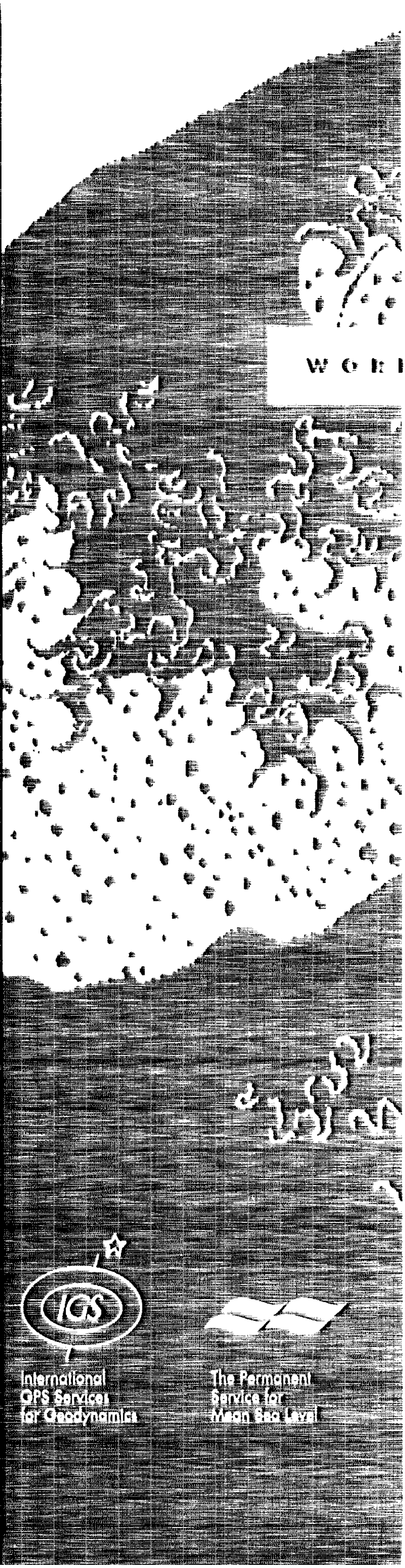


International GPS Service for Geodynamics

The Permanent Service for Mean Sea Level

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 tide 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

This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

IGS data and products are currently available, free of charge, to all users. Although the IGS strives for the highest quality of data and data products, it cannot make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information or product. Use of the IGS data and products is the sole responsibility of the user. The IGS is in the process of revising policy on data use and developing a commercial use policy.

IGS·PSMSL

CONTENTS

Session 1: Workshop Objectives and Science Questions

Session 2: The Measurements -- An Introduction

Session 3: Measuring Long-Term Sea Level Change

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

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

Session 5: Data Handling

Co-chairs: C. Nell (GSFC [IGS Global Data Center]),
M. Merrifield (Univ. Hawaii, Manoa)

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.

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.

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

LIST OF PARTICIPANTS

Name	***Institution***	em ail
Baker, Trevor F.	Proudman Oceanographic laboratory Permanent Service for Mean Sea Level (PSMSL)	tfb@pol.ac.uk
Beutler, Gerhord	Astronomical Institute University of Berne	beutler@aiub.unibe.ch
Bevis, Michael	University of Hawaii	bevis@soest.hawaii.edu
Bingley, Richard	University of Nottingham	richard.bingley@nottingham.ac.uk
Blewitt, Geoffrey	University of Newcastle upan Tyne	Geoffrey.blewitt@ncl.ac.uk
Boucher, Claude	Institute Geographique National ENSG/LAREG	cboucher@ign.fr
Chin, Miranda	Notional Oceanic and Atmospheric Administration (NOAA)	miranda@tango.grdl.noaa.gov
Collier, Wayne	National Oceanic and Atmospheric Administration (NOAA)	wayne.collier@noaa.gov
De Min, Erik	Survey Department, Rijkswaterstaat	e.j.dmin@mdi.rws.minvenw.nl
Denys, Paul	Otago University Dept. of Surveying	p.denys@spheroid.otago.ac.nz
Dickey, Jean	Jet Propulsion laboratory (JPL)	jod@logos.jpl.nasa.gov
Fisher, Steve	Jet Propulsion Laboratory (JPL) University Navstar Consortium (UNAVCO)	sfisher@ncar.ucar.edu
Gornitz, Vivien	Columbia University	ccvmg@nasagiss.giss.nasa.gov
Govind, Ramesh	Australian Surveying and land Information Group	rameshgovind@auslig.gov.au
Gross, Richard	Jet Propulsion laboratory (JPl	rsg@logos.jpl.nasa.gov
Gurtner, Werner	Astronomical Institute University of Berne	gurtner@aiub.unibe.ch
Haines, Bruce	Jet Propulsion laboratory (JPl	bjh@cobra.jpl.nasa.gov
Harrison, Christopher	University of Miami	charrison@rsmas.miami.edu
Johnson, Michael	National Oceanic and Atmospheric Administration (NOAA)/OGP	johnson@ogp.noaa.gov
Kakkuri, Juhani	Finnish Geodetic Institute	juhani.kakkuri@fgi.fi
Kouba, Jan	Geodetic Survey Canada Natural Resources Canada (NRCan)	kouba@geod.emr.ca
La Brecque, John	Jet Propulsion laboratory (JPL)	john.l.labrecque@jpl.nasa.gov
Le Provost, Christian	Centre National de la Recherche Scientifique Laboratoire des Ecoulements Geophysiques et Industrials	clp@img.fr
Moo, Ailin	University of Miami	mao@corsica.smas.miami.edu
Merrifield, Mark	University of Hawaii	markm@soest.hawaii.edu
Miller, Meghan	Department of Geology, Central Washington University	meghan@cwu.edu

LIST OF PARTICIPANTS

Name	*Institution*	*email*
Baker, Trevor F.	Proudman Oceanographic laboratory Permanent Service for Mean Sea Level (PSMSL)	tfb@pol.ac.uk
Beutler, Gerhard	Astronomical Institute University of Berne	beutler@aiub.unibe.ch
Bevis, Michael	University of Hawaii	bevis@soest.hawaii.edu
Bingley, Richard	University of Nottingham	richard.bingley@nottingham.ac.uk
Blewitt, Geoffrey	University of Newcastle upon Tyne	geoffrey.blewitt@ncl.ac.uk
Boucher, Claude	Institute Geographique National ENSG/LAREG	cboucher@ign.fr
Chin, Miranda	National Oceanic and Atmospheric Administration (NOAA)	miranda@tango.grdl.noaa.gov
Collier, Wayne	National Oceanic and Atmospheric Administration (NOAA)	wayne.collier@noaa.gov
De Min, Erik	Survey Department, Rijkswaterstaat	e.j.dmin@mdi.rws.minvenw.nl
Denys, Paul	Otago University Dept. of Surveying	p.denys@spheroid.otago.ac.nz
Dickey, Jean	Jet Propulsion Laboratory (JPL)	jod@logos.jpl.nasa.gov
Fisher, Steve	Jet Propulsion Laboratory (JPL) University Navstar Consortium (UNAVCO)	sfisher@ncar.ucar.edu
Gornitz, Vivien	Columbia University	ccvmg@nasagiss.giss.nasa.gov
Govind, Ramesh	Australian Surveying and Land Information Group	rameshgovind@auslig.gov.au
Gross, Richard	Jet Propulsion Laboratory (JPL)	rsg@logos.jpl.nasa.gov
Gurtner, Werner	Astronomical Institute University of Berne	gurtner@aiub.unibe.ch
Haines, Bruce	Jet Propulsion Laboratory (JPL)	bjh@cobra.jpl.nasa.gov
Harrison, Christopher	University of Miami	charrison@rsmas.miami.edu
Johnson, Michael	National Oceanic and Atmospheric Administration (NOAA)/OGP	johnson@ogp.noaa.gov
Kakkuri, Juhani	Finnish Geodetic Institute	juhani.kakkuri@fgi.fi
Kouba, Jan	Geodetic Survey Canada Natural Resources Canada (NRCan)	kouba@geod.emr.ca
La Brecque, John	Jet Propulsion Laboratory (JPL)	john.l.labrecque@jpl.nasa.gov
Le Provost, Christian	Centre National de la Recherche Scientifique Laboratoire des Ecoulements Geophysiques et Industrials	clp@img.fr
Mao, Ailin	University of Miami	mao@corsica.smas.miami.edu
Merrifield, Mark	University of Hawaii	markm@soest.hawaii.edu
Miller, Meghan	Department of Geology, Central Washington University	meghan@cwu.edu

LIST OF PARTICIPANTS [cont.)

Watkins, Mike	Jet Propulsion laboratory (JPL)	mmw@cobra.jpl.nasa.gov
Wilson, Clark R.	National Aeronautics and Space Administration Headquarters	cwilson@hq.nasa.gov
Woodworth, Philip	Permanent Service for Mean Sea Level (PSMSL) Proudman Oceanographic Laboratory	plw@pol.ac.uk
Wu, Xiaoping	Jet Propulsion Laboratory (JPL)	xpw@cobra.jpl.nasa.gov
Zerbini, Susanna	Department of Physics University of Bologna	zerbini@astbo1.bo.enc.it
Zlotnicki, Victor	Jet Propulsion Laboratory (JPL)	vz@pacific.jpl.nasa.gov
Zumberge, James F.	Jet Propulsion Laboratory (JPL)	jfz@cobra.jpl.nasa.gov

IGS-PSMSL

WORKSHOP OBJECTIVES AND SCIENCE QUESTIONS

Co-choirs:

Philip L. Woodworth
Permanent Service for Mean Sea Level
proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, Merseyside, U.K.

Ruth Neilan
International GPS Service
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, U.S.A.

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

Philip I.. Woolworth
Permanent Service for Mean Sea Level
Proudman Oceanographic Laboratory, Bidston Observatory
Birkenhead, Merseyside 1..43 7RA, U.K.

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) are 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 are 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 be 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 be 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 are known to approximately 0.3 mm/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 are 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 be useful for sea level studies is estimated to be 1 to 2 mm per year over 5 year intervals and 0.3 to 0.5 mm per year over intervals of a few decades.

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

It can be 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 are 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, one 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 GPS 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?

Third, 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 we 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: 'The 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 system.

* 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:

Are 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 be addressed by IOC Member States in respect of GLOSS development.

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

Are 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 included in the Proceedings of the Workshop.

POSTSCRIPT (APRIL 1997)

It is extremely encouraging that so many of the questions I listed 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, I would like to thank the IGS Central Bureau for their hospitality at JPL.

REFERENCES

Carter, W.E., Aubrey, D. G., Baker, T. F., Boucher, C., Le Provost, C., Pugh, D.T., Peltier, W. R., Zumberge, M., Rapp, R.H., Schutz, R. E., Emery, K.O. and Enfield, D.B. 1989. Geodetic fixing of tide gauge bench marks. Woods Hole Oceanographic Institution Technical Report, WI 101-89-31, 44pp.

Carter, W.E. (ed.). 1994. Report of the Surrey Workshop of the IAPSO Tide Gauge Bench Mark Fixing Committee held 13-15 December 1993 at the Institute of Oceanographic Sciences Deacon Laboratory, Wormley, UK. NOAA Technical Report NOSOESOO06. 81 pp.

Carter, W. E., Sasagawa, G, and Richter, B. (eds.) 1997. Proceedings of the Chapman Conference on Microgal Gravimetry: Instruments, Observations and Applications, held at Flagler College, St. Augustine, Florida, USA, 3-6 March 1997.

Douglas, B.C. 1991. Global sea level rise. Journal of Geophysics' Research, 96(C4), 6981-6992.

IERS. 1997. IERS missions, present and future. Report on the 1996 IERS Workshop. International Earth Rotation Service Technical Note 22, 50pp.

IOC. 1995. 10C group of experts on the Global Sea Level Observing System (GLOSS), fourth session, Bordeaux, France, 31 January - 3 February 1995. Intergovernmental Oceanographic Commission, Reports of Meetings of Experts and Equivalent Bodies, IOC/GE-GLOSS-IV/3, 18pp. & annexes.

IPCC.1995. Climate Change 1995. The science of climate change. Contribution of working group I to the second assessment report of the Intergovernmental Panel on Climate Change, eds. J, T.Houghton, L. G. Meira Filho, 13. A. Callander, N. Harris, A. Kattenberg and K. Maskell. Cambridge: Cambridge University Press. 572pp.

Melbourne, W. G., Davis, ES., Yunck, T.P. and Tapley, B.D. 1994. The GPS flight experiment on TOPEX/POSEIDON. Geophysical Research Letters, 21 (1 9), 2171-2174.

Mitchum, G.T. 1996. Monitoring the stability of satellite altimeters with tide gauges. Submitted to the Journal of Atmospheric and Oceanic Technology.

IGS-PSMSL

THE MEASUREMENTS —
AN INTRODUCTION

Co-chairs:

Gary Mitchum
University of South Florida
St. Petersburg, Florida, U.S.A.

Mike Watkins
Jet Propulsion Laboratory
California Institute of Technology
pasadena, California, U.S.A.

Summary of Session 2
The Measurements - An Introduction

Gary Mitchum
University of South Florida

Mike Watkins
Jet Propulsion Laboratory

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 little information at all about the types 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 Nerem. 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, he 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 sea 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 regularly 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 ultimately 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 due to true ocean signals. In assessing the errors due to the tide gauges, a set of calculations involving "replicate" measurements from independent tide gauges separated by less than a few meters was presented. The result was that daily sea 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 consistent with intercomparisons between tide-gauge sea levels and altimetric sea-surface heights. It was also argued that errors due to small-scale distortions of the sea surface height field near the land, which is often argued as being responsible for tide gauge/altimeter differences, are 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. Nerem emphasized the precision of the data returned from modern altimeters, such as T/P. Specifically, through improvements to the instrument and orbit determination, T/P has demonstrated a sea-level measurement accuracy of 3-4 cm, which in turn produces a global mean sea level measurement repeatability 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 sea 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 sea level rise estimates from tide gauges are truly aimed at inferring. Nerem emphasized that assessing long-term trends in sea 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. He pointed out that Mitchum [see 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 significantly 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

Gary T. Mitchum
Department of Marine Science
University of South Florida
140 Seventh Ave. South
St. Petersburg, FL 33701 USA

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

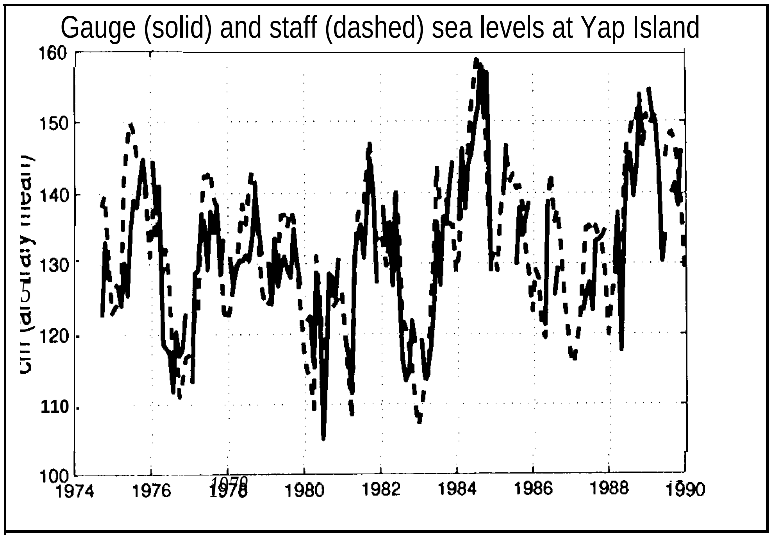


Fig. 1. Comparison of sea level from a tide gauge vs. that from a tide staff.

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.

REFERENCES

Cheney, R., L. Miller, R. Agreen, N. Doyle, and J. Lillibridge, 1994, TOPEX/POSEIDON: The 2-cm solution. *J. Geophys. Res.*, 99, 24,555-24,563.

IOC, 1985, *Manual on sea-level measurement and interpretation. Volume 1 - Basic procedures.* Intergovernmental Oceanographic Commission Manuals and Guides No. 14, IOC, Paris, 83 pp.

IOC, 1993, Joint IAPSO-IOC workshop on sea level measurements and quality control, Paris, 12-13 October 1992 (cd, N.E. Spencer). Intergovernmental Oceanographic Commission, Workshop Report No. 81, 167 pp.

IOC, 1994, *Manual on sea-level measurement and interpretation. Volume 2- Emerging Technologies.* Intergovernmental Oceanographic Commission Manuals and Guides No. 14, 10C, Paris, 72 pp.

Mitchum, G., 1994, Comparison of TOPEX sea surface heights and tide gauge sea levels. *J. Geophys. Res.,* 99, 24,541-24,553.

Mitchum, G., 1997, Monitoring the stability of satellite altimeters with tide gauges. *J. Tech.,* in press.

Mitchum, G., B. Kilonsky, and B. Miyamoto, 1994, Methods for maintaining a stable datum in a sea level monitoring system. *ZEEE* ***Oceans Proceedings,*** 25-30.

Pugh, D., 1987, *Tides, surges and mean sea-level: A handbook for engineers and scientists.* Wiley, 472 pp.

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

R. S. Nerem
Center for Space Research, The University of Texas at Austin

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

'I'he Contribution of Satellite Altimetry to Measuring Long-Term Sea Level Change

R. S. Nerem
Center for Space Research, The University of Texas at Austin

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 [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

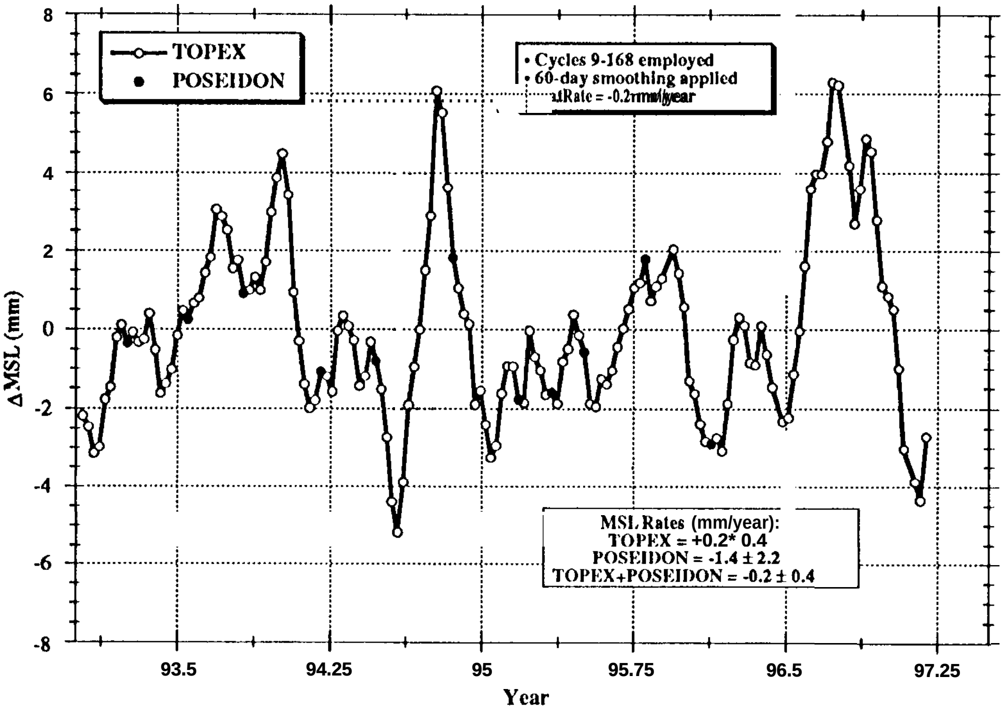
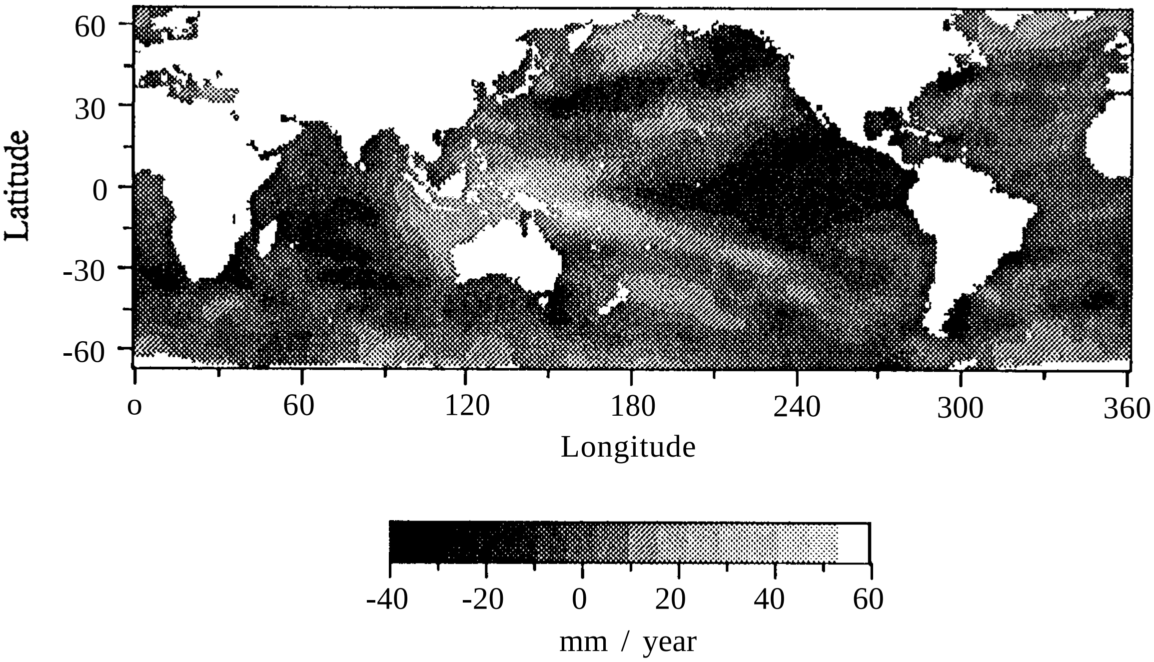


Figure 2. TOPEX/POSEIDON Sea Level Trends



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.

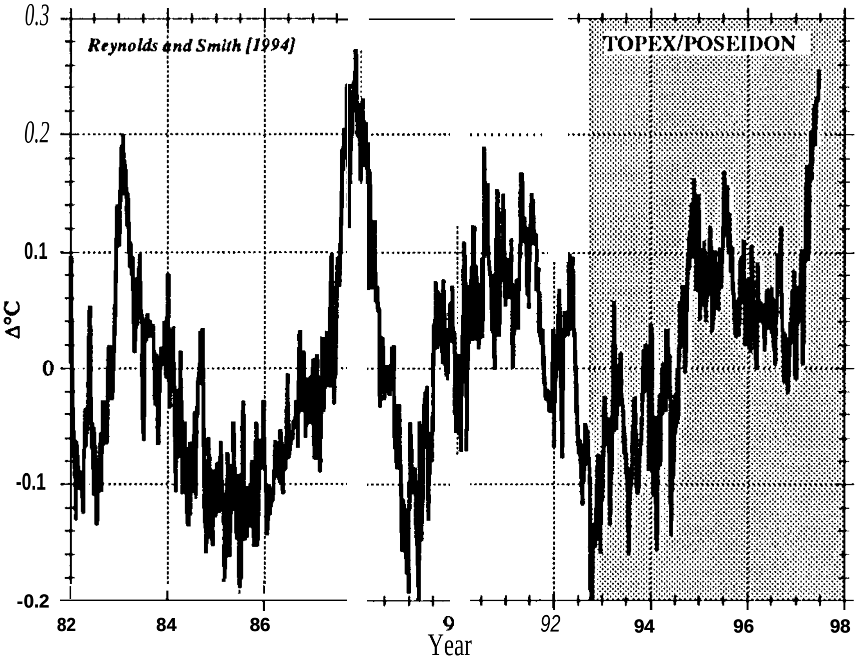
Table 1. Calibrated Estimate of Mean Sea Level Rise from T/P

	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**



Acknowledgments: Thanks to Gary Mitchum for providing summaries of his TOPEX altimeter calibration results and Bruce Haines for providing the results from Platform Harvest. This work was supported by a NASA TOPEX Project Science Investigation.

References

Barnett, T. P., The estimation of "global" sea level change: a problem of uniqueness, *J. Geophys. Res.*, 89(C5), pp. 7980-7988, 1984.

Born, G. H., B. D. Tapley, J. C. Ries, and R. H. Stewart, Accurate Measurement of Mean Sea Level Changes by Altimetric Satellites, *J. Geophys. Res.*, 91 (C1O), 11775-11782, 1986.

Carter, W. E., and 11 others, Geodetic fixing of tide gauge bench marks, *Woods Hole Oceanographic Institution Technical Report* WHOI-89-31, August, 1989.

Chambers, D. P., G. L. H. Kruizinga, J. C. Ries, C. K. Shum, and B. D. Tapley, Assessment of Systematic Errors in Satellite Altimetry Using Tide Gauge Measurements, *Eos Trans. AGU, 77(46),* Suppl., F17, 1996.

Chart, D. A., J. R. Hendricks, R. R. Leben, Using Upper Ocean Heat Storage Estimates from TOPEX Altimetry and Coincident XBTS to Estimate Altimeter Drift, *Eos Trans. AGU, 77(46),* Suppl., F17, 1996,

Christensen, E. J., B. J. Haines, S. J. Keihm, C. S. Morris, R. S. Norman, G. H. Purcell, B. G. Williams, B. C. Wilson, G. H. Born, M. E. Parke, S. K. Gill, C. K. Shum, B. D. Tapley, R. Kolenkiewicz, R. S. Nerem, Calibration of TOPEX/Poseidon at Platform Harvest, *J. Geophys. Res.*, 99(C12), 24465-24486, 1994.

Church, J. A., J. S. Godfrey, D. R. Jacket, and T. J. MacDougal, A model of sea level rise caused by ocean thermal expansion, *J. Climate,* 4(4), pp. 438-456, 1991.

