannual) and the spatial variations of the sca-surface topography of the Mediterranean and Black Sea from ERS-1, ERS-2 and TOPEX satellite altimetry;
h) filling the gap between the coastline (tide gauges) and the open sea covered by satellite altimetry in two selected coastal areas through air-borne laser altimetry;
i) merging of satellite altimetry, airborne altimetry and tide gauge data sets;
j) development of hydrodynamical and mathematical models to describe the interaction of atmosphere and ocean.

The tide gauge benchmarks heights of the stations in the network have been measured with GPS and Water Vapor Radiometers in the course of 1996. Absolute gravity measurements have been performed as well. The analysis and interpretation of the data is presently underway. Comparisons with the SELF 1 project results will be performed to provide first estimates of the vertical rates at the stations. An experiment is taking place at the Medicina station, near Bologna in Italy, to assess the accuracy with which vertical crustal movements can be determined both from a new type of superconducting gravimeter for continuous gravity registrations in combination with a new generation of absolute gravimeters for episodic gravity observations and from continuous and episodic GPS measurements. This experiment aims at providing significant improvements to the models, specifically those concerning fluid tides, ocean and atmospheric loading.

The analysis of Topex/Poseidon satellite altimeter data over a period of 3.5 years shows that the Mediterranean sea level has been rising and the study shows that the sea level rise is clearly not uniform with time, in SELF II Airborne Laser Altimetry is being used with the aim to determine sea level in coastal areas to bridge satellite altimetry of the deep sea with coastal tide gauge stations. A first experiment has been performed in the Ionian Sea and it proved to be quite successful.

As regards the geologic work, field and underwater surveys have been carried out in order to observe marine notches and terraces and to study carbonatic concretions typical of the coastal environments, which are related to palaeo-shorelines and are generally well-datable. This work is being performed along the north western coast of Sicily.

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