Douglas, B. C., Global Sea Level Rise, *J. Geophys.Res.,96(C4),6981* -6992, 1991.

Douglas, B. C., Global Sea Level Acceleration, *J. Geophys. Res.,* 97(C8), 12699-12706, 1992.

Douglas, B. C., Global Sea Level Change: Determination and Interpretation, *Rev. Geophys.*, Suppl., 1425-1432, 1995.

Emery, K. O., and D. G. Aubrey, *Sea Levels, Land Levels, and Tide Gauges,* Springer-Verlag, 1991.

Fu, L.-L., E. J. Christensen, C. A. Yamarone, M. Lefebvre, Y. Menard, M. Dorrer, and P. Escudier, TOPEX/POSEIDON mission overview, *J. Geophys. Res.,* 99(C12), 24369-24382, 1994,

Gornitz, V. and A. Solow, Observations of long-term tide-gauge records for indicators of accelerated sea level rise, in *Greenhouse Gas-Induced Climate Change: A Critical Appraisal of Simulations and Observations,* M. E. Schlesinger, cd., Elsevier, Amsterdam, pp. 347-367, 1991.

Groger, M., and H.-P. Plag, Estimations of a global sea level trend: Limitations from the structure of the PSMSL global sea level data set, *Global and Planetary Change, 8,* pp. *161-179, 1993.*

Guman, M. D., B, D. Tapley, C. K. Shum, and J, C. Ries, Global Mean Sea Level Change from Satellite Altimetry, *Eos Trans. AGU, 77(46),* Suppl., F9, 1996.

Haines, B., E, Christensen, R. Norman, M. Parke, G. Born, and S. Gill, *Eos Trans. Suppl., 77, W16, 1996.*

Hayne, G. S., D, W. Hancock, and C. L. Purdy, TOPEX altimeter range stability estimates from calibration mode data, *TOPEX/POSEIDON Research News, 3,* pp. 18-22, 1994.

Hendricks, J. R., R. R. Leben, G. H, Born, and C. J. Koblinsky, EOF Analysis of Global TOPEX/POSEIDON Data and Implications for Detection of Global Sea Level Rise, *J. Geophys. Res.*, 101(C6), 14131-14145, 1996.

Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Eds., *Climate Change 1995*, Cambridge Univ. Press, Cambridge, England, 572 pp, 1996.

Lambeck, K., Glacial rebound, sea level change, and mantle viscosity, *Q. J. Royal Astron. Sot., 31,* pp. 1-30, 1990.

Marshall, J.A., N. P. Zelensky, S.M. Klosko, D.S. Chinn, S.B. Luthcke, K.E. Rachlin, R.G. Williamson, The temporal and spatial characteristics of TOPEX/POSEIDON radial orbit error, *J. Geophys. Res., 1OO(C1* 2), 25331-25352, 1995.

Maul, G. A., and D. M. Martin, Sea level rise at Key West, Florida, 1846-1992: America's longest instrument record?, *Geophys. Res. Lett.*, 20(18), 1955-1958, 1993,

Minster, J.-F., C. Brossier, P, Rogel, Variations of the mean sea level from TOPEX/POSEIDON data, *J. Geophys. Res.*, 1OO(C12), 25153-25162, 1995,

Mitchum, G. T., Comparison of TOPEX Sea Surface Heights and Tide Gauge Sea Levels, *J. Geophys. Res.,* 99(C12), 24541-24554, 1994.

Mitchum, Gary T., Monitoring the stability of satellite altimeters with tide gauges, *J. Atmos. and Oceanic Tech.,* in review, 1996.

Morris, C. S., and S. Gill, Evaluation of the TOPEX/POSEIDON Altimeter System over the Great Lakes, *J. Geophys.Res.,99(C12),* 24527-24540, 1994.

Murphy, C. M, and P. Moore, Calculation of TOPEX altimeter range bias drift using tide gauge augmented single satellite crossovers, *Adv. Space Res.*, in review, 1996.

Nerem, R. S., E. J. Schrama, C. J. Koblinsky, and B. D. Beckley, A Preliminary Evaluation of Ocean Topography from the TOPEX/POSEIDON Mission, *J. Geophys. Res.*, 99(C12), 24565-24583, 1994.

Nerem, R. S., Global mean sea level variations from TOPEX/POSEIDON altimeter data, *Science*, 268,708-710, 1995a.

Nerem, R, S., Measuring global mean sea level variations using TOPEX/POSEIDON altimeter data, *J. Geophys. Res.*, 1OO(C12), 25135-25152, 1995b.

Nerem, R. S., B. J. Haines, J. Hendricks, J. F. Minster, G. T. Mitchum, and W. B. White, Improved determination of global mean sea level variations using TOPEX/POSEIDON altimeter data, *Geophys. Res. Lett.*, 24(1 1), 1331-1334, 1997.

Nouel, F., J. P. Berthias, M. Deleuze, A. Guitart, P. Laudet, A. Piuzzi, D. Pradines, C. Valorge, C. Dejoie, M. F. Susini, and D. Taburiau, Precise CNES orbits for TOPEX/POSEIDON: Is reaching 2 cm still a challenge, *J. Geophys. Res.,* 99(C12), 24405-24420, 1994.

Peltier, W. R., and A, M, Tushingham, Global sea level rise and the Greenhouse Effect: might they be connected?, *Science, 244(4906),* pp. 806-810, 1989.

Reynolds, R. W., and T. S, Smith, Improved global sea surface temperature analysis, *J, Climate, 7,* pp. 929-948, 1994.

Ruf, C. S., S. J. Keihm, B. Subramanya, M. A. Janssen, TOPEX/POSEIDON microwave radiometer performance and in flight calibration, *J. Geophys. Res.*, 99(C1 2), 24915-24926, 1994.

Stammer, D., R. Tokmakian, A. Semtner, and C, Wunsch: 1995, How closely does a 1/4 degree global ocean circulation model simulate large-scale observations?, *J. Geophys. Res.*, 101(C1O), 25779-25811, 1996.

Tapley, B. D., C. K, Shum, J. C. Ries, R. Suter, and B. E. Schutz, Monitoring Changes in Global Mean Sea Level Using Geosat Altimeter, in Sea Level Changes: Determination and Effects, Geophysical Monograph 69, IUGG Volume 11, AGU, 1992.

Tapley, B. D., J, C. Ries, G. W. Davis, R. J. Eanes, B. E. Schutz, C. K. Shum, M. M. Watkins, J. A. Marshall, R. S. Nerem, B. H. Putney, S. M. Klosko, S. B. Luthcke, D. E. Pavlis, R. G. Williamson, and N. P. Zelensky, Precision Orbit Determination for TOPEX/POSEIDON, *J. Geophys. Res.,* 99(C12), 24383-24404, 1994.

Tapley, B. D., M, M. Watkins, J. C. Ries, G. W. Davis, R. J. Eanes, S. R. Poole, H. J. Rim, B.E. Schutz, C. K, Shum, R. S. Nerem, F. J. Lerch, J. A. Marshall, S. M, Klosko, N. K. Pavlis, and R. G. Williamson, The JGM- 3 Gravity Model, *J. Geophys. Res.*, Vol. 101, No. B12, pp. 28029-28049, 1996.

Trenberth, K. E., and T. J. Hoar, The 1990-1995 El Nine-Southern Oscillation Event: Longest On Record, *Geophys. Res. Lett.*, 23(l), 57-60, 1996.

Trupin, A. and J. Wahr, Spectroscopic Analysis of Global Tide Gauge Sea Level Data, *Geophys. J. Int.*, Vol. 100,441-453, 1990.

Tushingham, A. M., and W. R. Peltier, ICE-3G: A new global model of late Pleistocene deglaciation based upon geophysical predictions of post glacial relative sea level change, *J. Geophys. Res.*, 96,4497-4523, 1991.

Unal, Y. S., and M. Ghil, Interannual and interdecadal oscillation patterns in sea level, *Climate Dynamics*, 11(5), 255-278, 1995.

Wagner, C. A., and R. E. Cheney, Global Sea Level Change From Satellite Altimetry, *J. Geophys. Res.*, 97(C1O), 15607-15615, 1992.

Warrick, R. A., E. M. Barrow, and T. M. L. Wigley (eds.), *Climate and sea level change: observations projections, and implications,* Cambridge Univ. Press, Cambridge, England, 1993.

White, N. J., R. Coleman, J. A. Church, P. J. Morgan, and S. J. Walker, A southern hemisphere verification for the TOPEX/POSEIDON satellite altimeter mission, *J. Geophys. Res.*, 99(C12), 24505-24516, 1996.

Woodworth, P. L., A Search for Acceleration in Records of European Mean Sea Level, *Int. J. Climatol.*, 10, 129-143, 1990.

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]*

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]*

IGS-PSMSL

MEASURING LONG-TERM SEA-LEVEL CHANGE

Co-chairs:

Geoff Blewitt
University of Newcastle
Newcastle upon Tyne, U.K.

Steve Nerem
University of Texas at Austin
Center for Space Research
Austin, Texas, U.S.A.

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

Geoffrey Blewitt (Geoffrey.Blewitt@newcastle.ac.uk)

Department of Geomatics, University of Newcastle,
Newcastle upon Tyne, NE1 7RU, United Kingdom

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.

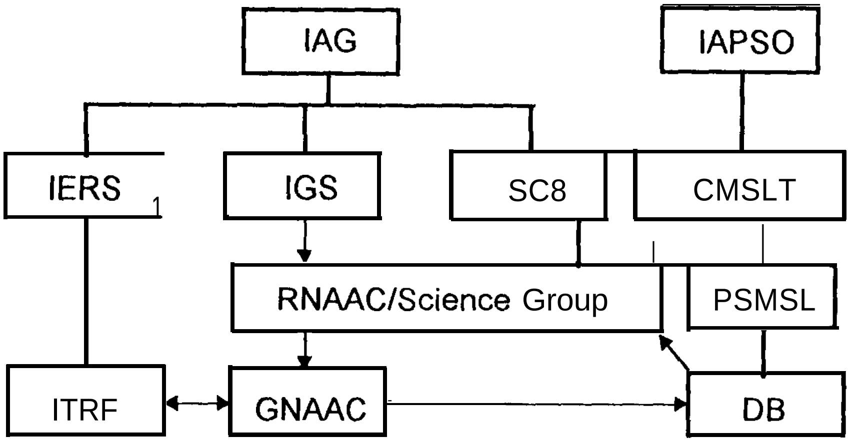


Figure 1: Chart illustrating organizational links and data flow to facilitate the activity of tide-gauge benchmark monitoring (explained in text).

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

Gary T. Mitchum
Department of Marine Science
University of South Florida
140 Seventh Ave. South
St. Petersburg, FL 33701 USA

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 $5/(50)^{½} = 0.7$ 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) (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 (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

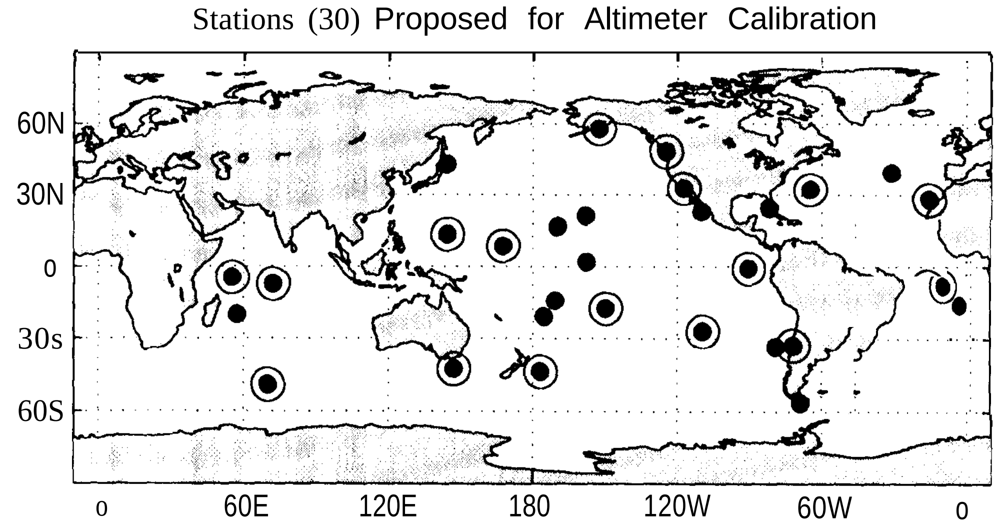


Fig. 1 Stations in the strawman list. Stations with circles have existing GPS receivers. Note that the distribution is equal area, but the plot is not.

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.

REFERENCES

Cheney, R., L, Miller, R. Agreen, N. Doyle, and J. Lillibridge, 1994, TOPEX/POSEIDON: The 2-cm solution. *J. Geophys. Res., 99,* ***24,555-24,563.***

Mitchum, G., 1994, Comparison of TOPEX sea surface heights and tide gauge sea levels. *J. Geophys. Res.,* 99, 24,541-24,553.

Mitchum, G., 1997, Monitoring the stability of satellite altimeters with tide gauges. *J. Tech.,* in press.

Nerem, R. S., 1995, Global mean sea level variations from TOPEX/POSEIDON altimeter data. *Science, 268, 708-710.*

Nerem, R. S., B.J. Haines, J. Hendricks, J.F. Minster, G.T. Mitchum, and W.B. White, 1997, Improved determination of global mean sea level variations using TOPEX/ POSEIDON altimeter data, *Geophys. Res. Lett.*, in press.

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

P.L. Woodworth
Permanent Service for Mean Sea Level
Proudman Oceanographic Laboratory, Bidston Observatory
Birkenhead, Merseyside L43 7RA, U.K.

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 approximately 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 we 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 itself. If one cannot model PGR there adequately, 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(12). (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 1/10'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 sea 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.

The 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.

CONCLUSIONS

- 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.

- The '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-rom. For information, consult:

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

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

REFERENCES

Baker, T.F., Woodworth, P.L., Blewitt, G. Boucher, C. and Woppelmann, G. 1997. A European network for sea level and coastal land level monitoring. Journal of Marine Systems (in press).

Carter, W.E., Aubrey, D. G., Baker, T. F., Boucher, C., Le Provost, C., Pugh, D.T., Peltier, W. R., Zumberge, M., Rapp, R.H., Schutz, R. E., Emery, K.O. and Enfield, D.B. 1989. Geodetic fixing of tide gauge bench marks. Woods Hole Oceanographic institution Technical Report, WHOI-89-31, 44pp.

Carter, W.E. (ed.). 1994. Report of the Surrey Workshop of the IAPSO Tide Gauge Bench Mark Fixing Committee held 13-15 December 1993 at the Institute of Oceanographic Sciences Deacon laboratory, Wormley, UK. NOAA Technical Report NOSOES0006. 81pp.

Douglas, B.C. 1991. Global sea level rise. Journal of Geophysical Research, 96,6981-6992.

Douglas, B.C. 1992. Global sea level acceleration. Journal of Geophysical Research, 97, 12699-12706.

Douglas, B.C. 1995. Global sea level change: determination and interpretation. Reviews of Geophysics, Supplement, 1425-1432. (U.S. national report to the International Union of Geodesy and Geophysics 1991-1994).

Ekman, M., 1988. The world's longest continued series of sea level observations. Pure and Applied Geophysics, 127, 73-77.

Emery, K.O. and Aubrey, D.G. 1991. Sea levels, land levels, and tide gauges. Springer-Verlag, New York, 237pp.

Gornitz, V. and Lebedeff, S. 1987. Global sea-level changes during the past century. In, Sea-level change and coastal evolution, edited by D.Nummedal, O. H. Pilkey & J. D. Howard, Society for Economic Paleontologists and Mineralogists, pp.3-16. (SEPM Special Publication No.41).

IOC. ***1985.*** Manual on sea-level measurement and interpretation. Volume 1 - Basic procedures. Intergovernmental Oceanographic Commission Manuals and Guides No. 14. IOC, Paris, 83pp.

IOC. 1993. Joint IAPSO-IOC Workshop on Sea level measurements and quality control, Paris, 12-13 October 1992. (ed. N, E, Spencer). Intergovernmental Oceanographic Commission, Workshop Report No. 81, 167pp.

10C. 1994. Manual on sea-level measurement and interpretation. Volume 2- Emerging Technologies. Intergovernmental Oceanographic Commission Manuals and Guides No. 14. IOC, Paris, 72pp.

10C. 1997. GLOSS Implementation Plan 1997. Report to be presented to the XIX'th Session of the Assembly of the Intergovernmental Oceanographic Commission in July 1997.

Lambeck, K. 1990. Glacial rebound, sea level change and mantle viscosity. Quarterly Journal of the Royal Astronomical Society,31, 1-30.

Mikolajewicz, U., Santer, B.D. and Maier-Reimer, E. 1990. Ocean response to greenhouse warming. Nature, 345, 589-593.

Mitrovica, J.X. and Davis, J.].. 1995. Present-day post-glacial sea level change far from the Late Pleistocene ice sheets: Implications for recent analyses of tide gauge records. Geophysical Research Letters, 22,2529-2532.

Peltier, W.R. and Tushingham, A.M. 1989. Global sea level rise and the greenhouse effect: might they be related? Science, 244, 806-810.

Peltier, W. R. and Tushingham, A.M. 1991, Influence of glacial isostatic adjustment on tide gauge measurements of secular sea level change. Journal of Geophysical Research, 96, 6779-6796.

Peltier, W .R. 1996. Global sea level rise and glacial isostatic adjustment: an analysis of data from the east coast of North America. Geophysical Research Letters, 23,717-720.

Pugh, D.T. and Maul, G.A. 1997. Coastal sea level prediction for climate change. To be published in a volume on Coastal Ocean Prediction by the American Geophysical Union (cd. C. Mooers).

Sherman, 1. and Woodworth, P.L. 1992. A comparison of late Holocene and twentieth-century sea-level trends from the UK and North Sea region. Geophysical Journal international, 109,96-105.

Trupin, A, and Wahr, J. 1990. Spectroscopic analysis of global tide gauge sea level data. Geophysical Journal international, 100,441-453.

Warrick, R. A., Le Provost, C., Meier, M. F., Oerlemans, J. and Woodworth, P. L. 1995. Lead authors of Chapter 7 (Changes in sea level) of Climate Change 1995. The science of climate change, Contribution of working group I to the second assessment report of the intergovernmental Panel on Climate Change, eds. J. T. Houghton, L. G. Meira Filho, B. A. Callander, N .Harris, A. Kattenberg and K. Maskell. Cambridge: Cambridge University Press. 572pp.

Woodworth, P.L., 1991. The Permanent Service for Mean Sea Level and the Global Sea Level Observing System Journal of Coastal Research, 7(3), 699-710.

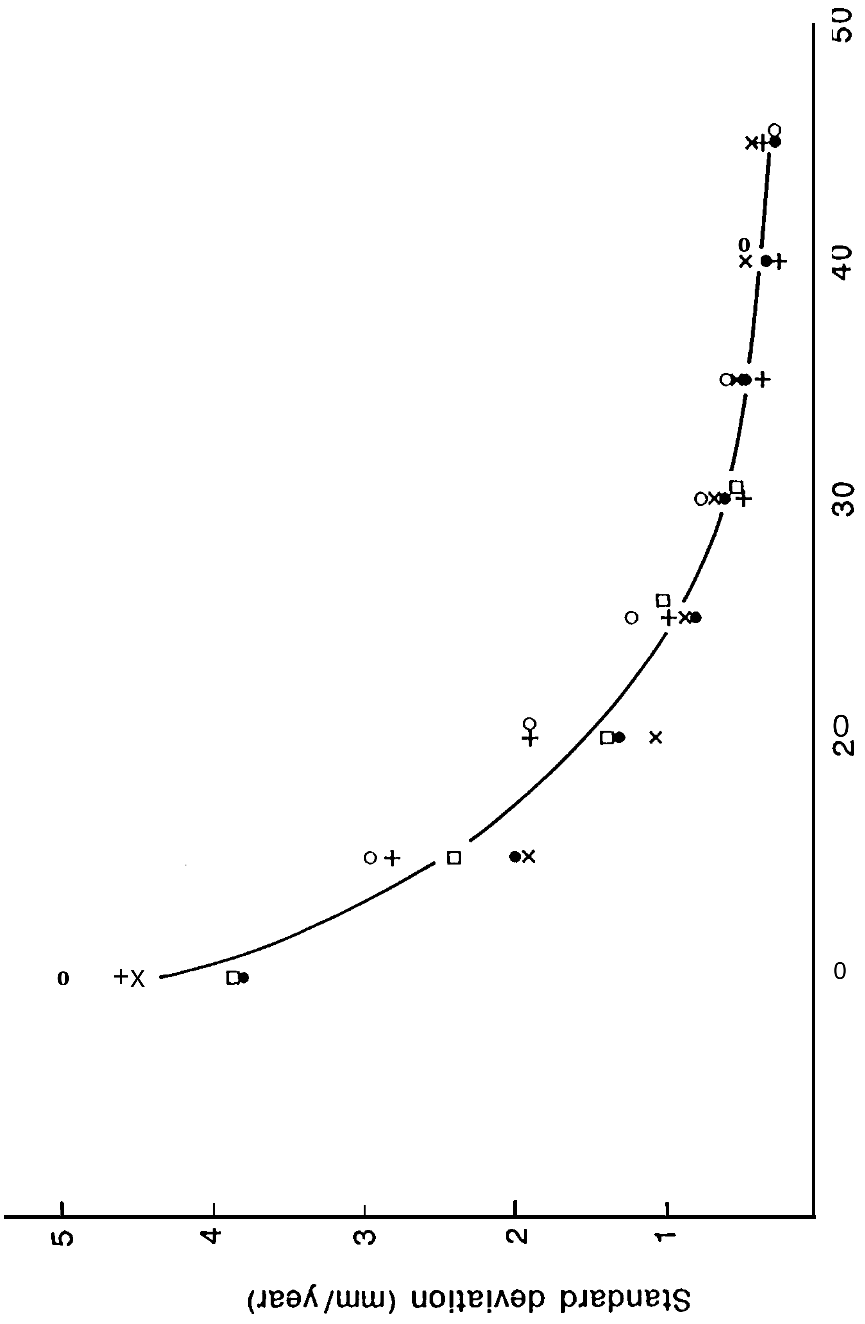


Fig.1. Standard deviations of trends computed over a given data time span, but with arbitrary start date, compared to the trend obtained from the entire twentieth-century using the PSMSL records for Newlyn (dots), Aberdeen II (vertical/horizontal crosses), Hoek van Holland (diagonal crosses), Esjberg (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).

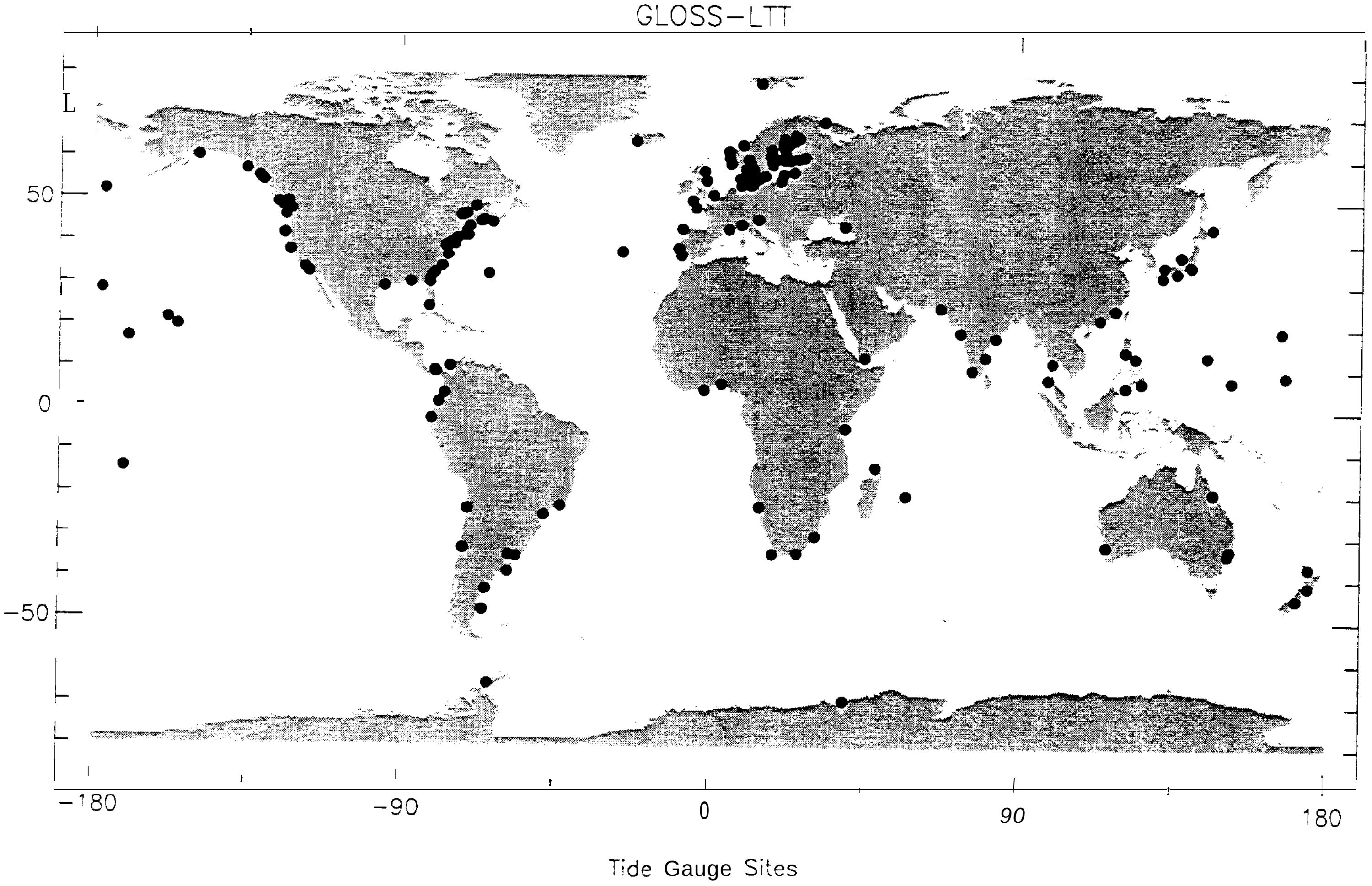


Fig.2. Distribution of tide gauge stations within the GLOSS-LTT set (IOC 1997).

SUSTAINABLE GEODETIC MONITORING OF THE NATURAL ENVIRONMENT USING THE IGS

Geoffrey Blewitt (Geoffrey .Blewitt@newcastle .ac.uk)
Philip Davies (P. B. H. Davies@newcastle. ac.uk)
Thierry Gregorius (T. L. H. Gregorius@newcastle .ac.uk)
Ra'ed Kawar (R. S. Kawar@newcastle. ac.uk)
Ugur Sanli (U. D. Sanli@newcastle.ac .uk)

Department of Geomatics, University of Newcastle,
Newcastle upon Tyne, NE1 7RU, United Kingdom

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 meticulous 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 cohesively 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.

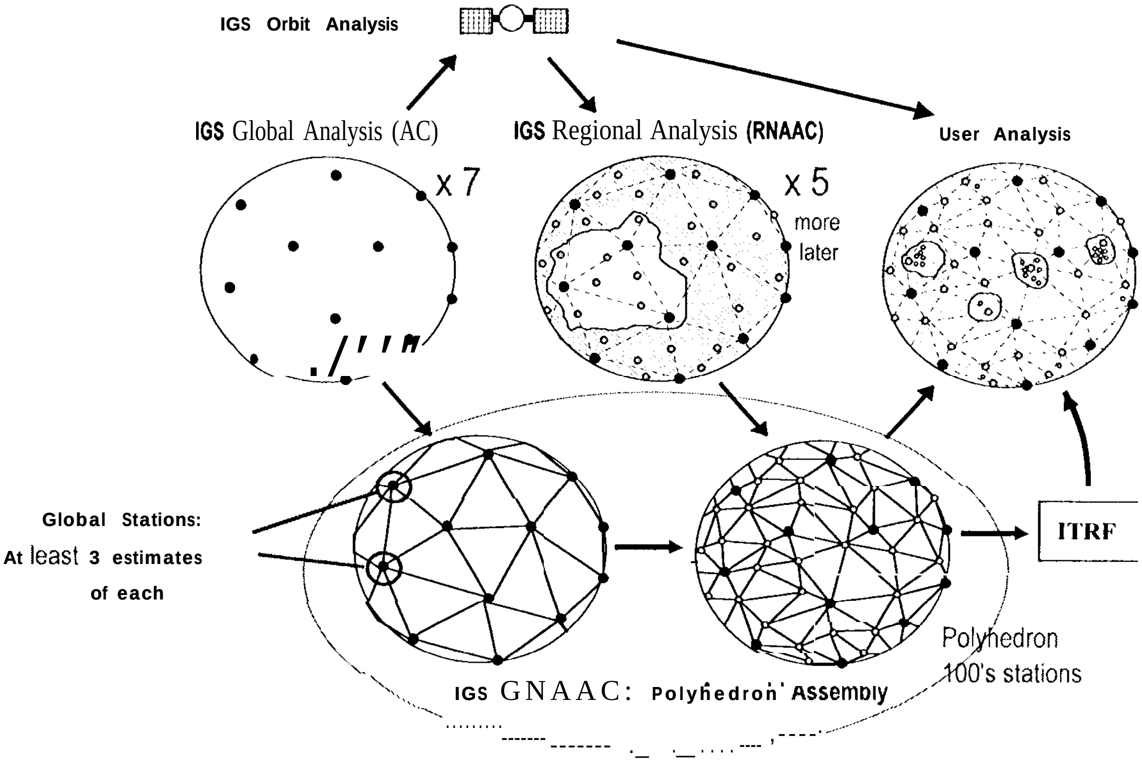


Figure 1: Schematic explanation of the distributed processing approach. Our proposal is for science groups to operate as RNAACS. The GNAACS would then take care of reference frame consistency, and input into ITRF.

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., station 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.

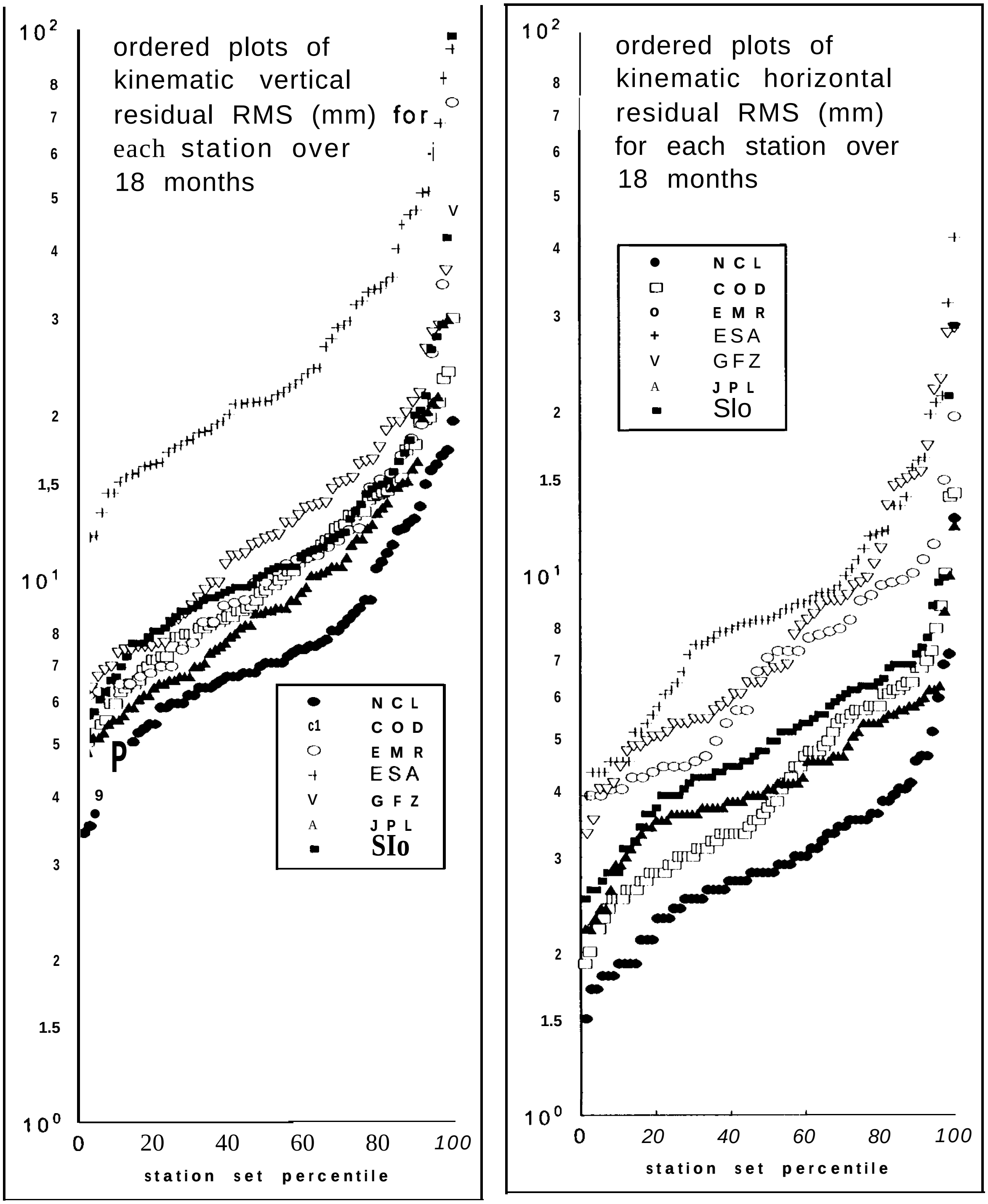


Figure 2: Ordered plots of station coordinate repeatability over 18 months for IGS Analysis Center solutions, and GNAAC solution (labelled NCL)

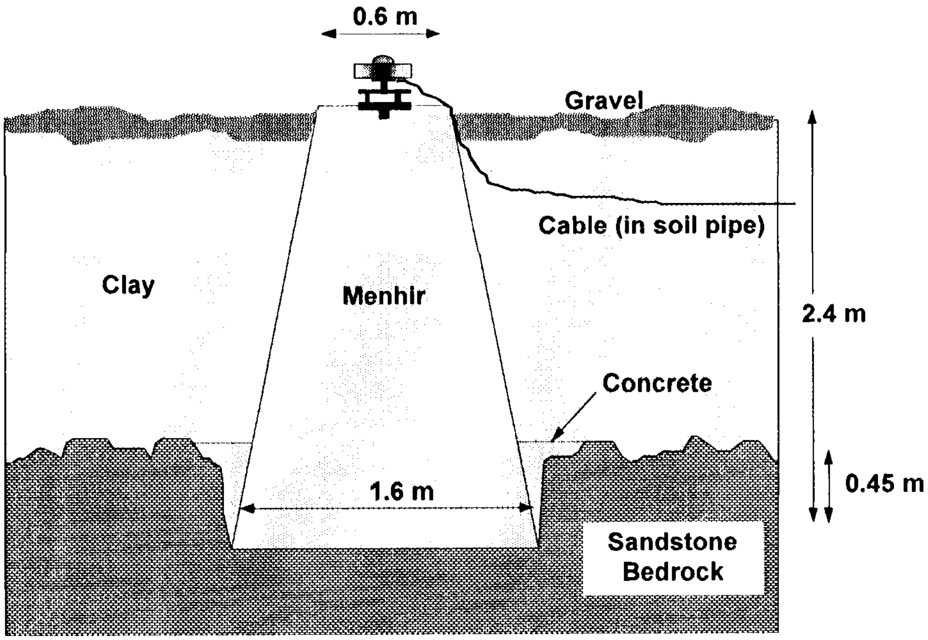


Figure 3: Neolithic menhirs (Late Stone Age standing stones) inspired our design of this geodetic monument, installed at station MORP near Newcastle

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 masoned 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.

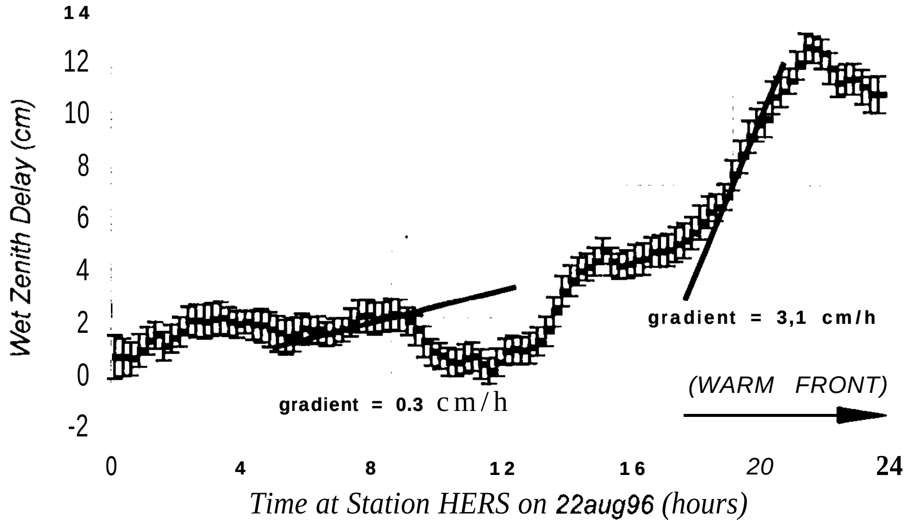


Figure 4: Onset of a warm front at station HERS can be detected by the steep gradient in stochastically estimated tropospheric delay

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.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Natural Environment Research Council, grant GR3/ 10041 and studentship GT4/94/386/G, from Shell UK Exploration and Production, contract C 10517, from the Grand Duchy of Luxembourg, grant BFR96/006, and from the Government of Turkey. We would like to thank people from all components of the IGS for the effort that goes into superb products. We are indebted to the Jet Propulsion Laboratory of the California Institute of Technology for the GIPSY OASIS II software, and for precise orbit and clock products required for precise point positioning. The SINEX format was originally developed by the SINEX Working Group, an IGS ad hoc committee (G. Blewitt, Y. Bock, C. Boucher, G. Gendt, W. Gurtner, and J. Kouba). We would also like to thank Z. Altamimi, J. Freymueller, M. Heflin, and T. Herring, for their valuable suggestions which were incorporated into SINEX.

REFERENCES

Baarda, W. 1967. Statistical concepts in geodesy, *NGS-publications on geodesy, New series, Vol. 2, No. 4,* Delft, The Netherlands.

Baarda, W. 1968. A testing procedure for use in geodetic networks, *NGC-publications on geodesy, Vol. 2, No. 5,* Delft, The Netherlands.

Bilham, R. 1991. Earthquakes and Sea-Level: space and terrestrial metrology on a changing planet, *Rev. Geophys., Vol. 29, No.* 1., p 1-29.

Blewitt, G. 1997. "GPS data processing methodology: From theory to applications, " in GPS for Geodesy, Eds. A. Kleusberg and P.J.G. Teunissen, P. J. G., Chapter 6, Springer (in press).

Blewitt G., ‘I’. Van Dam, and M.B. Heflin. 1995. Atmospheric loading effects and GPS time averaged positions, in *Proceedings of the 1st Turkish International Symposium on Deformations,* Istanbul, Turkey, p. 408-415.

Blewitt, G., 1993. Advances in Global Positioning System technology for geodynamics investigations, in *Contributions of Space Geodesy to Geodynamics: Technology,* Ed. by D. Il. Smith and D.L. Turcotte, p. 195-213, Pub. by American Geophysical Union (Geodynamics Series Vol. 25), Washington DC.

Blewitt G., Y. Bock, G. Gendt. 1993. Regional clusters and distributed processing, Position paper in *Proceedings of the IGS Workshop,* Ottawa, Canada, October 1993.

Blewitt G., Y. Bock, J. Kouba. 1995. Constructing the IGS polyhedron by distributed processing, appearing in *Zumberge and Liu [1995]* referenced below.

Blewitt, G., M.B. Heflin, F.H. Webb, U.J. Lindqwister, and R. P. Malla. 1992. Global coordinates with centimeter accuracy in the International Terrestrial Reference Frame using the Global Positioning System, *Geophys. Res. Let, Vol.* 19, p. 853-856.

Carter, W.E. (cd.). 1994. “Report of the Surrey Workshop of the IAPSO Tide Gauge Benchmark Fixing Committee, ” held 12-15 December at the Institute of Oceanographic Sciences Deacon Laboratory, Wormley, UK. NOAA Technical Report NOSOESOO06, 81pp.

Davies, P.B.H., and G. Blewitt. 1996. Newcastle upon Tyne IGS Global Network Associate Analysis Centre Annual Report 1995, appearing in “IGS 1995 Annual Report, ” p. 189-200, Eds. J.F. Zumberge, M.P. Urban, R. Liu, and R.E. Neilan, IGS Central Bureau, Pasadena, Calif. USA.

Davies, P. B.II., and G. Blewitt. 1997. Newcastle upon Tyne IGS Global Network Associate Analysis Centre Annual Report 1996, appearing in “IGS 1996 Annual Report, ” IGS Central Bureau, Pasadena, Calif. USA (in press).

Elgered, G., Jan M. Johansson, and B.O. Ronnang. 1990. Characterizing atmospheric water vapour fluctuations using microwave radiometry, in “Executive Summary, European Space Agency ESTEC/Contract No 8128/88 /NL/BI(SC), ” Chalmers Univ. of Technology, Sweden.

Grafarend E. and B. Schaffrin. 1979. Variance-covariance-component estimation of Helmert type, *Surveying and Mapping,* Vol. XXXIX No. 3, p. 225-234.

IGS. 1997. *International GPS Service For Geodynamics: Resource information, January 1997,* published by the IGS Central Bureau, Jet Propulsion Lab., Pasadena, Calif, USA.

Kosters A. and J. Kok. 1989. Statistical testing and quality analysis of observations and transformation parameters in combining 3-dimensional networks, Paper presented at the IAG Congress, Edinburgh, August 1989

McCarthy, D. (cd.), IERS Conventions (1996), *IERS Technical Note 21,* Observatoire de Paris, Paris, France, July 1996.

Mueller, 1.1. and G. Beutler. 1992. The International GPS Service for Geodynamics - Development and current structure, in *Proc. of the 6th Int. Geodetic Symp. on Satellite Positioning,* Columbus, Ohio, pp. 823-835

Mueller, 1.1. 1993. International GPS Service for Geodynamics: Terms of Reference, in *Proc. of the 1993 IGS Workshop,* edited by G. Beutler and E. Brockmann, published by the Univ. of Bern, Switzerland, pp. 10-14.

Rae, C.R. and J. Kleffe. 1988, "Estimation of variance components and applications," Elsevier, Amsterdam.

Sahin, M., P.A. Cross, and P.C. Sellers, Variance component estimation applied to Satellite Laser Ranging, *Bulletin Geodesique, Vol. 66,284.*

Sanli, U.D., and G. Blewitt. 1997. Monitoring tide gauges using different GPS strategies and experiment designs, appearing in these proceedings.

SINEX Working Group. 1996. "SINEX - Solution (software/technique) Independent EXchange Format Version 1.00 (June 30, 1996)," appearing in "IGS 1996 Analysis Center Workshop Proceedings, March 19-21 1996," Appendix 1, p. 233-276, Eds. R.E. Neilan, P.A Van Scoy and J.F. Zumberge, IGS Central Bureau, Pasadena, Calif., USA.

VanDam, T., G. Blewitt, and M .B. Heflin. 1994. Atmospheric pressure loading effects on GPS coordinate determinations, *Journal of. Geophysical Research, Vol. 99, No.* B1 *2, 23,939-23,950.*

Ziqiang O. 1989. Estimation of variance-covariance components, *Bulletin Geodesique Vol. 63,* p. *139-148.*

Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, and F.H. Webb, 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks, *Journ. Geophys. Res., 102, No.* B3, pp. *5005-5018.*

Zumberge J., and R. Liu (Eds.) 1995. Densification of the IERS Terrestrial Reference Frame through Regional GPS Networks, Workshop Proceedings, held Nov 30-Dec 2, 1994, published by IGS Central Bureau, Pasadena, California, USA.

Zumberge, J.F., R.E. Neilan, G. Beutler, and W. Gurtner. 1994. The International GPS Service for Geodynamics - Benefits to users, in *Proc. of* ***ION-94,*** *7th Int. Tech. Meeting,* Salt Lake City, Utah, USA, (and reproduced in reference *IGS* [1997], pp. 17-20).

SESSION 4

IGS-PSMSL

PRACTICAL EXPERIENCE AND CONSIDERATIONS:
PROJECTS PAST AND PLANNED

Co-chairs:

Trevor Baker
Permanent Service for Mean Sea Level
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead, Merseyside, U.K.

Susanna Zerbini
University of Bologna
Bologna, Italy

PRACTICAL EXPERIENCE AND CONSIDERATIONS: PROJECTS PAST AND PLANNED
SESSION SUMMARY

T.F. Baker
Proudman Oceanographic Laboratory, Bidston Observatory
Birkenhead, L437RA, UK

Susanna Zerbini
Department of Physics, University of Bologna
40127 Bologna, Italy

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 mm 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

S. Zerbini, Coordinator
Dept. of Physics, Univ. of Bologna

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

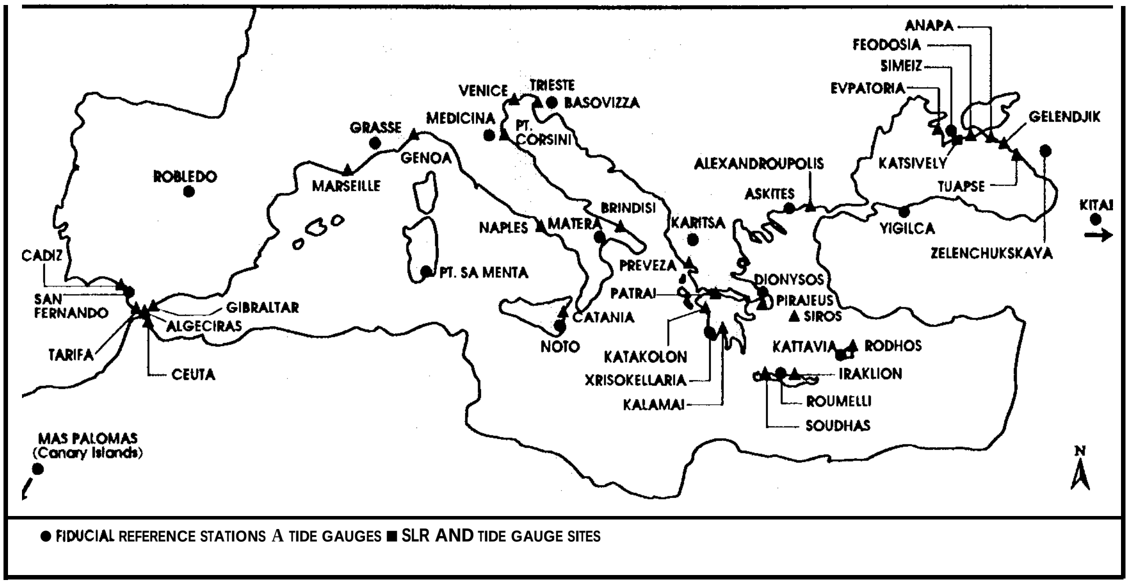


Figure 1. The SELF network.

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 sea-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.

ZERBINI S., PLAG H.-P., BAKER T., BECKER M., BILLIRIS H., BÜRKI B., KAHLE H.-G., MARSON I., PEZZOLI L., RICHTER B., ROMAGNOLI C., SZTOBRYN M., TOMASI P., TSIMPLIS M., VEIS G., VERRONE G., 1996. - Sea level in the Mediterranean: a first step towards separating crusts] movements and absolute sea-level variations. - *Global and Planet. Change, 14:* 1-48,

MONITORING VERTICAL LAND MOVEMENTS AT TIDE GAUGES IN THE UK

Vidal Ashkenazi, Richard M Bingley, Alan H Dodson, Nigel T Penna
Institute of Engineering Surveying and Space Geodesy, University of Nottingham
Nottingham, NG72RD UK

Trevor F Baker
Proudman Oceanographic Laboratory, Bidston Observatory
Merseyside, 1.43 7RA UK

ABSTRACT

The development of techniques for the application of GPS to monitoring long term vertical land movements at tide gauges, has been on-going at the IESSG since the late-1980s. Following on from the recommendations of Carter et al (1 989), there have been three projects for monitoring vertical land movements at selected sites of the UK National Tide Gauge Network. This paper presents the experiences and results from these projects.

The paper also gives details of a new project, which is due to start in August 1997, for the continued monitoring of the vertical land movements at selected sites of the UK National Tide Gauge Network, using a combination of a small number of continuously operating GPS receivers and episodic GPS measurements.

INTRODUCTION

in 1988, the international Association for Physical Sciences of the Ocean (IAPSO) Commission on Mean Sea Level and Tides reviewed the geodetic fixing of tide gauge benchmarks (TGBMs) at a workshop held at the Woods Hole Oceanographic Institute in the USA (Carter et al, 1989). The "IAPSO Committee" recommended that TGBMs should be connected to the International Terrestrial Reference Frame (ITRF) and monitored through episodic GPS campaigns, with simultaneous measurements made at tide gauge GPS stations and fundamental ITRF stations.

hollowing on from these recommendations, in 1990 the UK Ministry of Agriculture Fisheries and Food (MAFF), through the long term commission with POL, initiated a project for monitoring vertical land movements at selected sites of the UK National Tide Gauge Network using GPS. The first MAFF/POL project (UKGAUGE I) involved nine tide gauges, mainly on the South and East coasts of the UK, observed during three episodic GPS campaigns from 1991 to 1993. At the same time, the European Commission funded the EUROGAUGE project, where two episodic GPS campaigns were carried out in 1993 and 1994, at a network of sixteen tide gauges along the Atlantic Coast of Europe, including five in the UK.

The aim of the UKGAUGE I and EUROGAUGE projects was to prove zero vertical land movement, while providing first epoch measurements for longer term studies of mean sea level variations at specific tide gauges. Following on from the success of these projects, MAFF and POL initiated a second project (UKGAUGE 11) which involved a network of sixteen tide gauges, around the entire coast of the UK, observed during three episodic GPS campaigns during 1995 and 1996.

Since 1988, there have been significant advances in GPS technology, with cheaper and more reliable GPS receivers, the completion of the GPS satellite constellation and the establishment of the International GPS Service for Geodynamics (IGS). At a second workshop held at the Institute of Oceanographic Sciences in the UK in 1993, the "IAPSO Committee" recommended that continuously operating GPS receivers should be installed at 100 or so tide gauges around the world to form a core network of a global absolute sea level monitoring system, with regional densification of this core network carried out through episodic GPS campaigns or the use of continuously operating GPS receivers (Carter, 1994).

Following on from these recommendations, MAFF and POL have now initiated a third project (UKGAUGE 111), which will begin in August 1997, for the continued monitoring of the vertical land movements at selected sites of the UK National Tide Gauge Network, using a combination of a small number of continuously operating GPS receivers and episodic GPS measurements.

UK TIDE GAUGE GPS CAMPAIGNS 1991 TO 1996

Figure 1 illustrates the monitoring strategy employed in the UK for determining the height of a Tide Gauge Bench Mark (TGBM) in the ITRF and monitoring vertical land movement, using high precision GPS. The tide gauges were selected based on the criteria that they should have at least 20 years of data in the PSMSL archive, and / or be a part of GLOSS.

At each site a tide gauge GPS station (TGGS) has been established, in addition to the existing TGBM. The TGGS has been located as close to the tide gauge as possible, but in a location suitable for GPS measurements, and installed in bedrock or a substantial concrete structure, such as a pier or sea wall piled down to bedrock. For the UKGAUGE 1 and 11 projects, brass survey markers were used, whereas for the EUROGAUGE project a special semi-permanent monument was designed.

For each episodic GPS campaign, simultaneous GPS observations were made over a 5 day period at a sub-set of the TGGSs shown in Figure 2, and a number of fiducial GPS stations in Europe, which were originally part of the Cooperative International GPS network (CIGNET) and are now part of the IGS global GPS network. The data from these campaigns has been processed using the in-house developed GPS Analysis Software (Stewart et al, 1995), originally using the fiducial GPS technique and latterly using the IGS precise ephemerides.

Through the high precision GPS measurements carried out as part of the episodic GPS campaigns, the coordinates of the TGGSs are determined in the ITRF. Following on from this, the height of the TGBM can be determined by making a local precise spirit levelling connection between the TGGS and the TGBM (Baker, 1993).

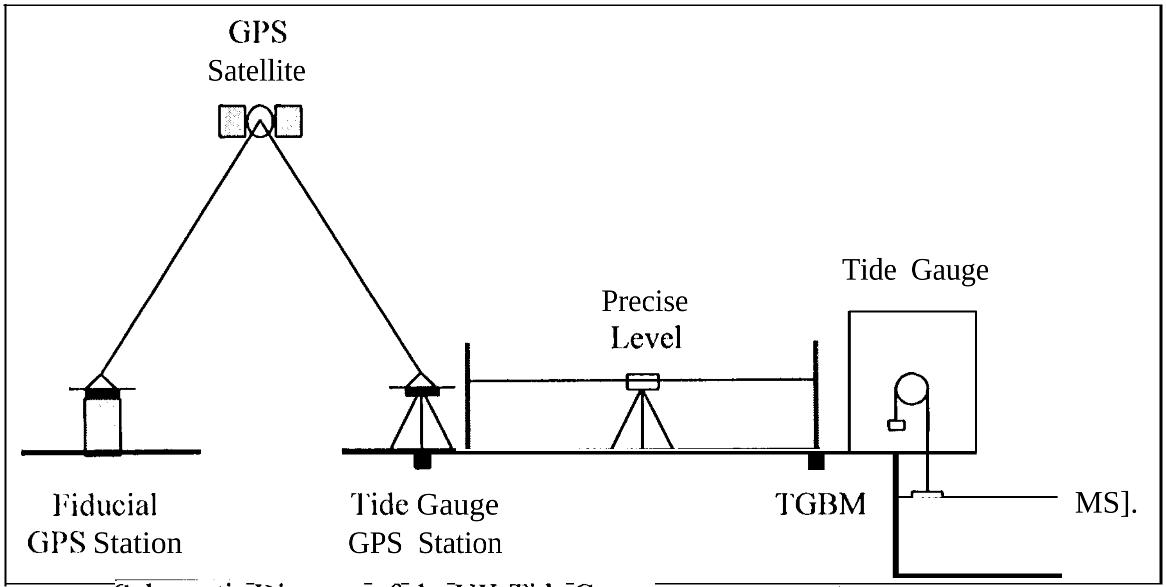


Fig. 1. Schematic Diagram of the UK Tide Gauge Monitoring Strategy

The UKGAUGE I Project

The UKGAUGE 1 project involved nine tide gauges, mainly on the South and East coasts of the UK, observed during three episodic GPS campaigns in September 1991, August 1992 and August 1993 (Ashkenazi et al, 1993; Ashkenazi et al, 1994). The TGGSs were occupied for between 8 and 10 hours per day, for 5 consecutive days, using a combination of Trimble 4000 SST and SSE GPS receivers, all with Geodetic antennas.

The EUROGAUGE Project

The EUROGAUGE project involved sixteen tide gauges along the Atlantic Coast of Europe, including five in the UK, five in France, three in Spain and three in Portugal, observed during two episodic GPS campaigns in November 1993 and March 1994 (Ashkenazi et al, 1996). The TGGSs were occupied for 24 hours per day, for 5 consecutive days, using Trimble 4000 SSE GPS receivers with Geodetic antennas.

The UKGAUGE II Project

The UKGAUGE II project involved sixteen tide gauges, all around the coast of the UK, observed during three episodic GPS campaigns in September 1995, November 1995 and September 1996. During each episodic GPS campaign, the TGGSs were occupied for 10 hours per day, for 5 consecutive days, using a combination of Trimble 4000 SST, SSE and SS1 GPS receivers, with Geodetic and Compact antennas, and Ashtech Z-XII GPS receivers, with Compact and Dome Margolin antennas

The Combined Data Set

Summaries of the receiver and antenna types used, and the data availability from all eight episodic GPS campaigns are shown in Tables 1 and 2. It can be seen that the sixteen TGGSs and two other stations have been observed in a varying number of episodic GPS campaigns.

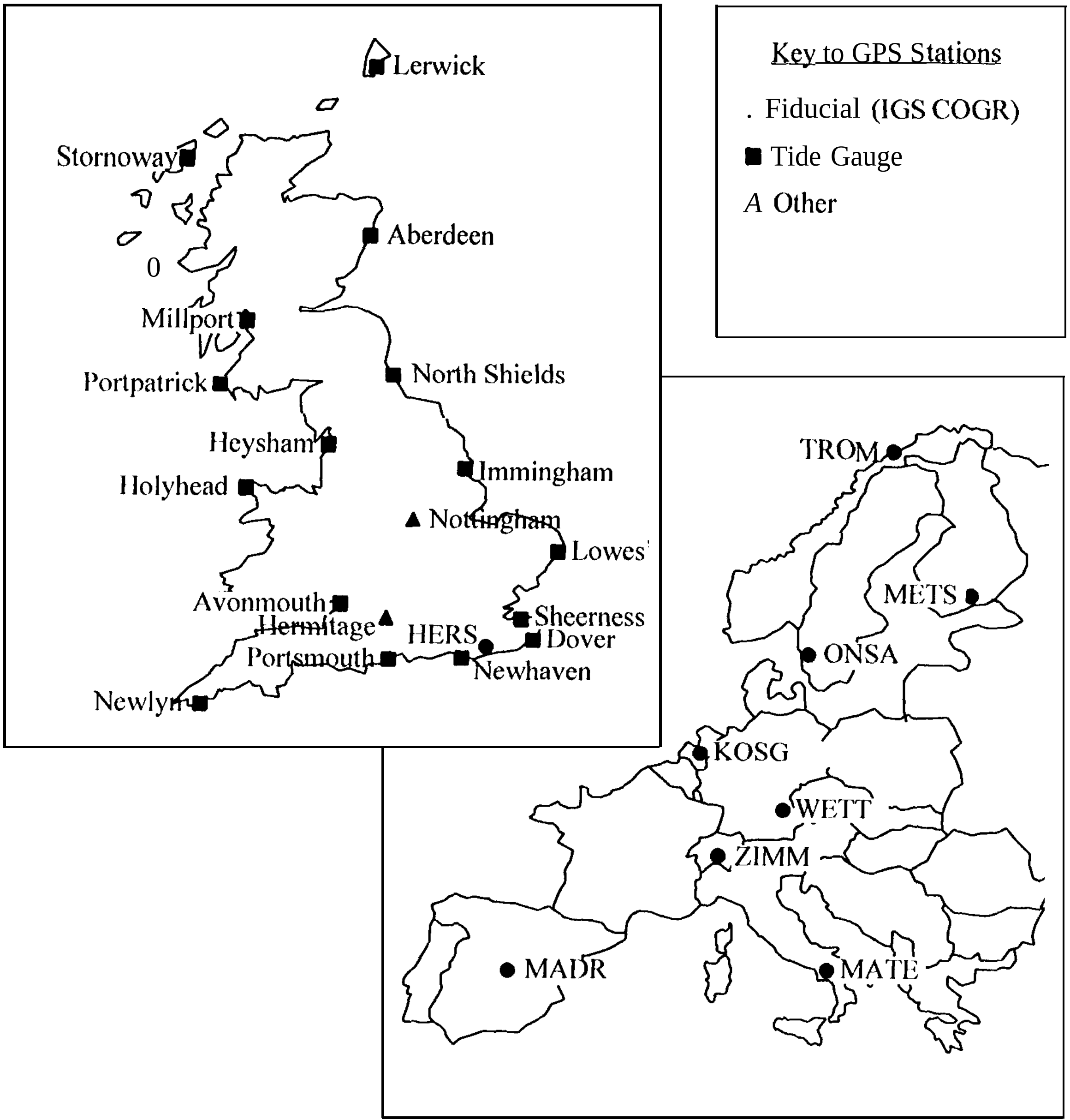


Fig. 2. UK Tide Gauge GPS ampaigns 1991 to 1996: Network Map

Only one TGGS (Portsmouth) was observed in all eight, one TGGS (Newlyn) and one other station (Nottingham) were observed in seven, two TGGSs (Portpatrick and Dover) were observed in six. three TGGSS (Sheerness, Aberdeen and Lerwick) and one other station (Hermitage) were observed in five, two TGGSs (Newhaven and Lowestoft) were observed in four, two TGGSS (North Shields and Stornoway) was observe in three, four TGGSs (Avonmouth, Holyhead, Heysham and Millport) were observed in two, and one TGGS (Immingham) was only observed in one episodic GPS campaign.

Table 1. UK Tide Gauge GPS Campaigns 1991 to 1996: Receivers/Antennas

Station	Campaigns and Epochs							
	UK91	UK92	UK93	EC93	EC94	UK95A	UK95B	UK96
	1991.70	1992.60	1993.61	1993.88	1994.21	1995.68	1995.91	1996.70
Newlyn	ST/G	ST/G	SE/G	SE/G	SE/G	SE/G	SE/C	
Portsmouth	ST/G	ST/G	SE/G	SE/G	SE/G	ST/G	AZ/C	AZ/C
Sheerness	ST/G	ST/G	SE/G			SE/C		SI/G
Portpatrick	ST/G	ST/G	ST/G			SE/G	SE/G	SE/C
N Shields						ST/G	SE/G	SE/G
Aberdeen	ST/G		SE/G			SE/G	SE/G	SE/G
Newhaven	ST/G	ST/G	SE/G				ST/G	
Dover	ST/G	ST/G	SE/G	SE/G	SE/G		ST/G	
Lowestoft	ST/G	ST/G	SE/G				SE/G	
Immingham							SE/C	
Lerwick		ST/G	ST/G	SE/G	SE/G		AZ/C	
Avonmouth						SE/G		SE/C
Holyhead						AZ/C		AZ/C
Heysham						SE/G		AZ/T
Millport						SE/C		AZ/T
Stornoway				SE/G	SE/G	AZ/C		
Hermitage	ST/G		SE/G			ST/G	SE/G	SE/C
Nottingham	ST/G		SE/G	SE/G	SE/G	SE/G	SE/G	SI/G

ST/G = Trimble 4000 SST Receiver with Geodetic Antenna (# 14532-00)
SE/G = Trimble 4000 SSE Receiver with Geodetic Antenna (# 14532-00)
SE/C = Trimble 4000 SSE Receiver with Compact Antenna (# 22020-00)
SI/G = Trimble 4000 SS1 Receiver with Geodetic Antenna (# 14532-00)
AZ/C = Ashtech Z-XII Receiver with Compact Antenna (# 70071 8)
AZ/T = Ashtech Z-XII Receiver with Dome Margolin Antenna (# 700936)

Table 1 highlights the mixture of receivers and antennas that have been used in the eight episodic GPS campaigns. This is typical for a series of episodic GPS campaigns carried out over such a time interval (5 years), with improvements in GPS receiver technology, ie the replacement of Trimble 4000 SST receivers with Trimble 4000 SSE / SS1 and Ashtech Z-XII receivers, and the limited availability of such a large number (up to 13) of GPS receivers to observe simultaneously in a single episodic GPS campaign.

Table 2 highlights another problem with episodic GPS campaigns, in that different GPS stations often have to be used at the same tide gauge site. This is due in part to the establishment of semi-permanent monuments as alternative TGGSs at the five tide gauges involved in the EUROGAUGE project, but has also been due to the temporary obstruction of a TGGS during an episodic GPS campaign, with the need to observe at an auxiliary station. To date, different GPS stations at the same tide gauge site have been connected by precise levelling, via the TGBM.

Table 2. UK Tide Gauge GPS Campaigns 1991 to 1996: Data Availability

Station	Campaigns and Epochs							
	UK91	UK92	UK93	EC93	EC94	UK95A	UK95B	UK96
	1991.70	1992.60	1993.61	1993.88	1994.21	1995.68	1995.91	1996.70
Newlyn	A	A	A	B	B	A	A	
Portsmouth	A	B	A	B	B	A	A	A
Sheerness	A	A	A			A		B
Portpatrick	A	A	A			A	A	A
N Shields						A	A	A
Aberdeen	A		A			A	A	A
Newhaven	A	A	A				A	
Dover	A	A	A	B	B		A	
Lowestoft	A	A	A				A	
Immingham							A	
Lerwick		A	A	B	B		A	
Avonmouth						A		A
Holyhead						A		A
Hey sham						A		A
Millport						A		A
Stornoway				A	A	A		
Hermitage	A		A			A	A	A
Nottingham	A		A	A	A	A	A	A

A = where GPS observations have been made at the UKGAUGE TGGS, such that the 3-d coordinates of the UKGAUGE TGGS can be computed directly.

B = where GPS observations have been made at an auxiliary station, which has then been connected by precise levelling, so that only the height of the UKGAUGE TGGS can be computed indirectly.

Preliminary Results

The data from the eight episodic GPS campaigns has been processed and analysed at the University of Nottingham using the in-house developed GPS Analysis Software (GAS), originally using the fiducial GPS technique and latterly using the IGS precise ephemerides. In all cases, the ITRF stations Onsala, Wettzell and Madrid were held fixed to coordinates computed in ITRF94, at the epoch of the episodic GPS campaign, and models for earth body tides, tropospheric delay, antenna phase centre variations and ocean tide loading (Baker et al, 1995) were applied.

A sample of the preliminary results are shown in Figures 3 and 4. In these figures, the height is shown with an error bar based on the repeatability, not the standard error. Figure 3 shows the height results obtained for the IGS station at Kootwijk, with the thick line being the equivalent ITRF value at each epoch. Comparisons of the computed values with the ITRF value at each epoch show that the height of Kootwijk has been determined to an accuracy of better than 15 mm in all of the episodic GPS campaigns. It should be noted, however, that there was no data for Kootwijk in 1991.

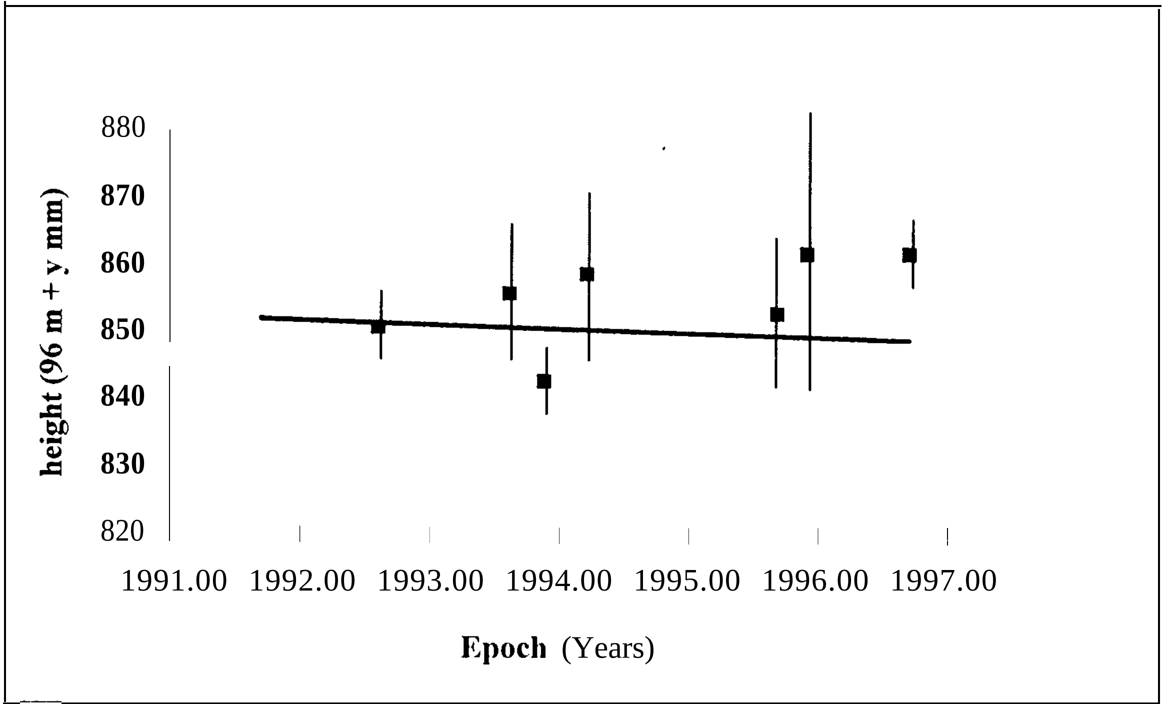


Fig. 3. UK Tide Gauge GPS Campaigns 1991 to 1996: Height Results for Kootwijk

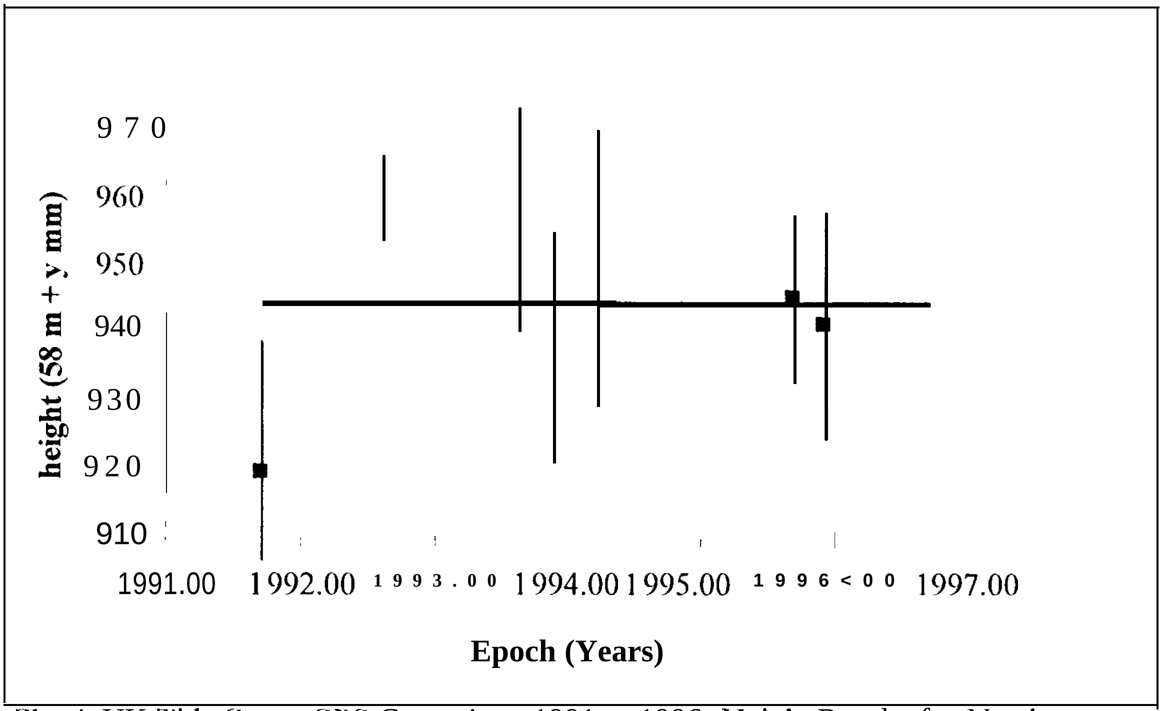


Fig. 4. UK Tide Gauge GPS Campaigns 1991 to 1996: Height Results for Newlyn

Figure 4 shows the height results obtained for the TGGS at Newlyn, with the thick line being the mean from the seven episodic GPS campaigns. Comparisons of the computed values for consecutive episodic GPS campaigns illustrate that the accuracy of the height of Newlyn has improved significantly over the five year period, and particularly since 1993 following the establishment of the IGS.

UK TIDE GAUGE GPS MEASUREMENTS 1997 TO 2000

Following on from the recommendations of Carter (1994), MAFF and POL have now initiated a third project (UKGAUGE III), which will begin in August 1997, for the continued monitoring of the vertical land movements at selected sites of the UK National Tide Gauge Network, using a combination of continuously operating GPS receivers (COGRs) at five tide gauges and episodic GPS measurements (EGM) at eleven tide gauges, as shown in Figure 5.

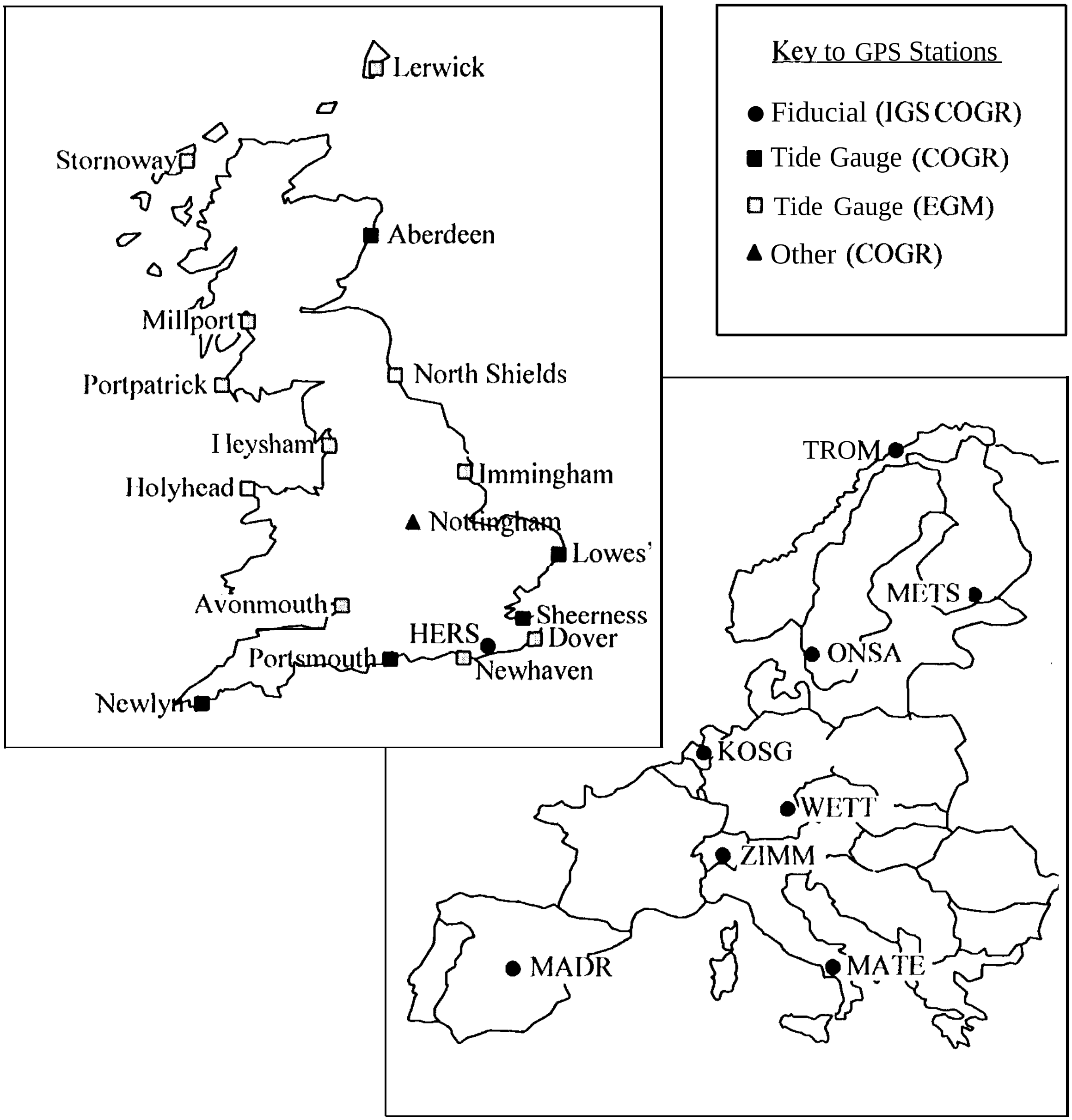


Fig. 5. UK Tide Gauge GPS M asurements 1997 to 2000: Network Map

The first COGR was installed at Sheerness in March 1997, the second will be installed at Aberdeen in June 1997, and the other three will be installed by the end of 1997. For the episodic GPS measurements, it is proposed that a single 'roving' GPS receiver will be used to make observations, over a 5 day period each year, at each of the eleven tide gauges separately. In order to avoid some of the problems encountered in episodic GPS campaigns, a dedicated GPS receiver / antenna will be used as the 'rover', effective y acting as a 'quasi-COGR' at these sites.

CONCLUSIONS

Eight episodic GPS campaigns have been carried out to date for monitoring vertical land movements at sixteen tide gauges, which form part of the UK National Tide Gauge Net work. The preliminary results indicate that the heights of the TGGSS have been determined to an accuracy of 15 mm or better.

The continued monitoring of the vertical land movements at the sixteen tide gauges, will be carried out through the establishment of continuously operating GPS receivers (COGRs) at five sites, and episodic GPS measurements at the other eleven sites, using a single 'roving' GPS receiver.

Acknowledgements The UKGAUGE I and 11 projects were funded by the UK Ministry of Agriculture Fisheries and Food (MAFF) through the long term commission with 1'01., with invaluable fieldwork assistance provided by the Ordnance Survey of Great Britain and the UK Military Survey. The EUROGAUGE project was funded by the European Commission Science Program (EC Contract SC1*-CT92-0821) and was a collaboration between the University of Nottingham (UK), the Instituto Portugues de Cartografia e Cadastro (Portugal), the Institute Géographique National (France), the Instituto Geográfico National (Spain), the Ordnance Survey of Great Britain (UK), the Proudman Oceanographic Laboratory (UK), the Consejo Superior de Investigaciones Cientificas (Spain) and the University of Newcastle-upon-Tyne (UK). The authors would like to acknowledge other 1 ESSG colleagues who have contributed directly to this work, most notably Dr Glen Beamson and Dr Chia Chyang Chang.

REFERENCES

Ashkenazi, V, R M Bingley, G M Whitmore, and T F Baker, 1993, Monitoring Changes in Mean-Sea-Level to Millimetres Using GPS, *Geophysical Research Letters, 5* September 1993, Vol 20, No 18, pp 1951-1954.

Ashkenazi, V, G A Beamson, R M Bingley, A H Dodson, M P Stewart, and T F Baker, 1994, UKGAUGE: The United Kingdom Tide Gauge Monitoring Project, *Proceedings of the International Symposium on Marine Positioning (INSMAP 94)*, Hannover, Germany, September 1994,pp251 -260.

Ashkenazi, V, R M Bingley, C C Chang, A H Dodson, 1' F Baker, A Rius, P A Cross, J A Torres, C Boucher, H Fagard, J L Caturla, R Quiros, and C Calvert.Ashkenazi, V, 1996, The Results of EUROGAUGE: The West European Tide Gauge Monitoring Project, XXI General Assembly of the European Geophysical Society, The Hague, The Netherlands, May 1996.

Baker, T F, 1993, Absolute Sea Level Measurements, Climate Change and Vertical Crustal Movements, *Global and Planetary Change, 8(1993),* Elsevier Science Publishers B V, pp 149-159.

Baker, T F, D J Curtis, and A H Dodson, 1995, Ocean Tide Loading and GPS, *GPS World,* March 1995, pp 54-59.

Carter, W E, D G Aubrey, T F Baker, C Boucher, C Le Provost, D T Pugh, W R Peltier, M Zumberge, R H Rapp, R E Schutz, K O Emery, and D B Enfield, 1989, Geodetic Fixing of Tide Gauge Benchmarks, *Woods Hole Oceanographic Institute Technical Report, WHO1-89-31,* 44 pp.

Carter, W E (cd), 1994, Report of the Surrey Workshop of the IAPSO Tide Gauge Bench Mark Fixing Committee held at the Institute of Oceanographic Sciences, UK, in December 1993, *NOAA Technical Report NOSOESOO06, 81* pp.

Stewart, M P, G H Ffoulkes-Jones, W Y Ochieng, and P J Shardlow, 1995, GPS Analysis Software (GAS) Version 2.3 User Manual, *IESSG Publication,* University of Nottingham, UK.

A GPS Network for Monitoring Absolute Sea Level in the Chesapeake Bay: BAYONET

R. S. Nerem [†]
Center for Space Research, The University of Texas at Austin

T. M. vanDam and M. S. Schenewerk
Geosciences Laboratory, National Oceanic and Atmospheric Administration

Introduction

Approximately 4100 km^2 of the Chesapeake Bay is covered by wetlands of which 58% are forested wetlands and 28% are salt marshes [U.S. *Department of Commerce, 1990]*. Unfortunately, these fragile ecosystems, which support an abundance of wildlife, are being lost at an alarming rate due to an increase in sea level. For example, one-third of the total area of the Backwater National Wildlife Refuge (Figure 1) (approximately 20 km^2) was lost between 1938 and 1979 *[Weatherman,* 1992]. It is likely that many factors are responsible for wetlands loss in the Chesapeake Bay region, some which have global implications, and some which reflect local phenomena. However, understanding the mechanisms responsible for wetlands deterioration and loss has been impeded by the lack of adequate data: quantitative monitoring of the types and distribution of flora, boundaries of specific habitat types, and spatial variations in sea level and land subsidence.

Wetlands in general are very susceptible to high rates of sea level rise. During episodes of gradual sea level increase, like that resulting from global climate change, the salt marshes can keep pace with the rising water levels by backfilling and trapping sediments and their own organic detritus in the water column *[Weatherman,* 1991]. The zonation of plant species in the marsh responds by moving progressively landward. However, if the sea level rises significantly faster than the rate at which the marsh can retreat, the marsh will essentially drown and be lost. A catastrophic mechanism of marsh loss which can accompany a rapid increase in sea level is the formation of extensive interior marsh ponds. These shallow-water bodies enlarge and coalesce drowning large areas of marsh vegetation and effectively produce rapid coastal submergence *[Orson et al.,* 1985],

Tide gauge measurements taken over the last half century currently provide one of the only means of quantifying the amount of sea level rise in the Chesapeake Bay. The rates of sea level rise observed at a number of gauges there between the years of 1930 and 1993 are shown in Table). The average rate of sea level rise observed in the Bay over this time period is 3.5 mm/year. Global mean sea level rise is generally thought to be between 1.5 and 2 mm/year over the same time period [*Tushingham and Peltier, 1989; Trupin and Wahr,* 1990; *Douglas,* 1991; *Unal and Ghil, 1995].* Thus, rates of relative sea level rise in the Chesapeake Bay are approximately twice the global average pointing to both shore erosion and marshland pond developments as likely factors in wetland loss.

However, tide gauges do not by themselves provide estimates of absolute sea level, rather they provide estimates of sea level relative to the ground or a pier (or actually a tide gauge benchmark on the ground if leveling is performed) to which the tide gauges are attached. For example, if the ground is subsiding, a tide gauge would observe a rise in

---

[†] Also with the Dept. of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin

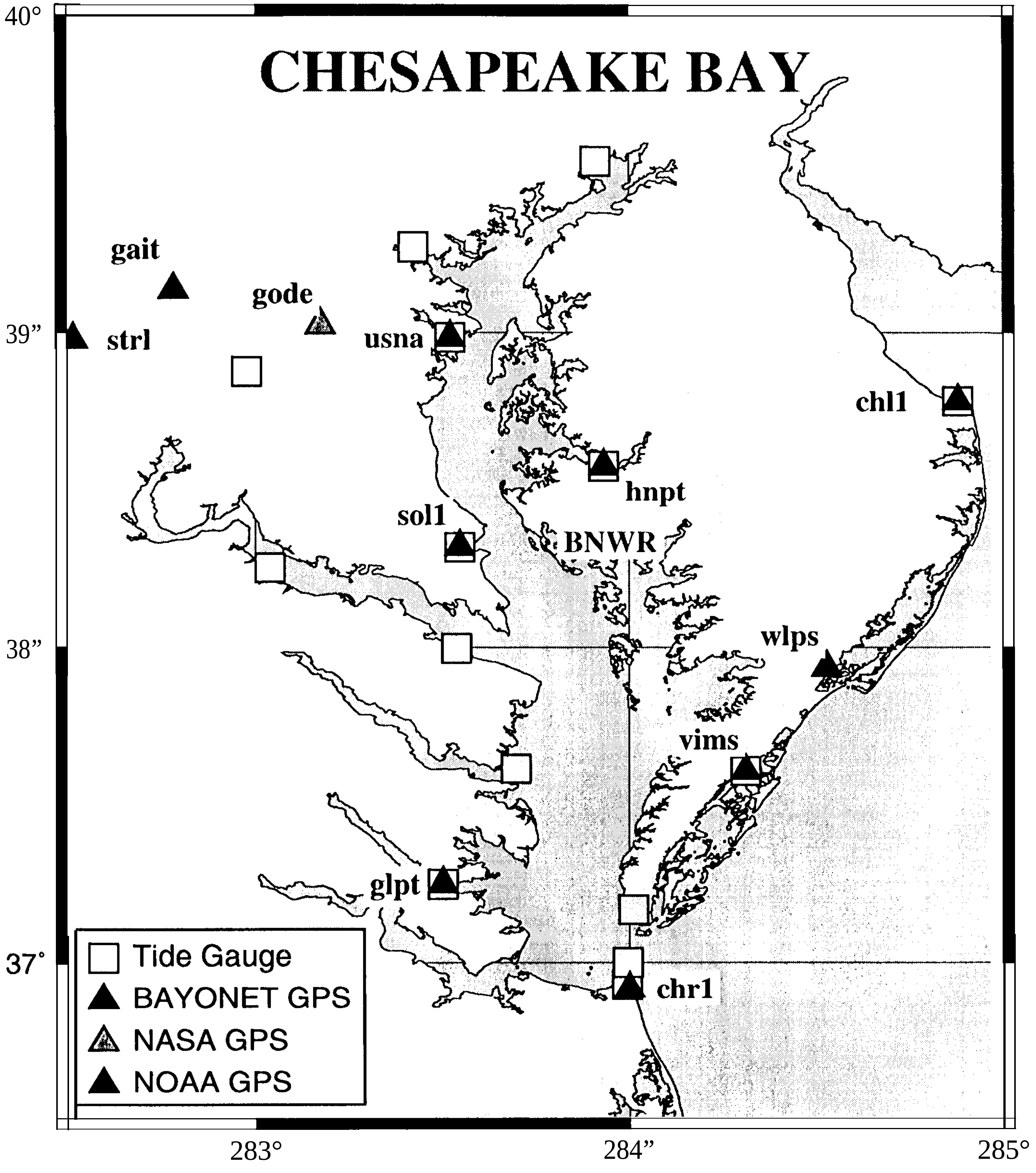

CHESAPEAKE BAY
40°
39”
38”
37°
283°
284”
285°
gait
gode
strl
usna
chl1
hnpt
sol1
BNWR
wlps
vims
glpt
chr1
□ Tide Gauge
▲ BAYONET GPS
▲ NASA GPS
▲ NOAA GPS

Figure 1

relative sea level, whereas absolute sea level may have remained constant. There are a variety of reasons the ground may subside or uplift including post-glacial rebound (PGR) of the crust *[Tushingham and **Peltier**,* 1991], sediment loading of the crust, clay compaction caused by fluid extraction, and tectonic activity. In the Chesapeake Bay, a significant portion of the relative sea level rise is believed to be due to subsidence caused by post-glacial effects. The bay lies in the region of the "peripheral bulge", a dynamically supported geologic structure surrounding the main area of post-glacial rebound in Canada *[Davis and **Mitrovica**, 1996].* As the glaciers retreated, the mechanism supporting the peripheral bulge vanished and the collapse of the bulge which began in the Holocene continues today. Table 1 also shows estimates of the expected PGR signal for the tide gauges in the Chesapeake Bay using the model of ***Peltier** and **Jiang*** [1996].

Local subsidence caused by extensive groundwater extraction may also contribute to the sea level rise signal in the Bay. Fresh water is being pumped from aquifers surrounding the Bay to support agriculture and industry **[*Smigai and Davis, 1987; Gornitz***
*and **Seeber**,* 1990; ***Holdahl** and Morrison,* 1974]. Water levels in monitoring wells in the vicinity of the Patuxent River Naval Air Station near Solomons Island, Maryland have dropped by 9 meters in the last 50 years as a response to the growth of the facility and the surrounding community.

Table 1. Sea level trends at tide gauges in the Chesapeake Bay: 1930-1993

Tide Gauge	Lat	Lon	Sea Level Trend (mm/year)	PGR † (mm/year)	Corrected Sea Level (mm/year)
Annapolis; MD	38.983	-76.480	3.4 ± 0.2	0.9	2.5
Baltimore, MD	39.267	-76.578	3.() ± 0.2	1.0	2.0
Cambridge, MD	38.575	-76,068	8.8 ± 2.5	0.9	7.9
CBBT, VA	37.000	-76.003	7.5 ± 1.1	0,8	6.7
Colonial Beach, VA	38.253	-76.962	5.4 ± 1.1	0.9	4.5
Gloucester, VA	37.247	-76.500	6,2 ± 2.2	0.8	5.4
Hampton Roads, VA	36.927	-76.006	4.1 ± 0.2	0.8	3.3
Harve De Grace, MD	39.537	-76.090	-1.4 ± 1.1	1.0	-2.4
Kiptopeke, VA	37.167	-75.988	3.2 ± 0.3	1.1	2.2
Lewisctta, VA	37.997	-76.463	4.1 ± 1.0	0.8	3.3
Lewes, DE	38,782	-75.120	3.0 ± 0.2	1.2	1.8
Solomons Island, MD	38.317	-76.453	3.3 ± 0.2	0.9	2.4
Wachapreague, VA	37.607	-75.687	6.7 ± 1.4	1,1	5.6

† *Peltier [1994], Peltier and Jiang* [1996]

Tide gauges around the world with records longer than about 50 years, including those on the east coast of the U. S., provide one of the only means of measuring relatively recent changes in global mean sea level ***[Douglas,*** 1995]. While satellite altimetry has shown promise for monitoring long-term variations in sea level, including global mean sea level [*Nerem et al.,* 1997], the sea level record from satellite altimetry is still of insufficient length for detecting sea level variations related to global climate change, Therefore, tide gauge data will remain an important resource for measuring long-term sea level rise for some time to come (even after a suitably long record of altimeter data has been collected, tide gauge data will still be critical for monitoring the altimeter calibration and tying different missions together). However, all recent estimates of global sea level rise derived from tide gauge data have depended on the use of a model to correct for the effects of post glacial rebound [*Tushingham and **Peltier**, 1989, **Trupin** and **Wahr**,* 1990, *Douglas,* 1990; ***Unal** and **Ghil**, 1995],* as summarized by *Douglas [1995],* These models, which depend on values of the lower mantle viscosity and the historical ice load, are subject to large uncertainties [*Davis and Mitrovica*, 1996]. In addition, tide gauge records do not account for other sources of ground movement such as subsidence caused by fluid withdrawal or other tectonic motion [*Mitchel et al.*, 1994]. In essence, even the best models are no substitute for monitoring the ground motion using precise geodetic techniques.

The capability of precisely monitoring the vertical position of geodetic sites using Satellite Laser Ranging (SLR) [*Dunn et* al., 1993] or Very Long Baseline Interferometry (VLBI) [*Carter et al.*, 1986; *Herring, 1986]* has been available for some time. However, it is often not feasible to position these relatively large observatories in the cramped quarters that often house tide gauges, not to mention the prohibitive cost of providing continuous monitoring for a large number of gauges. However, with the emergence of the Global Positioning System (GPS) as a relatively inexpensive alternative for providing precise point positioning [*Blewitt*, 1993], it is now possible to continuously monitor the precise position of a significant number of tide gauges at relatively modest costs.

The Chesapeake Bay GPS Network: BAYONET

The Chesapeake Bay provides a convenient laboratory for studying the effects of long-term sea level change, whether these changes are representative of global or local phenomena, The shoreline slopes in the bay are remarkably flat, thus even a 1 mm rise in sea level can cause the loss of 1 meter of horizontal shoreline. These shallow slopes coupled with the extensive wetlands that surround the Bay, make this region very sensitive to changes in sea level. In addition, the Bay lies in a region for which the PGR estimates are very uncertain [*Davis and Mitrovica*, 1996]. Therefore, measurements of absolute sea level in this region would provide insight into a number of issues including "global" climate change (and its spatial variation), local subsidence, and the viscosity of the lower mantle (a parameter that has been difficult to constrain in PGR models).

A number of studies have pointed out the importance of geodetic monitoring of tide gauge benchmarks [e.g. *Bilham, 1991; Carter et al., 1989a;* 1989b] in order to measure their movement, but only recently has GPS monitoring achieved the accuracy and affordability to permit the determination of absolute sea level at a significant number of tide gauges. *Douglas [1990]* has argued that at least 50 years of tide gauge data are required in order to sufficiently average out decadal sea level variations [*Chelton and Enfield*, 1986; *Pugh, 1987; Sturges, 1987],* thus in general, only tide gauges with sea level records approaching this length should be considered candidates for continuous GPS monitoring. In most cases, the rate of crustal uplift/subsidence caused by tectonic motion and PGR may be considered to be constant on time scales of several hundred years, thus these rates may be extrapolated to the entire tide gauge record once determined from a suitably long GPS occupation. Depending on the cause, local subsidence rates may vary on much shorter time scales, thus caution must be used when extrapolating the GPS results across the historical tide gauge record.

In 1993, NOAA and NASA/Goddard Space Flight Center began a joint effort to develop a GPS network near tide gauges in the Chesapeake Bay (BAYONET). The first site was located at Solomons Island, Maryland, on the western side of the bay southeast of Washington, D.C. A site at Annapolis, Maryland followed in 1994, and three additional sites were installed in 1995. Figure 1 summarizes the locations of these sites. Almost all the sites have Turborogue receivers and Dorne-Margolin antennas, with a few exceptions. Most of these sites also have modern tide gauges based on NOAA's Next Generation Water Level Measurement System (NGWLMS) [*Beaumariage and Scherer*, 1987]. The location of the receivers with respect to the tide gauges varies by site, determined by issues such as sky visibility, site security, and the availability of power and communications. Obviously it is preferable to collocate the receiver antenna with the tide gauge, however this is not always possible. In some cases, it is possible to locate the GPS antenna somewhere on the tide gauge hut. However, in most cases, such as Solomons Island, it was necessary to locate the antenna some distance inland (a few hundred meters) from the tide gauge. In all cases, first order leveling is performed by NOAA on roughly a yearly basis between the tide gauge benchmarks and the GPS antenna. The data (collected at 30-second intervals) are remotely downloaded daily by NOAA and placed in the appropriate data archives (NOAA's CIGNET and NASA's CDDIS), where they are publicly available.

Table 2. The BAYONET GPS Network

‘site “ Name	Station Label	Lat	Lon	Rec Type	Ant Type	Install Date	Gauge Type
Solomons Island MD	SOL1	38.3	-76.4	T	DM	10/93	N
Annapolis MD	USNA	38,9	-76.5	TR	DM	1/95	N
Horn Point MD	HNPT	38.6	-76.1	TR	DM	12/95	N
Gloucester Point VA	GLPT	37.2	-76.5	TR	DM	7/95	N
Wachapreague VA	VIMS	37.6	-75.7	TR	DM	7/95	N

T=Trimble SSE 4000, TR=Allen Osborne Turborogue, DM=Dorne Margolin with T type choke ring, N=NOAA Next Generation Water Level Measurement System

NASA and NOAA maintain several other continuous sites in the Chesapeake Bay region which, while not strictly a part of BAYONET, nevertheless provide important extensions to the network coverage as well as fiducial sites for tying BAYONET to the International Terrestrial Reference Frame (ITRF). In addition, the U.S. Coast Guard has installed several sites to provide differential navigation for marine vessels. The data from these sites are made available by NOAA as part of the Continuously Operating Reference System (CORS) [*Strange and Weston, 1995].* Figure 1 summarizes the locations of all of the GPS receivers operating in the Chesapeake Bay region for which data are available on a routine basis.

Preliminary Results

At least several years of GPS data are required before an accurate estimate of the vertical rate of motion of the tide gauge is obtained. The vertical repeatability of daily solutions for most of the Chesapeake Bay sites is about 10 mm (and less than 4 mm in the horizontal), however there are also short term motions, such as atmospheric pressure loading [wm *Dam and Wahr, 1987]* which can be reduced through either averaging or modeling. The largest source of error for the vertical position component is the attenuation of the GPS signals by water vapor. Although the effects of water vapor are empirically removed through its dependence on elevation angle, significant residual errors still remain, Water vapor can be a significant error source at coastal locations due to its large spatial variability there.

The BAYONET site with the longest GPS data record is Solomons Island, whose time series is currently over 3 years in length. Figure 2 shows a plot of the daily vertical position of Solomons Island with respect to the IGS (International GPS Service) site at NASA/Goddard Space Flight Center (GODE). The daily vertical repeatability is about 10 mm, the vertical rate is +0.5 mm/year, and the scatter is 0.4 mm/year. Also shown is the daily results after smoothing with a 10 day boxcar filter. Clearly, much of the 10 mm scatter of the height estimates arises from coherent phenomena, such as water vapor error or pressure loading. The source of the abrupt change in mind-1995 is unknown, but is believed to related to GODE and not SOL1. We are attempting to develop better models forthese phenomena in order to reduce the averaging time required to determine the long-term vertical rates. Currently, our preliminary results suggest that atime series of at least 3 years in length will be required to determine the vertical rate to an accuracy of 1 mm/year or better.

Figure 2. Vertical Position of SOL1

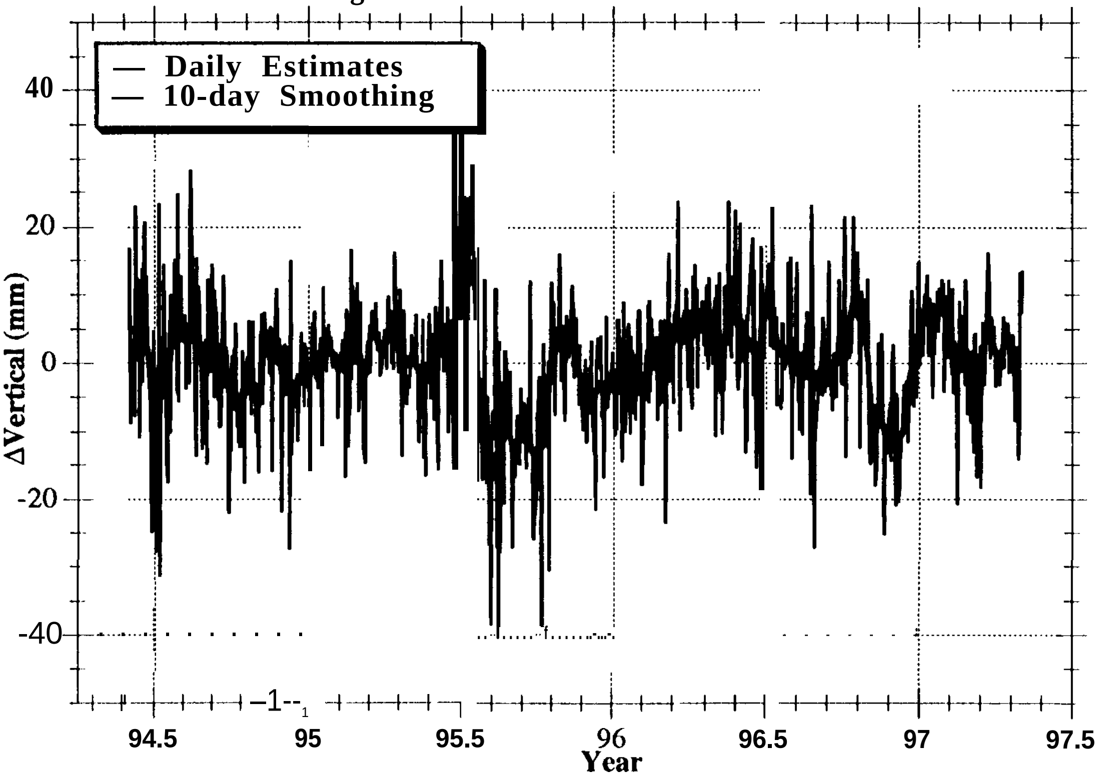


Table 1 shows the vertical rate estimates for the BAYONET sides, all with respect to GODE. The data from GLPT show some anomalous behavior, possibly due to radio interference, and have thus been omitted. With the exception of SOL 1, the remaining sites tend to suggest subsidence relative to GODE (which has been determined using VLBI and SLR to be stable in the vertical at less than a mm/year) of a few mm/year.

Site ID	Rate (mm/yr)	Sigma (mm/yr)
HNPT	-5,2	0.8
SOL1	**+0.5**	**0.4**
USNA	-2.3	0.4
VIMS	-1.2	0.7

Future Work

We have been funded by NSF and NASA to extend the BAYONET network north along the east coast of the U.S. in order to develop a better understanding of the differential rates of sea level rise observed on either side of the PGR “hinge point” at New York City, as discussed by *Douglas [1991]* and *Davis and Mitrovica [1996]*. While Davis and Mitrovica can apparently explain the difference by changing the lower mantle viscosity in their post glacial rebound model, this result is not without controversy. The

GPS monitoring of a dozen or more tide gauges on the east coast will establish this region as an important benchmark for studies of global sea level change in general. A number of tide gauges on the east coast have been in operation for 50 years or longer, thus these gauges would be targeted for GPS monitoring.

The Chesapeake Bay is only one piece of a global puzzle of tide gauge observations of climate-induced sea level change convolved with vertical crustal motion. Many groups around the world are actively pursuing GPS instrumentation/monitoring programs for their tide gauges so that eventually, a global network of GPS instrumented tide gauges will exist. This global network will allow for new insights into the causes of mean sea level change as well as provide boundary conditions for the development of improved post-glacial rebound models and their dependent parameters (e.g. lower mantle viscosity [see *Johanssen et al., 1995]).*

Acknowledgments

A number of individuals at NOAA and NASA have contributed to the development of the BAYONET network including John Bosworth, Miranda Chin, Tom Clark, Gerry Mader, Ernie Marion, John Chase, Ross MacKay, and Carey Nell. Support for this investigation was provided by Miriam Baltuck and John Labrecque of the Solid Earth Sciences Branch at NASA Headquarters and by Stan Wilson at NOAA, Additional thanks are also due to the organizations providing secure sites and support for our GPS equipment (and power/communications in some cases) including the Chesapeake Biological Laboratory at the University of Maryland in Solomons Island, the U.S. Naval Academy, Horn Point Biological Laboratory, the Virginia Institute of Marine Sciences in Gloucester Point and the Backwater National Wildlife Refuge.

References

Beaumariage, D. C., and W. D. Scherer, New Technology Enhances Water Level Measurement, *Sea Tech.,* **28(5),** pp. 29-32, 1987.

Bilham, R., Earthquakes and Sea Level: Space and Terrestrial Metrology on a Changing Planet, *Rev. Geophys.*, Vol. 29, No, 1, pp. 1-29, 1991.

Blewitt, G., Advances in Global Positioning System Technology For Geodynamics Investigations: 1978-1992, Contribution of Space Geodesy to Geodynamics: Technology, AGU Geodynamics Monograph Series, Vol. 25, pp. 195-213, 1993.

Carter, W. E., D. S. Robertson, T. E. Pyle, and J. Diamante, The Application of Geodetic Radio Interferometric Surveying to the Monitoring of Sea-Level, *Geophys. J. R. Astron. Sot.,* Vol. 87, pp. 3-13, 1986.

Carter, W. E., D. G. Aubrey, T. Baker, C. Boucher, C. LeProvost, D. Pugh, W. R. Peltier, M. Zumberge, R. H. Rapp, B. E. Schutz, K. O. Emery, and D. B. Enfield, Geodetic Fixing of Tide Gauge Bench Marks, Woods Hole Oceanographic Institution Technical Report WHOI-89-31, August, 1989a.

Carter, W. E., M. Chin, J. R. MacKay, G. Peter, W. Sherer, and J. Diamante, Global Absolute Sea Level: The Hawaiian Network, *Mar. Geod.*, Vol. 12, pp. 247-257, 1989b.

Chelton, D. B. and D. B. Enfield, Ocean Signals in Tide Gauge Records, *J. Geophys. Res.,* Vol. 91, No. B9, pp. 9081-9098, 1986.

Davis, J. L., and J. X. Mitrovica, Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America, *Nature, 379,331-333, 1996.*

Douglas, B.C., Global sea level rise, *J. Geophys. Res.,* 91,6081 -6992., 1991.

Dunn, P. J., M. H. Torrence, R. Kolenkiewicz, and D. E. Smith, Vertical Positioning of Laser Observatories, Contribution of Space Geodesy to Geodynamics: Crustal Dynamics, AGU Geodynamics Monograph Series, Vol. 23, pp. 99-106, 1993.

Gornitz, V., and L. Seeber, Vertical crustal movements along the east coast, North America, from historic and Late Holocene sea level data, *Tectonophysics, 178,* 1990.

Herring, T. A., Precision of Vertical Position Estimates from Very Long Baseline Interferometry, *J. Geophys. Res.,* Vol. 91, pp. 9177-9182, 1986.

Holdahl, S. R. and N. L Morrison, Regional investigations of vertical crustal movements in the U. S., using precise relevelings and mareograph data, *Tectonophysics, 23, 373-390, 1974.*

Weatherman, S. P., Coastal land loss in the Chesapeake Bay Region: An historical analogy approach to global climate analysis and response, in *The Regions and Global Warming: Impacts and Response Strategies,* J. Schmandt, cd., Oxford press, p. 17-27, 1992.

Weatherman, S. P., Impact of Climate-induced sea-level rise on coastal resources, in *Global Climate Change and Life on Earth,* R. L. Wyman, cd., Chapman and Hall, New York, Chapter 10, p. 170-179, 1991.

Mitchel, C. E., P. Vincent, R. Weldon, and M. Richards, Present-day vertical deformation of the Cascadia margin, Pacific Northwest, United States, *J. Geophys. Res.,* Vol. 99, pp. 12,257-12,277, 1994,

Orson, R. W., W. Penageotou, and S. P. Weatherman, Response of tidal salt marshes of the U.S. Atlantic and Gulf coasts to rising sea levels, *J. Coastal Res.,* 1,29-37, *1985.*

Peltier, W. R. and A. M. Tushingham, Global Sea Level Rise and the Greenhouse Effect: Might They be Connected?, *Science,* Vol. 244, pp. 806-810, 1989.

Peltier, W. R., Ice Age Paleotopography, *Science, 265, 195-201,* 1994.

Peltier, W. R., and X. Jiang, Mantle viscosity from the simultaneous inversion of multiple data sets pertaining to postglacial rebound, *Geophys. Res. Lett.,* 101,503-506, 1996.

Pugh, D. T., *Tides, Surges, and Mean Sea Level,* John Wiley and Sons, 1987.

Smigai, M. J. and R. G. Davis, Ground-water levels from the Maryland observation-well network, 1943-1986, Maryland Geol. Surv., Basic Data Report, 17, 1987.

Sturges, W., Large-Scale Coherence of Sea Level at Very Low Frequencies, *J. Phys. Oceanog.,* Vol. 17, 1987.

Strange, W. and N, Weston, The establishment of a GPS Continuously operating reference station system as a framework for the National Spatial Reference System, *Inst. of Navigation,* p. 19-24, 1995,

Trupin, A. and J. Wahr, Spectroscopic Analysis of Global Tide Gauge Sea Level Data, *Geophys. J. Int.*, Vol. 100, pp. 441-453, 1990.

Tushingham, A. M., and W. R, Peltier, ICE 3-G: A New Global Model of Late Pleistocene Deglaciation Based Upon Geophysical Predictions of Post Glacial Relative Sea Level Change, *J. Geophys. Res.*, Vol. *96, No. B3,* pp. 4497-4523, 1991.

Unal, Y. S., and M. Ghil, Interannual and interdecadal oscillation patterns in sea level, *Climate Dynamics*, 11,255-278, *1995.*

U.S. Department of Commerce, Estuaries of the United States, A special NOAA 20th Anniversary Report, 1990.

vanDam, T. M. and J. M. Wahr, Displacements of the Earth's surface due to atmospheric pressure loading: Effects on gravity and baseline measurements, *J. Geophys. Res., 92,* 1282-1286, 1987.

Precise Sea Surface Measurements Using DGPS Buoys

M. Parke, J. Blaha, and C.K. Shum

Abstract: Differential GPS (DGPS) buoys have the potential to provide sea level information at space and time scales shorter than available from altimeter data. They can be used to calibrate altimetric measurements at any location that can be reasonably reached as well as being a valuable adjunct to regional experiments. This paper discusses the potential of DGPS buoys and a series of proposed experiments aimed at furthering the development of DGPS buoy technology and use of DGPS buoys for oceanographic and geodetic experiments. We feel that over the next decade DGPS buoys will become an accepted and valued tool for sea level research.

Introduction:

Use of differential GPS measurements for precise sea level measurements began in the late 1980's when enough of the GPS constellation was established to allow for demonstration experiments to be conducted. Experiments with precision DGPS sea level have thus far shown tantalizing glimpses of the potential for this method to provide meaningful sea level measurements for use in oceanography and geodesy. Only short baselines have been used between the DGPS buoy and the reference fiducial site.

Blomenhofer and Hein have worked with tethered buoys and near real time sea level measurements (Hein, et al., 1990; Blomenhofer and Hein, 1994). NOAA worked initially with DGPS on board ships entering and leaving harbor to estimate the amount ships "squat" under acceleration and therefore the channel clearance needed (Martin, personal communication). This was followed by about a month and a half of continuous measurements from a buoy that compared favorably with a neighboring tide gauge (Shannon and Martin, 1996). Kelecy et al., 1994 showed that two widely differing platforms (a spar and a floater) gave equivalent sea level measurements. Born et al., 1994 used the spar design to provide a calibration estimate for TOPEX/POSEIDON. Key et al., 1997 used the floater design to demonstrate the ability of DGPS buoys to provide spatial sea level mapping instead of just time series. Schutz et al, 1996, used the floater design for the calibration of TOPEX/POSEIDON in Galveston Bay. Figure 1 shows an example ofa comparison of DGPS sea level using the floater buoy at Texaco's platform Harvest with the NOAA acoustic t ide gauge mounted there as part of the T/P calibration/validation exercise (after Key et al., 1997). The DGPS sea level has been filtered with a double running mean filter with length 2.5 minutes to remove waves. The mean difference between the measurements over this period is -0.03 cm with a standard deviation of 0.7 cm. There is never a difference of more than 1.5 cm. Determination of sea state and wave height spectra from DGPS buoy measurements has been discussed and evaluated (Hein et al., 1990, Born et al., 1994).

The main design requirement for accurate sea level is accurate knowledge of the vertical distance from the waterline to the GPS antenna, Almost any platform can be utilized if there is a clear view for the GPS antenna (little multi-path) and sufficient care is taken to either know or monitor the buoy w

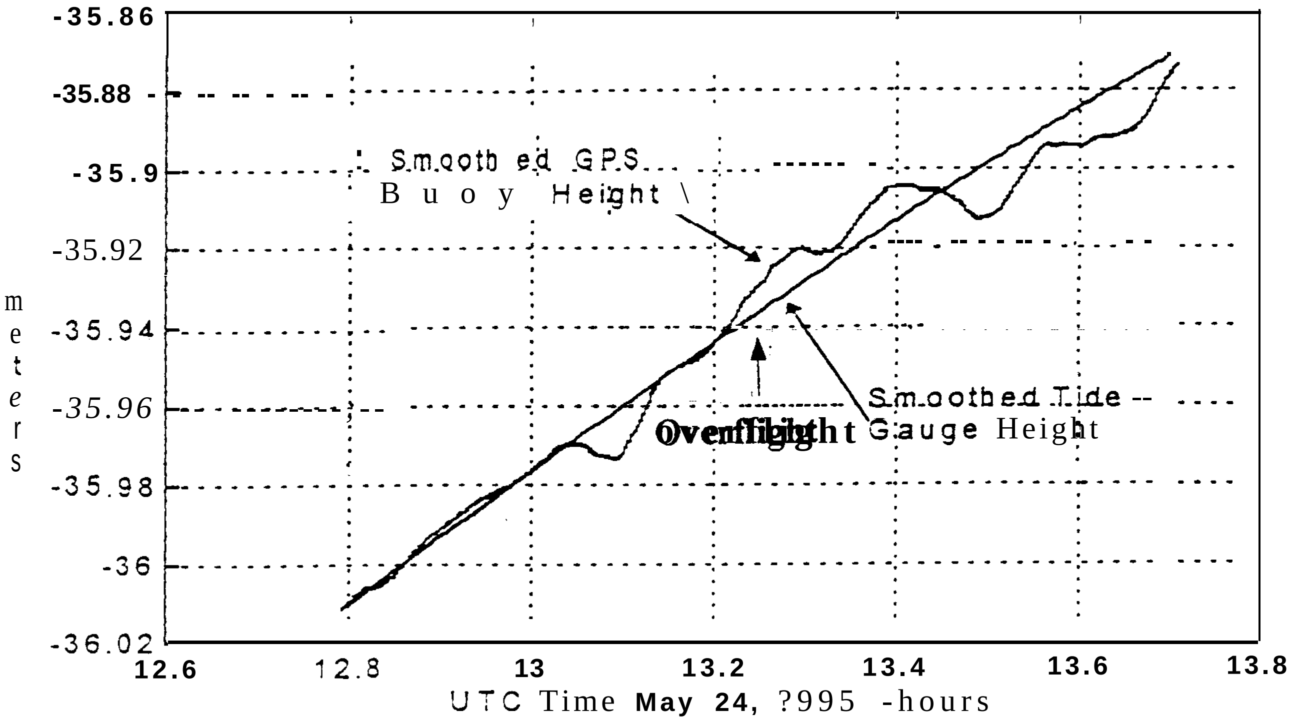


Figure 1: A comparison of double pass filtered DGPS sea level with NOAA acoustic tide gauge data at Texaco's platform Harvest on 24 May 1995. The mean difference is -0.03 cm with a standard deviation of 0.7 cm.

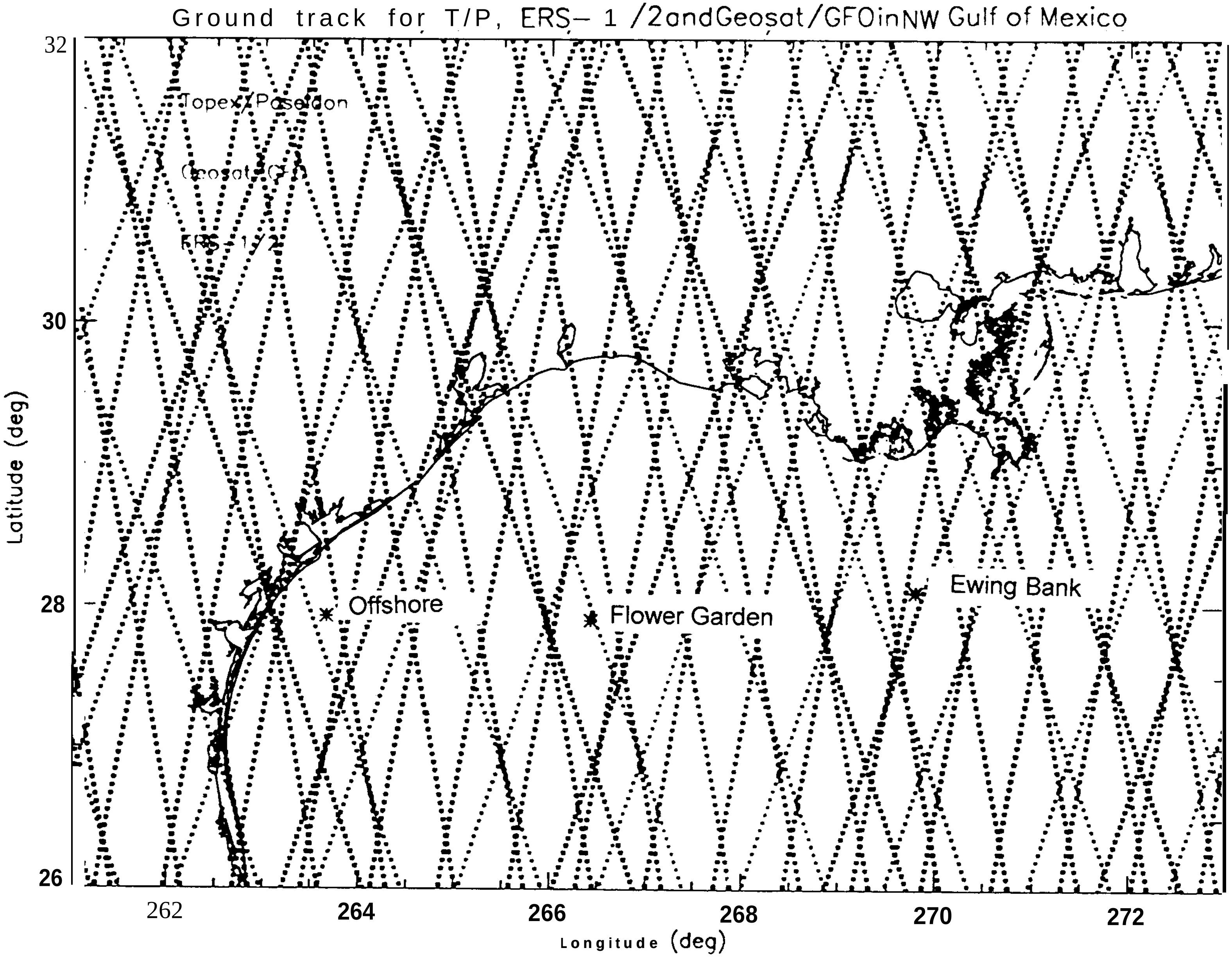


Figure 2: Ground tracks for ERS- 1/2, TOPEX/POSEIDON, and GFO-1 over the northwest Gulf of Mexico

orientation and motion. Sufficiently fine temporal sampling will then produce an estimate of wave heights.

To have widespread usefulness for the oceanographic and geodetic communities, DGPS techniques need to be demonstrated over much longer baselines. Much work also needs to be done to design buoys for specific applications and to make best use of limited power and communications. The intent of this paper is to describe some future experiments that we hope will explore the limitations of DGPS techniques and demonstrate further the usefulness of these measurements.

Planned Experiments:

As a beginning caveat, only part of what is described here is presently funded and so some of the research may change over time or not occur.

1) Satellite altimeter calibration:

This is perhaps the best demonstrated of the uses for DGPS buoys. The primary emphasis will be to conduct DGPS calibration measurements in conjunction with an experiment to establish a low cost permanent site in the Gulf of Mexico for multiple altimeter instrument calibration and verification. Figure 2 shows the three dominant ground tracks used by satellite altimeters. There are locations where all three ground tracks are nearly coincident. If a suitable platform near one of these sites can be located, it would be well suited for calibrating present and future planned satellite missions.

Other calibration sites are being considered. If cooperative arrangements can be made with coastal colleges and universities for local offshore calibration sites, then the latitude dependence of the altimeter error can be investigated. One of limitations of the Harvest/Lampedusa sites is that although they are well separated in longitude, they are close to the same latitude and so may be missing a latitudinal dependence to the altimeter error.

2) Aircraft altimeter calibration

Aircraft altimeter measurements are being developed as a means of measuring tides and sea level in boundary seas where due to the need for high spatial and temporal resolution, altimeter data is inadequate and conventional measurements logistically difficult and expensive. This is also a potential application for DGPS buoys as discussed later. Because DGPS measurements can be easily organized in any near shore environment, they are ideal for aircraft altimeter calibration.

3) DGPS accuracy versus distance

The troposphere provides the greatest limitation to DGPS accuracy as the baseline distance between the buoy and fiducial site increases, The degree of this limitation is not well known. Thus an experiment is planned late this year to piggyback on a Texas A&M cruise along a T/P ground track from Galveston Bay to the Yucatan Peninsula (the track heading southeast from Galveston Bay in Figure 2). It is planned that there will be fiducial sites on both ends of the track. The cruise will last about ten days. If possible, the ends of the cruise will be scheduled to correspond to T/P overflights,

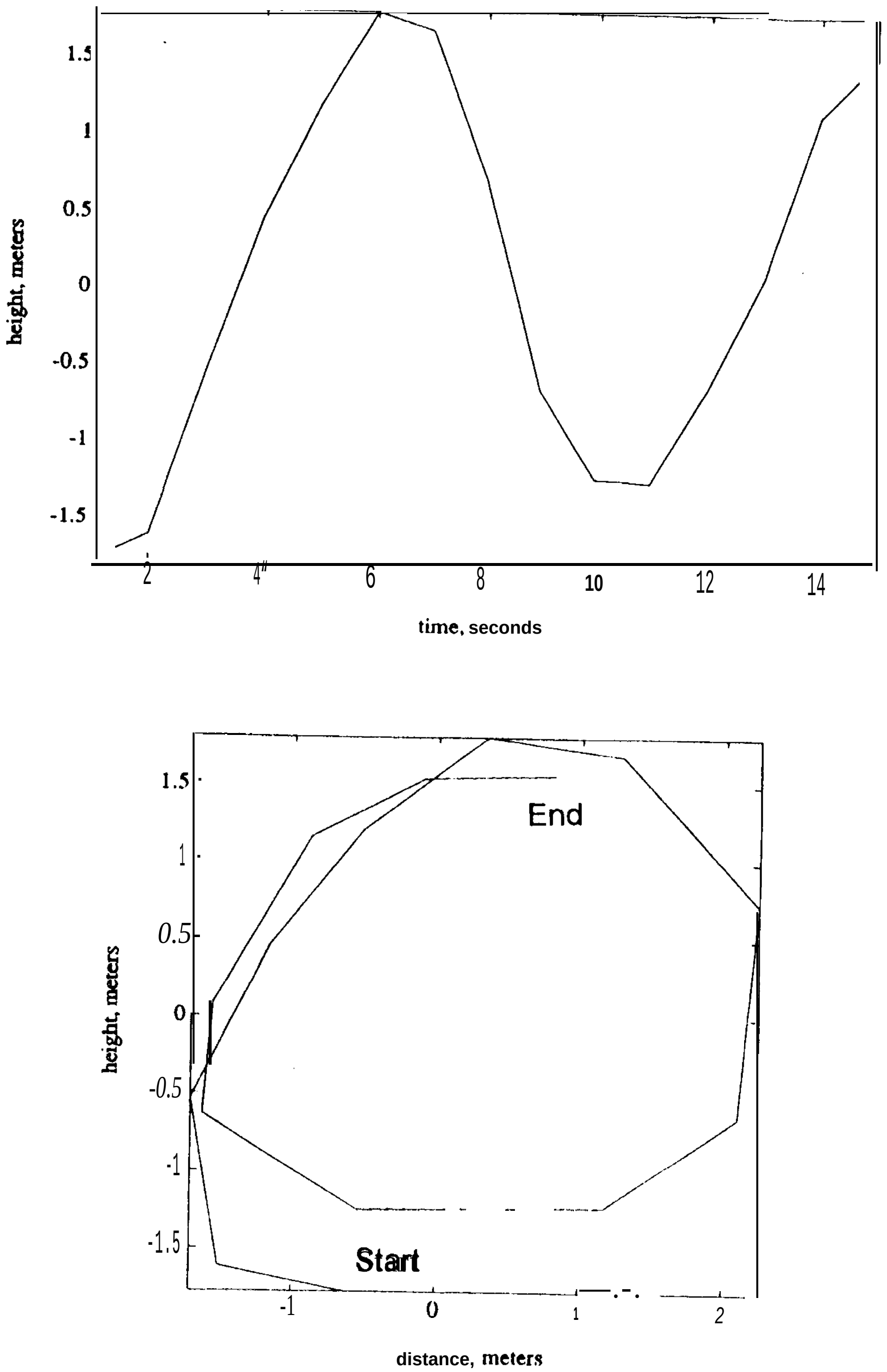


Figure 3: Top panel -once per second DGPS sea level for one wave period measured during the mapping exercise of Key et al., 1997. Bottom panel - vertical versus horizontal motions for the same period. A mean drift of the buoy has been removed and the coordinate system rotated to the direction of wave propagation.

thus providing two calibration estimates also. DGPS measurements will be taken periodically along the track, producing a sequence of measurements that are successively further from the first fiducial site and closer to the second. This experiment should provide the first practical experience with long baselines. It should demonstrate the ability to coordinate DGPS measurements with a conventional oceanographic cruise and the oceanographic value of taking such measurements.

4) Directional wave spectra from DGPS buoys

Figure 2 shows wave height versus time and the vertical buoy position for a floater buoy during one wave period. The data was taken from the mapping measurements of Key et al., 1997. A mean drift rate was subtracted from the horizontal position and the coordinate system rotated into the direction of wave propagation, A wave orbit consistent with classical theory can be seen. Thus it is clear that there is some information in DGPS measurements about directional wave spectra, not just wave heights. It is not at all clear what the limitations are. We are planning an experiment to use either a floater buoy or a tethered buoy (to be developed) along side of a wave spectra buoy to compare measurements. If sufficient information is available in the DGPS measurements, then we will work on development of a buoy specifically for this application.

5) Coastal and boundary sea oceanography

Oceanography in coastal waters and boundary seas involves relatively high frequencies and wavenumbers. We feel there is a role for DGPS measurements coordinated with conventional cruises and for measurements in areas that are logistically difficult for one reason or another. Four kinds of buoys should be useful for such experiments, tethered buoys, towable buoys, aircraft launched buoys, and floater buoys. Our plan is to develop several varieties of buoys for different purposes. We will investigate the addition of DGPS sea level to TABS buoys. TABS buoys have been developed by Texas A&M to provide ocean and meteorological data for the Navy and a number will be deployed in the Gulf of Mexico. We will also work on developing an aircraft deployed tethered buoy for use in boundary seas and a towable buoy that can be used for sea level mapping either for oceanographic or geodetic purposes

Discussion:

The sea level measurement by DGPS buoys is equivalent to the measurement produced by radar altimetry. When properly corrected, both produce an estimate of sea level in absolute coordinates which therefore includes contributions from the marine geoid, tides, and other oceanography. The oceanographic contributions include steric and dynamic height changes. While there are other methods for measuring these contributions, such as CTD measurements to determine water density and combining a bottom pressure gauge with an inverted echo sounder to look at time changes in sea level, each of these methods has limitations that are different from the DGPS limitations and there is a strong role for DGPS measurements in coordination with other oceanographic measurements.

DGPS measurements can be tied to many different platform designs if sufficient care is taken to monitor the relationship of the GPS antenna to sea level. The simple floater design discussed previously would be well suited to piggybacking on a cruise with periodic hydrographic stations. The only unknown limitation is how far from the fiducial site and under what atmospheric conditions can absolute accuracy be maintained, This will be investigated as part of the Gulf of Mexico cruise described above. Other buoy designs might include towable buoys for mapping experiments and ships of opportunity, drifting DGPS buoys, tethered buoys, and aircraft launched buoys.

DGPS sea level measurements can provide absolute sea level measurements over length and time scales that are impossible to achieve with satellite altimetry and thereforewould have a meaningful role that could be played in regional oceanographic experiments such as mapping coastal sea level variations due to tides, currents, jets, fronts, and eddies. In sufficiently inactive waters, DGPS can also be used for experiments to map the marine geoid and infer gravity depending on how many measurements are taken and the nature of the local oceanography.

It has been shown by various experimenters that DGPS can provide accurate absolute sea level positioning from a wide variety of buoy designs over relatively short baselines. To be routinely useful for oceanographic research, accuracy over longer baselines needs to be demonstrated. Processing of sea level and wave statistics needs to become more routine for many applications. Development of buoy designs for many applications has yet to be done. There is a lot of progress that needs to be made before DGPS can be a routine part of oceanographic measurements but the future looks bright and we are looking forward to great progress over the next decade.

References:
Born, G. H., M.E. Parke, P, Axelrad, K.L. Gold, J. Johnson, K.W. Key, and D. Kubitschek, Calibration of the TOPEX altimeter using a GPS buoy, JGR, 99(C1 2), 24517-24526, 1994.

Blomenhofer, H. and G.W. Hein, Calibrating the TOPEX/POSEIDON altimeter using DGPS in buoys, paper presented at Third International Conference on Differential Satellite Navigation Systems, Royal Inst. of Navigation, London, April 18-22, 1994.

Hein, G. W., H. Landau, and H. Blomenhofer, Determination of instantaneous sea surface, wave heights and ocean currents using satellite observations of the Global Positioning System, Marine Geodesy, 14, 217-224, 1990.

Kelecy, T. M., G.H. Born, M.E. Parke, and C. Rocken, Precise mean sea level measurements using the Global Positioning System, JGR, 99(C4), 7951-7959, 1994.

Key, K.W, M.E. Parke, and G.H. Born, Mapping the sea surface using a GPS buoy, accepted by Marine Geodesy, 1997.

Schutz, B. E., G.L.H. Kruizinga, D. Kuang, P.A.M. Abusali, C.K. Shum, R. Gutierrez, S. Nelson, E. Rodriquez, Galveston Bay experiment for altimeter calibration, presented at the Western Pacific Geophysics Meeting, Brisbane, Australia, 1996.

Shannon, B and D, Martin, Kinematic GPS observations to estimate a mean lower low water dredging datum directly in a navigation channel, ASPRS/ACSM annual convention and exhibition, vol. 2, GIS and GPS, Bait. MD, Apr 22-25, 1996.

BIFROST PROJECT: THREE YEARS OF CONTINUOUS GPS OBSERVATIONS

Jan M. Johansson[1] Hans-Georg Scherneck[1] Martin Vermeer[2]
Hannu Koivula[2] Markku Poutanen[2] James L. Davis[3]
Jerry X. Mitrovica[4]

August 13, 1997

ABSTRACT

We describe the operations within SWEPOS with geophysical purpose to detect crustal motions in Fennoscandia. For this purpose a project named HIFROST was created; BIFROST stands for Baseline Inferences for Fennoscandian Rebound Observations, Sea-level and Tectonics. We show solutions of site positions obtained from 1000 days of operation of SWEPOS. We determine their variations in time, discerning them from plate or frame orientation, and discuss a number of perturbation effects, First results are presented, indicating movements which generally support the notion of a dominating displacement pattern due to the postglacial rebound of Fennoscandia. However, deviations exist. In order to discern regional movements of a presumably tectonic origin the coverage of the region must be extended, both concerning the areas that neighbor Sweden and array densification within the country. We foresee observing operat ions of at least ten years if deformation rates of 0.1 mm/ yr are to be concluded at a 95 percent confidence level.

BACKGROUND

The BIFROST project defines a study program on Baseline Inferences For Rebound Observations, Sea Level, and Tectonics. As a response the DOSE proposal of NASA at the beginning of this decade, the capabilities of GPS-based space geodesy were proposed to discern movements of surfaces in the course of postglacial rebound with

---

[1] *Onsala Space Observatory, Chalmers University of Technology, S-439 92 ONSALA, Sweden phone +46 31 7725500, fax +46 31 7725590, corresponding author: Johansson, e-mail: jmj@oso.chalmers.se*

[2] *Finnish Geodetic Institute, FIN-02431 Masala*

[3] Harvard Smithsonian Center for Astrophysics, Cambridge, MA 02138

[4] *Physics Dept., Univ. of Toronto, Ont., Canada*

bearing on climatic change, It was realized that only space techniques are able to separate vertical crustal movement from changes of the sea level and the geoid, The space-based methods have also been recognized as sufficiently sensitive to resolve horizontal deformation expected in the course of the glacially induced isostatic rebound at rates of millimeters per year over distances between ten and several thousand kilometers [*BIFROST Project,* 1996].

in this report we empasize the goal to discriminate vertical motion due to the crust from vertical motion of the reference surface and a remaining, largely constant global sea surface term.

BIFROST processing of continuous GPS observations at permanent stations utilizes the regional networks that where established beginning in 1993. They comprise the SWEPOS array in Sweden and the FinnNet array in Finland. Permanent stations also exist within the SATREF network of Norway, but for the present study we have not been able to include their data in the standard solutions (cf. Fig. 1).

In the analysis data observed in and obtained from the IGS network are processed together with the regional data for the purpose of obtaining constraints for mapping the solutions into the international reference frame. Thus, it is possible to arrive at single-site positions and rates rather than baseline vectors.

In BIFROST collocation and ties between permanent GPS and tide gauges are maintained by campaigns, typically one every year or every second year, cf. Table 1. Regarding the permanent array as a backbone network, realizing that the largest distance between a Scandinavian (Swedish Finnish Russian) tide gauge and a GPS station in the area of the uplift is less than 100 km, the accuracy of the tie is at a level comparable to what could be extrapolated from the permanent array. The internal consistency of the tide gauge results, which encompass typically on the order of 100 years of data, is at a level below 0.5 mm/yr which does not suggest that tectonic motion on a regional scale to be an important origin of vertical motion (difference after fitting a low order polyonmial to the data of *Ekman* [1996].

The noise in tide gauge observations and the precision with which sea level rates can be determined (0.1 mm/yr from 100 yr observation duration) hint at a required GPS precision for vertical rate determination of 3 mm/yr to achieve consistent noise levels assuming 10 years of simultaneity (project lifetime). That GPS precision can be accomplished in annual campaigns assuming the precision rule of *Coates et al.* [1985]!

DATA FLOW IN SWEPOS

Since November 1, 1994 the National Land Survey (NLS) hosts the operational centre of SWEPOS, responsible for the downloading, RINEX-conversion, and archiving of data from the SWEPOS sites. Data sampling rate is 15 s and the elevation cutoff level is 4° or 5° in the TurboRogue or Ashtech case, respectively. The PC which connects to the TurboRogue (Ashtech) receivers' RS232 port serves as a backup storage with a capacity of 180 (500) Mbyte of disk memory. Storage operations to the PC's are performed several times per day. A total of four weeks worth of data will fit on the disk. In the case of the TurboRogue, four days worth of data is kept in the internal memory.

To offload the data the site is dialed up from the control centre in an automated process. One day's load of data is transferred at a time, 2.5 Mbyte in compressed form, through a 19,200 baud high-speed modem, consisting of the following data types: Pseudorange measurements from C/A-code and from the P-code on both L1 and L2 frequencies; carrier phase observations on L1 and L2; Doppler frequency observations; and satellite broadcast ephemeris.

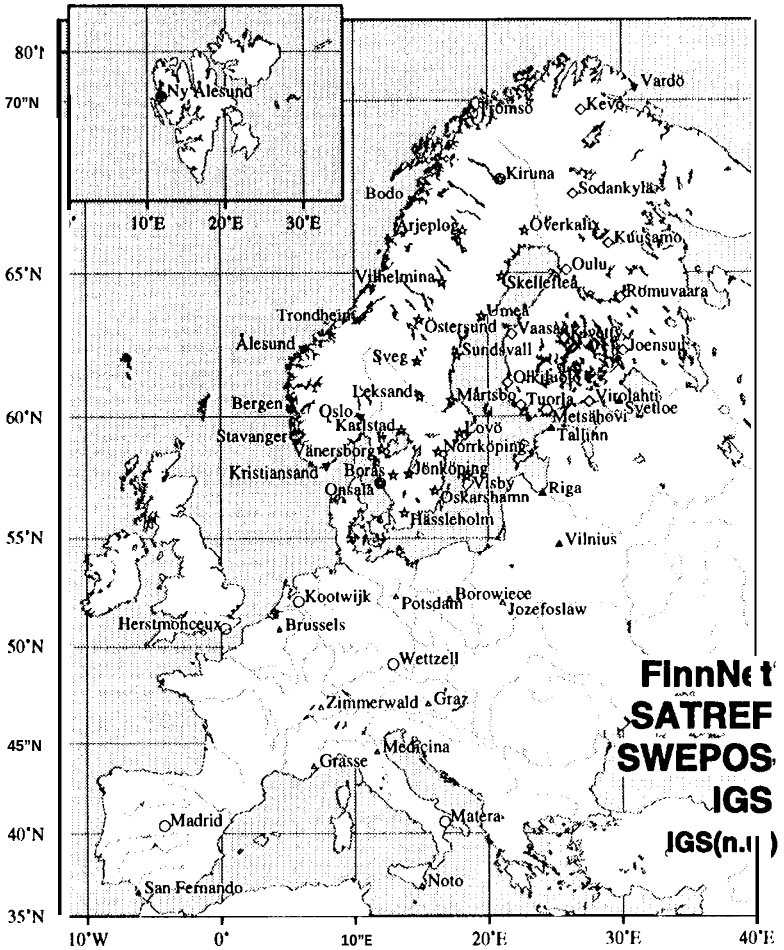


Figure 1: Permanent GPS Stations in the area of Fennoscandia and Baltic and the European IGS sites regularly included ("n. i." - not included) in the solutions derived for the BIFROST project

The Onsala Space Observatory keeps an independent archive, obtaining the data mostly from the NLS operational center via the INTERNET. Prior to this date, and eventually in the case of problems, data have been downloaded to OSO from the SWEPOS stations directly.

A subset of the the SWEPOS stations together with a selection of SATREF (Norway) and other stations from the Baltic states, Greenland, and Iceland, are analyzed at the NKG (Nordic. Geodetic Commission) Local Analysis Centre at Onsala Space Observatory as an effort for the European Reference Frame (EUREF).

Table 1: BIFROST GPS determinations of tide gauges

	1993	1994	1995	1996	1997
Smögen		x			x
Klagshamn	x	x			x
Kungsholmsfort	x	x			x
Öland S.	x	x			x
Visby hamn	x	x			x
Kastellholmen	x	x			x
Spikarna	x	x		x	x
Ratan	x	x		x	x
Furuögrund	x	x		x	x
Kalix Storö		x	x	x	

FINNNET - THE FINNISH PERMANENT GPS NETWORK

The **Finnish Geodetic institute** (FGI) is maintaining the Finnish permanent GPS-network, FinnNet, comprising of 12 GPS-stations. Most sites are established with a 2.5 m tall steel grid tower for the GPS antenna. Beneath the tower is a hut housing the Ashtech Z-12 geodetic GPS receiver. The data is transferred by modem and a dial-up telephone line to the databank at the FGI. Subsets of the data are distributed to international data archives via Internet. The stations at Joensuu, Metsähovi, Sodankylä, and Vaasa are also members of the EUREF permanent network.

IGS

Data from the IGS of satellite observations incorporated into the standard solution concerns the following sites: Tromsö and Ny Ålesund (Norway), Metsähovi (Finland), Herstmonceux (UK), Kootwijk (Holland), Madrid (Spain), Matera (Italy), Wettzell (Germany). This data is acquired regularly via Internet.

Ancillary data bases specifying the reference sites setup, local ties between monuments etc. are also provided in the IGS archives.

SOLVING GEODETIC PARAMETERS

The dual-frequency GPS phase and pseudorange data are processed at the OSO regional processing center using the 2nd release of GIPSY software developed at Jet Propulsion laboratory (JPL) [e.g., *Webb and Zumberge* 1993, and references therein]. Selected periods of the SWEPOS data are also processed using the Bernese Software ver. 4.0 [*Rothacher et al.,* 1996]. This redundant procedure may reveal erroneous data. and possible modeling discrepancies,

The data from about 40 continuously operating GPS stations reprocessed. All processing is pm-formed automatically, i.e., noninteractively. For the standard data analysis an elevation cutoff-angle of 15°is used for all sites giving the lowest uncertainties in the estimation of horizontal and vertical baseline components [*Jaldehag et al.*, 1996].

improved satellite orbits and earth orientation parameters are readily available from the IGS processing centers. For the our standard analysis we have adopted a weighted combination of the estimated orbits from the seven analysis centers. The combined IGS products are available within less than one month after data collection. With the present distribution of tracking stations, models, and processing techniques, the accuracy of the IGS orbit determination is known to be approximately 10 centimeter, or better. In the standard BIFROST analysis we adopt the combined IGS products and no further estimations of satellite orbits nor earth orientation parameters are carried out.

Data processing utilizes a regional "no-fiducial" technique wherein the coordinates of site position have only weak a priori constraints. The coordinates of the sites are estimated as bias terms with a priori uncertainties of 10 m (IGS sites with well determined coordinates) or 1 km (regional sites). Constraints are thereafter applied to transfer the results into a terrestrial reference frame,

The zenith values, one for each site, of the propagation delay due to water vapor (often referred to as the wet delay) are estimated as random walk bias terms. The signal propagation delay due to the other constituents of the neutral atmosphere, is calculated based on a standard atmosphere and the latitude and height of the site. This parameter, normally referred to as the dry delay, is not further estimated in the analysis,

The parameters estimated in the standard analysis are:

- stations clocks (white noise parameter)
- satellite clocks (white noise parameter)
- phase ambiguities (white noise parameter)
- stations coordinates (constant bias)
- tropospheric delay (random walk parameter)
- ionospheric delay (calculated from dual frequency observations)

Tides, earth orientation parameters and satellite positions are acquired from e.g. the IGS and not further estimated. However, at the postprocessing stage also these parameters are investigated.

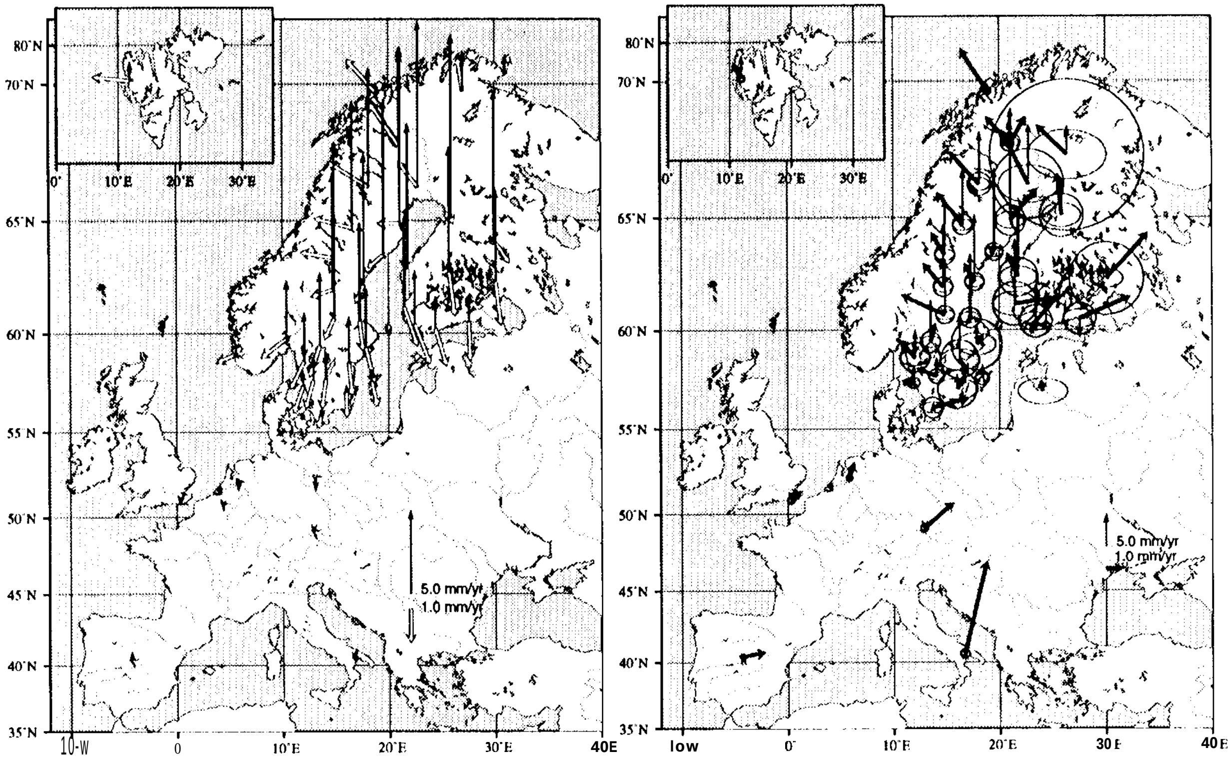


Figure 2: Modelling results (left) and observations (right) in the form of vectors of motion, Horizontal motion is shown as wide vectors, vertical as narrow vectors pointing up.

RESULTS FROM THREE YEARS OF OPERATION

As of current, more than there years of SWEPOS operation and daily analyses of SWEPOS data and within the BIFROST project have resulted in a large number of repeated independent determinations of positions and baseline variations. BIFROST stands for Baseline Inferences for Fennoscandian Rebound Observations, Sea-level and Tectonics. The main final products from the analyses are

- estimates of site positions and variance/covariance between the estimates in the ITRF geocentric reference frame;
- estimates of baseline components between the sites and variance/covariance between the estimates.
- estimates of the tropospheric delay parameters for each site.

For item 2 a reference solution is selected. The differences of successive site position determinations are then displayed in e.g., local coordinates North, East, Vertical.

SITE MOTION ANALYSIS

The following items can be addressed and conclusions, although still preliminary, can be expected: Can rates of change of site position rather than baseline components be estimated, or, conversely, is the degree of covariance of SWEPOS and IGS site positions in the daily solution so great that useful information can only be extracted from differential movement, i .e.,. baseline determinations ? Second, does an assessment of site position evolution confirm expectations on monument stability or, conversely, do we find signatures of random walk as proposed in *Johnson and Agnew [1* 995] ?

PERTURBING EFFECTS ON SITE POSITIONS

While a permanent network has a number of advantages, primarily that antennas remain in the same place, and while continuous operation and data processing provides an excellent statistical basis for analysis, certain limitations exist, which require solutions or awareness. This has consequences also in the final stages of data analysis and interpretation.

If tile permanent network is simultaneously used as a geodetic reference network, additional requirements arise. The specification of absolute position, which is more difficult in vertical component due to geometric dilution, must be as neutral as possible with respect to equipment used in e.g.,. high definition land surveys. Some trade-ofr of performance for a pure crustal deformation purpose is inevitable.

Unattended stations in remote, cold areas are exposed to the problem of snow and ice deposition on the antenna itself or on protection surfaces [*Jaldehag et al.,* 1996a]. Radomes are necessary to cover and protect the antenna assembl y, imp] ying consequences for both snow and ice deposition and antenna receiving conditions. The problem turned out to be nontrivial. In the long term, a sacrifice on the data available for the analysis might be more worthwhile to accept than overloading the project with complicated safeguard measures.

Inhomogeneous antenna diagrams may occur due partly to scattering off objects in the immediate environment (parts of the mounting assembly, pillar) and nearby surfaces (roofs, trees), but clue also to elevation angle dependent transmission properties of e.g.,. antenna radomes. The effects of these antenna heterogeneity patterns are s ystemat ic offsets of the phase cent re from the nominal reference point, varying with the observation angles. Errors can occur in the range of tens of millimeters [*Elósegui et al., 1995].* For applications aiming to determine changes in position this may become negligible if the distribution of satellite viewing angles can be considered invariable. The serious implication is that a decision on a certain elevation cutoff angle cannot be revised after some years into the project as reprocessing of the data accumulated thus far will become more and more infeasible.

The final choice of radome, to be implemented during autumn 1996, emphasizes a more uniform antenna diagram, trading-off' data quality in the case of observations taken under snow; they may have to be discarded. The temporal pattern is easy to identify on the basis of the observations themselves, but also more sophisticated

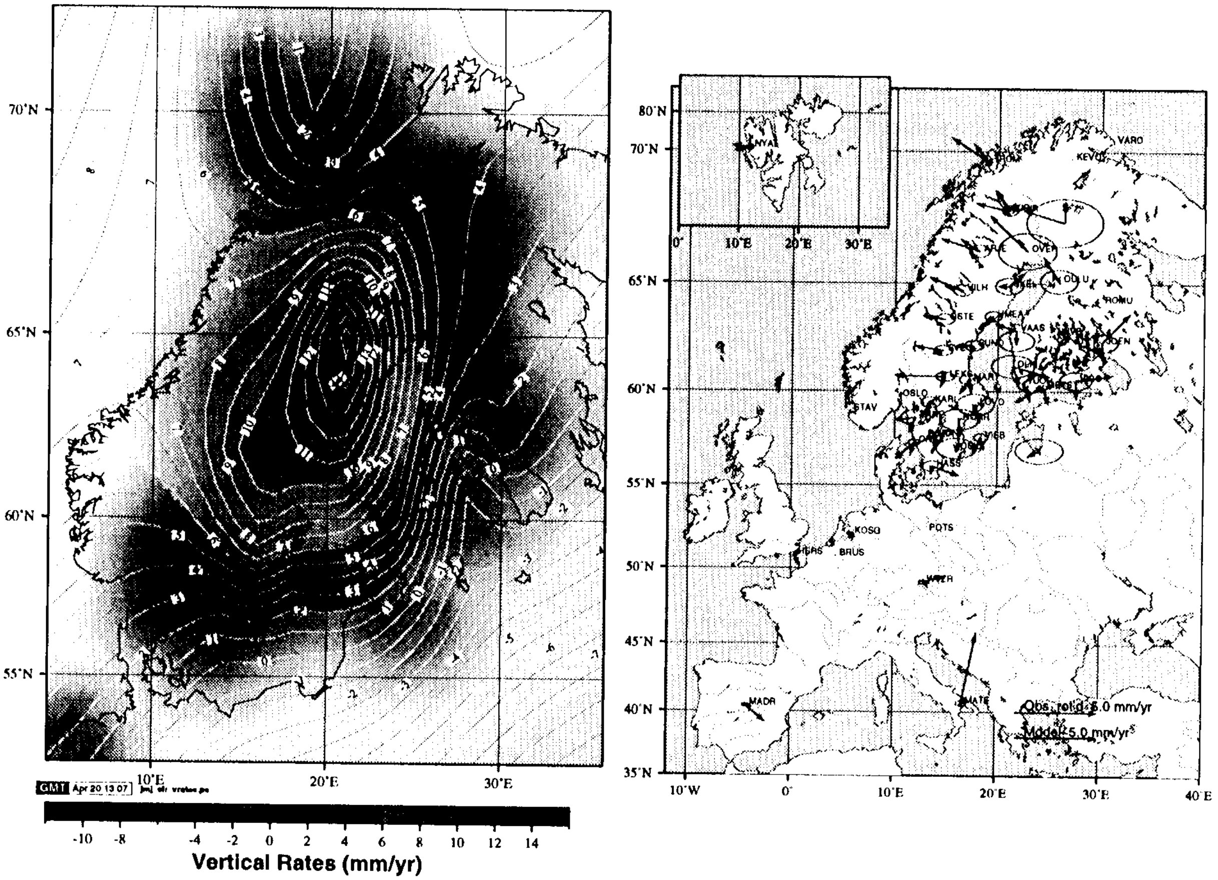


Figure 3: Left frame shows a contour plot of vertical rate estimates based on more than 1000 days of BIFROST GPS operation and data analysis. About 50 stations are regularly included in the BIFROST GPS solutions. Outside Sweden, observations at reference stations of the network of the other nordic countries and of the International GPS Service (IGS) are included. The right frame shows the horizontal rate estimates operations, uncertainties are 0.5 (0.7) mm/yr in the horizontal (vertical) except at the sites in Finland which have larger errors due less data analyzed. Also shown are the predicted motions from a geophysical model described by Mitrovica et al., 1994].

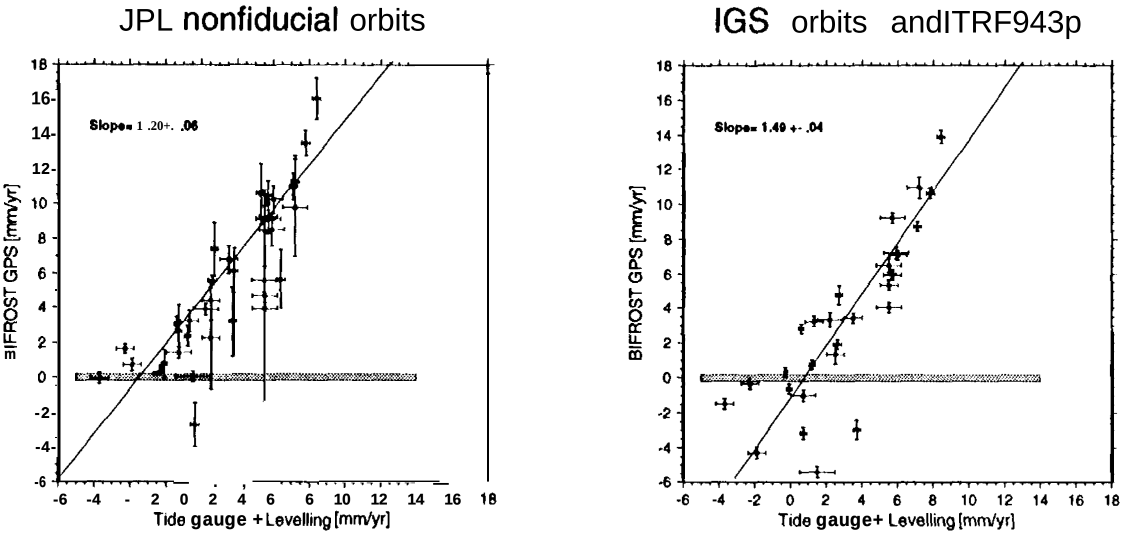


***Figure 4*:** GPS vertical crustal rates from SWEPOS analysis versus rates of land emergence determined by Ekman (1995) using Mareograph and Precise Levelling data. Nonfiducial orbits (left frame) and IGS orbits (right frame). A line of regression (solid) is fit considering one sigma limits in both data types. The results with the IGS arc mapped into a frame that follows the geocentric rotation of the ITRF94 sites but suppresses their vertical motion.

rejection criteria based on local meteorological data appear feasible. The level of these perturbations may reach several centimeters [*Jaldehag et al.,* 1996a].

ANALYSIS OF GPS SITE POSITION SOLUTIONS

For the time being we determine preliminary results of site position rates by simultaneous least-squares fit of

- a box car train, i.e.,. bias terms that allow discontinuity of site position at known instances
- one slope for the whole scope of each site position component, conceptually representing the motion
- annual, semi-, ter-, and quater-annual sinusoids and cosinusoids that absorb some of the climatic problems, of which snow effects are the most important group.

The climatic signatures regularize the data to some degree. However, a fit is only reasonable if the box car sections are long enough to yield acceptable levels of parameter correlation, 'This is the case if the data spans more than one year, Signal separation has maximum impact if the data coverage (including the effects of variable data weights) is heterogeneous. The data to which the model is fitted consists of the post-processed time series of site position estimates, separately component by component and site by site.

GPS post-processing starts with the nonfiducial gipsy solutions; they are first projected into a reference frame (for instance the ITRF94) performing a free network adjustment with respect to the IGS sites that participated in the GPS analysis. At present wc compare two different sets of gipsy solutions: Using IGS orbits or fiducial orbits [*Zumbergc et al., 1997];* they give slightly different results.

At this stage the site position series contain the motions of the tectonic plates and the discrepancies of the motions at the stations used to maintain the reference frame. Therefore, as the last step the site motion is transformed (‘(mapped”) as if viewed from a rigid, co-moving plate. Here, there are several options for construction of the co-moving frame. Most simply one could use the tectonic motions of the plate model (rotations around the geocentre). Second, one can construct a rigid frame that moves with the ITRF (ln the case of the nonfiducial orbits, the JPL site data base is used instead of the ITRF for internal consistency). Using a six parameter transform, the movement contains a rotational and a translational part, Most obviously, the set of European ITRF sites is seen to have a nonzero motion component along the mean radius vector, This motion implies a bias in the estimated vertical rates,

If we estimate only three frame rotation parameters, a frame is achieved that rotates together with the ITRF sites but avoids the radial motion. If the geocentre could bc determined exactly, than this system would be most suitable as it avoids rebound signatures at the tracking stations to bc absorbed in the frame. It also makes the frame motion less susceptible to tilting.

By the same token the scale factor of the frame is kept fixed since the rebound area undergoes area] strain, and we wish to preserve this component of the deformation in the station data.

in the ITRF option, one important modification of the rigid frame motion is needed in order to avoid another bias in the rate determination: The GPS orbits prior to July 1, 1995, relate to the ITRF93N frame. Thus, we *add* the differential motion of the new versus the old frame to the site positions of prior to this date. The difference amounts to r x w = [2.31, -1.09, 0.08] mm/yr.

RESULTS AND DISCUSSION

RATE ESTIMATES

Displaying the site position rates on one map (Figure 2) we show the results in the form of motion vectors together with their 95 percent confidence limits. This figure comprises more than 1000 daily SWEPOS solutions. The results confirm largely the pattern predicted by e.g., *Mitrovica et al.* [1 994]. The left frame in Figure 2 shows predicted rates using the ICE-3G model of *Tushingham and Peltier [1* 991] and an Earth structure with a lithosphere 120 km thick, and upper and lower mantle viscosity of 1 x 10^{21} and 2 x 102] ,respectively.

We notice, however, that one of the stations in the central uplift area has a much larger vertical rate. Also, the observed horizontal rates appear greater than the predictions by about a factor of two. However, conclusions at this stage would be highly preliminary. Considering an expected lifetime of the project of ten years, quantitative comparison with the large number of modelling results and attempts of parameter inversion are kept for the future.

We have excluded stations where the amount of data and the total time span are small. Due to the radome changes the introduction of jumps yields a nonnegligible degree of correlation between biases and rates. Also, the seasonal signatures cannot be reduced if the length of data branches is less than one year lest one is to accept large correlation with the estimated rate.

Allowing for a non-geocentric rotation, the Up component of the Onsala-Wettzell baseline rate, for instance, changes by -0.6 mm/yr, and the Up-component of the Hässleholm-Umeå baseline by -0.1 mm /yr. The Onsala-Wettzell result shows a frame tilt in the opposite sense of the tilt that would be expected according to postglacial uplift. In this particular frame we use eight European IGS stations. If the number of frame sites are reduced to three (Onsala, Madrid, Wettzell), the frame absorbs almost all relative vertical motion; the up rate of the Onsala-Wettzell baseline becomes 0.6 ±1 mm/yr. These dependencies together with the aim to resolve vertical rates unbiased with respect to the frame suggested us to use only the subset of motion that carries along the spherical shell, and which is representative of observed tectonic plate motion.

COMPARISON WITH TIDE GAUGE AND LEVELLING DATA

In Figure 4 we show the vertical rates determined at fifteen SWEPOS, four FinnNet and two IGS sites versus the results from mareograph analysis and geodetic levelling (Ekman, 1996). This data type will be denoted ML, henceforth. At Ny Ålesund we use the revised estimate of Breuer and Wolf (1995). The ML data for the two IGS sites have been taken from the vertical projection of the rates given in the ITRF94. In the left diagram we show the GPS results based on the nonfiducial orbits while in the right diagram a pure-rotation co-moving frame has been aligned with the ITRF94 sites, The rates of change of the ML data represent relative land uplift. in the central uplift area it is less then the vertical motion of the crust by an amount corresponding to the rebound of the geoid. The rate uncertainty dots not yet allow to resolve details of the interrelation, specifically the long-wavelength enhancement of the geoid change as compared with the solid surface. Therefore, a straight line fit will do. We find a ML rate retardation of 29 percent. This appears large compared to even extreme models. Quite on the opposite side of the scale, Ekman and Mäkinen (1996) propose a value of only on the order of 5 percent.

In comparison with the ML rates, the GPS rates at Skellefteå and Vänersborg appear anomalous, causing the slope of GPS versus ML to steepen. When we reprocess the GPS data fit without modelling the annual and sub-annual oscillations, the rate estimate of Skellefteå increases by 2 mm/yr while that of Vänersborg increases

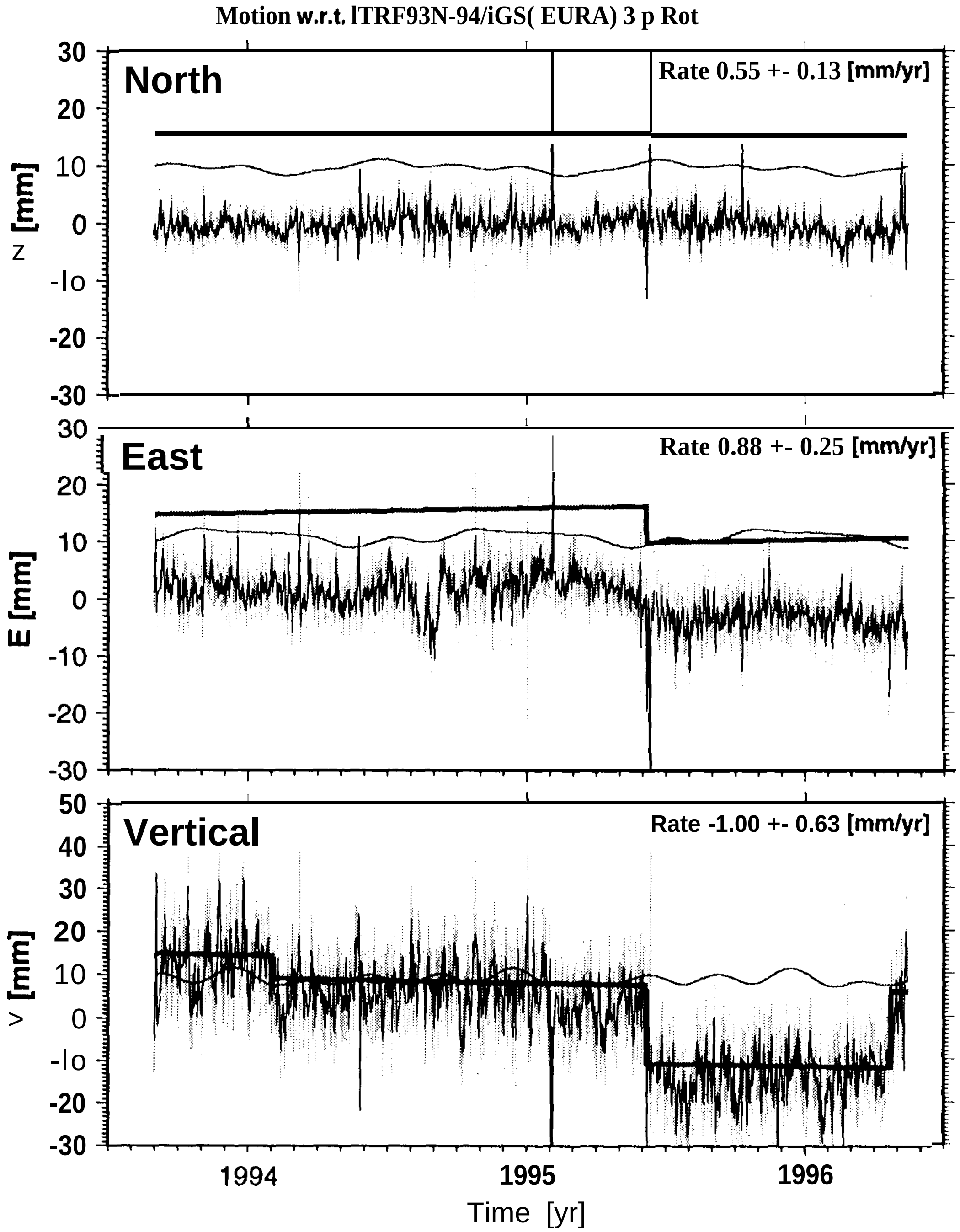


Figure 5: Single site solution, Hässleholm. Results from daily solutions are shown as the noisy thin line on a grey background signifying the 95% confidence limit. The positions are shown after free network adjustment and alignment with a rigid frame that corotates with the the European subset of the ITRF94.

Another set of rotation parameters applies for the time before July 1, 1995, to account for the relative motion of the GPS orbits as they related to the predecessor ITRF93N frame. (Continued below Fig. 6) by 1 mm/yr. Both stations have less data---they came online in April and June, respectively, and the estimates of offsets, rates, and sinusoids have still a high degree of correlation. Thus, we expect a future result to settle at a slope which is closer to unity, unless Skellefteå continues to be affected by a local problem. Considering the short distance between Skellefteå and Umeå, and even more so between the GPS station and the Furuögrund tide gauge, on which the MI, estimate is based, the possibility to find an explanation within the realm of glacial rebound theory and ice load is unlikely. Most probably, the effect of the radome change is overestimated,

The intercept of the regression line at zero crustal rate, diminished by the geoid rate at that node, would under ideal circumstances indicate the amount of land emergence independent of glacial isostasy. The geoid rate at the node can be assumed to be less than 0.1 mm/yr. Assuming the latter term to be negligible, our estimate of the nonisostatic water level rate is 1.4±0.3 mm/yr. From global sea level studies *Douglas [1991]* inferred +2 mm/yr for the North Sea.

Discussing the solutions with the IGS orbits, we concentrate on the problem of the vertical rates estimated by GPS probably being offset by a translation of the ITRF94 with respect to the geocentre (more accuratly: the subset of ITRF sites used in the projection of the solution). Most prominently we find a much higher geoid admittances (near 50 percent). This value is under all circumstances unrealistic and relates most probably to a north-south tilt of the reference frame. In the case where we suppress the translation, the sea level rate estimate becomes -1,4 ±0.3 mm/yr, i.e.,. our finding has the opposite sign compared to *Douglas [1 991]*. If only the coastal sites in Fennoscandia are included, i.e.,. if we restrict the comparison to mareographs and GPS, we determine the intercept at -1,1 ±0.3 mm/yr and the slope to be 1.29±0.06. In this reduced set the influence of the high Skellefteå GPS rate is strong. In all, remaining systematic errors, including a weakness in the realization of the geocentre is the probable cause of the inverse sea level signature.

If we relate our results to the full velocity field of ITRF94, then e.g. Onsala obtains an additional vertical rate of 1.2 mm/yr. This is the effect of the common, translational mode affecting the European sites in the ITRF94 catalogue mentioned above (seen in similar, but more scattered values also in the ITRF93) [*Boucher et al.,* 1996, *Boucher et al.,* 1994]. The intercept point is found at -1 mm/yr (land emergence) equal to 1 mm/yr sea level rise.

At the centre of the network the common translation mode corresponds with an average vertical motion of roughly -3 mm/yr superimposed on the postglacial rebound. That is, at Onsala for instance the ITRF94 specifies a **subsidence** of 1.2 mm/yr while postglacial rebound would suggest a rise of 0.86 mm/yr. Likewise, at Wettzell (Tromsø) ITRF94 specifies -4.0 mm/yr (-0.4 mm/yr) while postglacial rebound models would reconcile with rates of -0.1 (+0.5) mm/yr

We must not forget that the purpose of the analysis is the determination of motion of rigid surface independent of geoid or mean sea level, If the GPS orbits distributed by IGS would not be affected by this Europe-wide rate of the ITRF94, then a rigid frame with the vertically reduced motion (i .e. pure geocentric rotation) would be a more stable frame than a frame moving together with the regional reference sites in

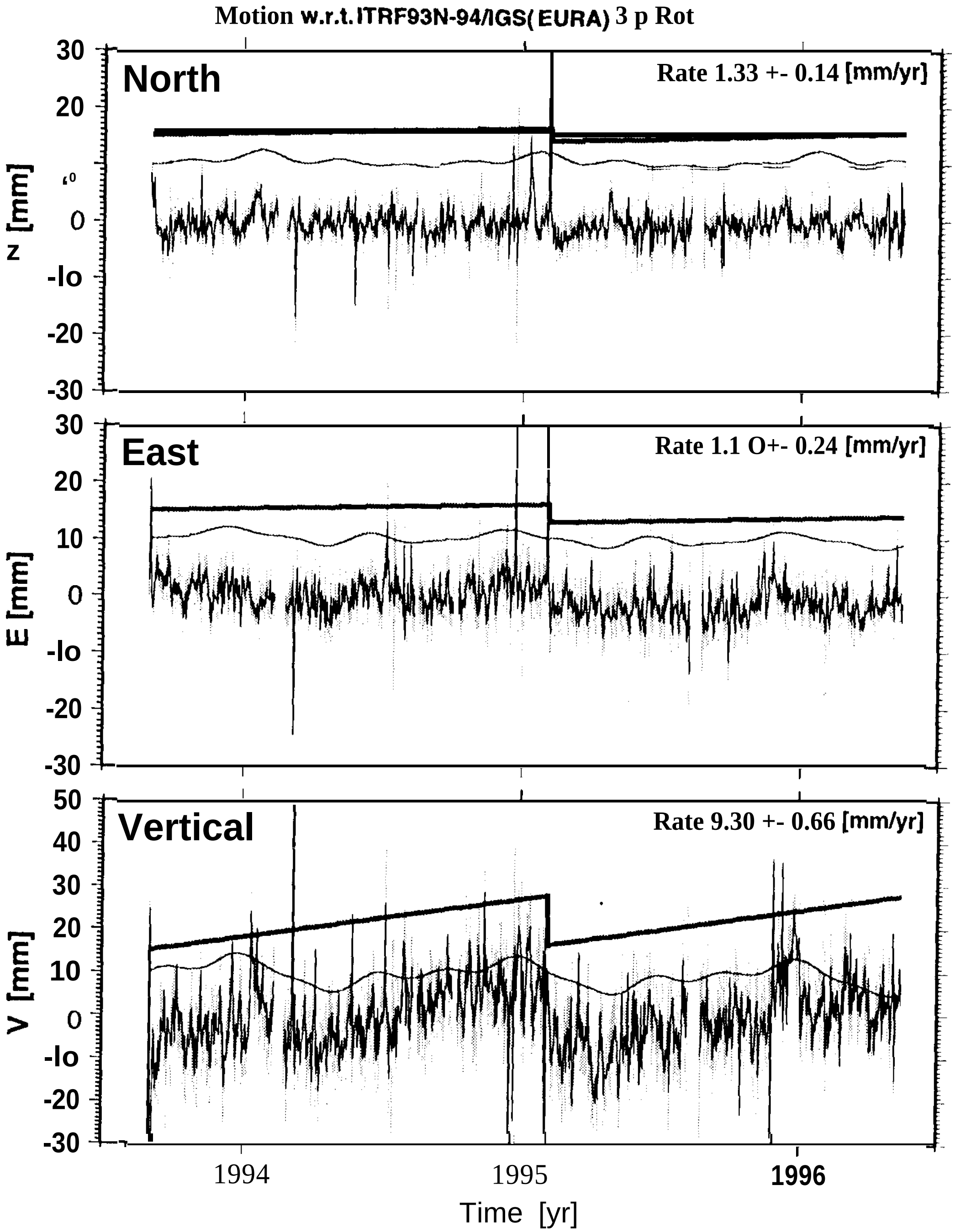


Figure 6: Single site solution, like in Fig. 5, for Umeå, however. (Cent'd from previous figure:)

Station model least-squares fit assumes for each component a constant linear rate. Additional systematic features that are included in the model are position offsets. Their start and stop times are defined from known changes of the antenna mount or radome replacements. Slope and off'set terms are combined in the thick line. Seasonal oscillations included in the fit are shown as a thin, wiggling line.

all respects.

If we assume a global sea level rise and in particular the North Sea value of *Douglas* [1991] to be more realistic than a drop, the comparison of the two ITRF94 based solutions show that the IGS orbits over northern Europe follow with the geocentric motion of the European tracking stations; therefore, the six-parameter frame yields more internally consistent results despite the vertical motion of Wettzell, Onsala, and Tromsø is probably strongly biased. In summary the result on the nonisostatic water level rate from the comparison of tide gauges and GPS is very much dependent on the determination of the geocentre.

The discussion suggests for the future that we rather advocate the use of nonfiducial orbits, leading to site position solutions that can be constrained to a geocentre that is maintained in separate, multi-agency multi-technique efforts.

ACKNOWLEDGEMENT

We would especially like to thank our colleagues in the geogroup at Onsala Space Observatory and at the Finnish Geodetic Institute. We also want to extend out appreciation to the National Land Survey of Sweden, and the BIFROST group for valuable contributions to the manuscript and to the project. This research was in part supported by the EC Environment and Climate Research Programme, the Swedish Natural Research Council, and the Swedish National Space Board. We have used GMT graphics software from *Wessel and Smith* [1995].

REFERENCES

BIFROST Project, Bennett, R.A., Carlsson, T.R., Carlsson, T. M., Chen, R., Davis, J. L., Ekman, M., Elgered, G., Elósegui, P., Hedling, G., Jaldehag, R.T.K., Jarlemark, P. O. J., Johansson, J. M., Jonsson, B., Kakkuri, J., Koivula, H., Milne, G. A., Mitrovica, J.X., Nilsson, B.I., Ollikainen, M., Paunonen, M., Poutanen, M., Pysklywec, R.N., Rönnäng, B.O., Scherneck, H.-G., Shapiro, I.I., and Vermeer, M., 1996. GPS measurements to constrain geodynamic processes in Fennoscandia, *EOS Trans. American Geophys. Union,* 77, p.337+339.

Boucher, C., Altamimi, Z., and Duhem, L., *Results and Analysis of the ITRF93*, IERS Technical Note 18, Observatoire de Paris, 313pp, 1994.

Boucher, C., Altamimi, Z., Feissel, M., and Sillard, P., *Results and Analysis of the ITRF94*, IERS Technical Note 20, Observatoire de Paris, 157pp, 1996.

Breuer, D., and Wolf, D., 1995, Deglacial land emergence and lateral upper-mantle heterogeneity in the Svalbard archipelago---1. First results for simple load models, *Geophys. J. Int.,* 121, 775-788.

Coates, R. J., Frey, H., Mead, G.D., and Bosworth, J. M., 1985. Space-age geodesy: The NASA Crustal Dynamics Project, *IEEE Trans. Geosci. Remote Sensing,* GE-23, 360-368.

Douglas, B. C., 1991. Global Sea Level Rise, *J. Geophys. Res.,* 96, 6981-6992.

Ekman, M., 1996. A consistent map of the postglacial uplift of Fennoscandia, *Terra Nova,* 8, 158-165.

Ekman, M., and Makinen, J,, 1996. Recent postglacial rebound, gravity change and mantle flow in Fennoscandia, *Geophys. J. Int.,* **126, 229-234,**

Elósegui, P., J. L. Davis, R. 'l'. K. Jaldehag, J. M. Johansson, A. E. Neill, and I. I. Shapiro, 1995, Geodesy Using the Global Positioning System: The Effects of Signal Scattering on Estimates of Site Position, *J. Geophys. Res.,* **100,** 9921-9934.

Jaldehag, R.T.K, Johansson, J, M., Rönnäng, B, O., Elósegui, P., Davis, J.I,., Shapiro, 1.1., and Neil], A, E., 1996. Geodesy using the Swedish Permanent GPS Network: Effects of signal scattering on estimates of relative site positions, *J. Geophys. Res.,* 101, 17,841-17,860

Jaldehag, R.T.K, Johansson, J. M., Davis, J.I,., and Elósegui, P., 1996a. Geodesy using the Swedish Permanent GPS Network: Effects of snow accumulation on estimates of site positions, *Geophys. Res. Letters,* 23, 1601–1 604.

Johnson, H. O., and Agnew, D. C., 1995. Monument motion and measurement of crustal velocities, *Geophys. Res. Letters, 22, 2905-2908.*

Mitrovica, J. X., Davis, J,],., Shapiro, I.I., 1994. A spectral formalism for computing three-dimensional deformations due to surface loads, 2. Present-day glacial isostatic adjustment, *J. Geophys. Res.,* **99,** 7075 -7101.

Rothacher, M., G. Beutler, W. Gurtner, E. Brockmann, and I,. Mervart, 1993. *Bernese GPS* Software *(Version 3.4), 1993 Documentation,* Astronomical Institute, University of Berne.

Tushingham, A. M. and Peltier, W. R., 1991. Ice-3G: A New Global Model of Late Pleistocene Deglaciation Based Upon Geophysical Predictions of Post-Glacial Relative Sea Level Change, *J. Geophys. Res.,* **96,**, pp. 4497–4523.

Webb F H, Zumberge J F, 1993. *An Introduction to GIPSY/OASIS-II* **Precision** *Software for the Analysis of Data* **from** *the Global Positioning System,* JPI, Pub]. No. D-] 1088, Jet Propulsion Laboratory, Pasadena, Cal.

Wessel, P. and Smith, W.H.F., 1995. New version of the Generic Mapping Tools released, *EOS Trans. American Geophys. Union, 76, 329.*

The Applicability of CORS for Tide Gauge Monitoring

M. Schenewerk, T. vanDam, N. Weston
(all at NOAA)

The Continuously Operating Reference Station (CORS) network coordinated by the National Geodetic Survey, NOAA, is a group of GPS reference stations which will provide code range and carrier phase data to users in support of postprocessing applications. Government, academic, and private users will be supported in performing after-the-fact positioning of fixed points and moving platforms. Ultimately, the CORS network is expected to consist of 100-200 stations located nationwide.

The GPS data is being recorded at a 30 second sampling rate in the Receiver Independent Exchange (RINEX 2) format, version 2 (1). The data sets are available for 31 days and can be retrieved over the INTERNET. After that period, the data are archived on CD ROM and will be available by special request. The address for anonymous FTP access to CORS data and information is cors.ngs.noaa.gov. Access is also provided through the World Wide Web (http://www.ngs.noaa.gov or more specifically http://www.ngs.noaa.gov/CORS/cors-data.html).

Currently, the National Geodetic Survey provides data from over 90 sites.

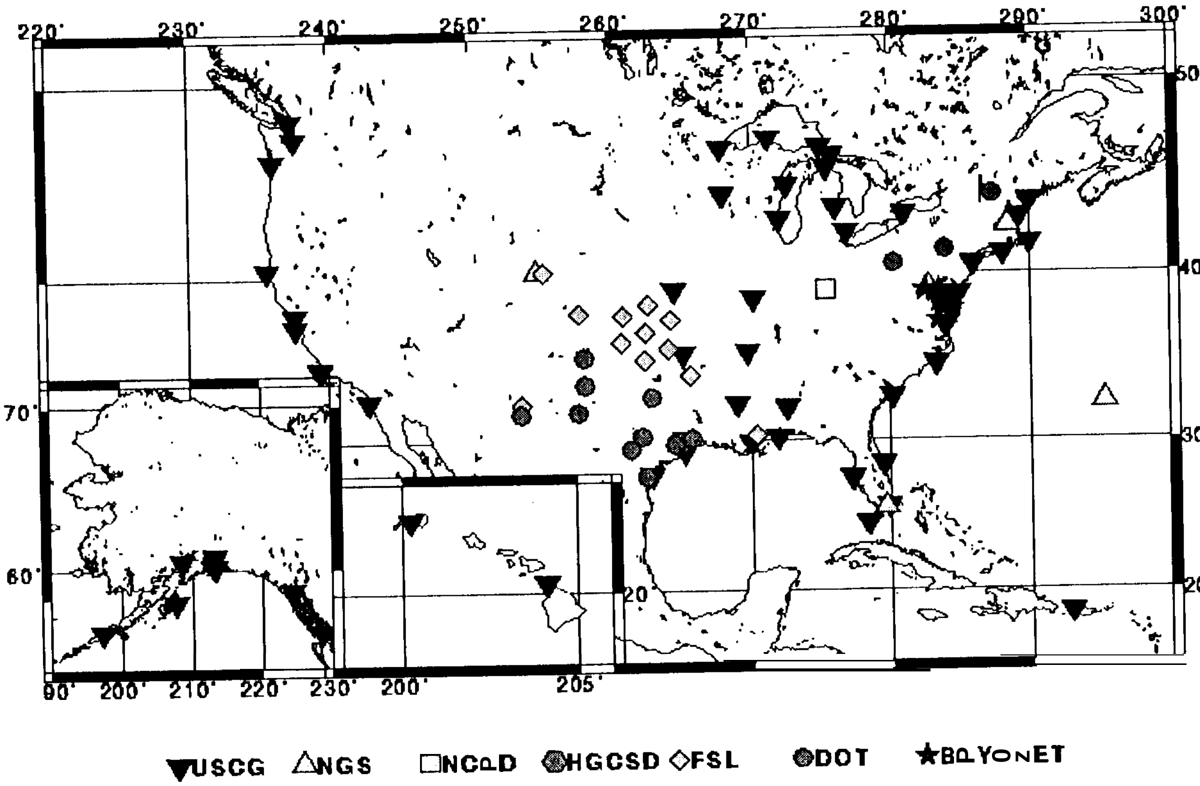


Figure 1: CORS Available Trhough NGS

During the 14 month period that started in December 1994, the U.S. Coast Guard (USCG) began installing a 48 station Differential GPS (DGPS) network along the U.S. coast for maritime navigation. The network includes the Atlantic, Pacific, and Gulf coasts, the Great Lakes, southern Alaska, Hawaii, and Puerto Rico. By agreement, NGS will utilize data from these stations as part of the NGS CORS network and will make the data available for postprocessing applications. Additional stations will be added over the next two to three years by the USCG in support of the U.S. Army Corps of Engineers for river navigation (approx. 15 stations), by the Forecast Systems Laboratory, NOAA (approx. 18 stations), and by the Federal Aviation Administration to support air navigation (approx. 29 stations). The sites will be CORS compatible and most are expected to become apart of the CORS network. Further stations will be added, where possible, to provide complete national coverage. Figure 1 indicates the locations of CORS whose data are currently distributed through this service. The broad categories of parent organizations are indicated by the symbol and color coding.

More directly relevant to this workshop is the proximity of CORS to tide gauges. Figure 2 shows the locations of tide gauges in North America whose data are distributed by NOAA. Each site is identified by a circle ‘whose size is proportional to the distance to the nearest CORS.

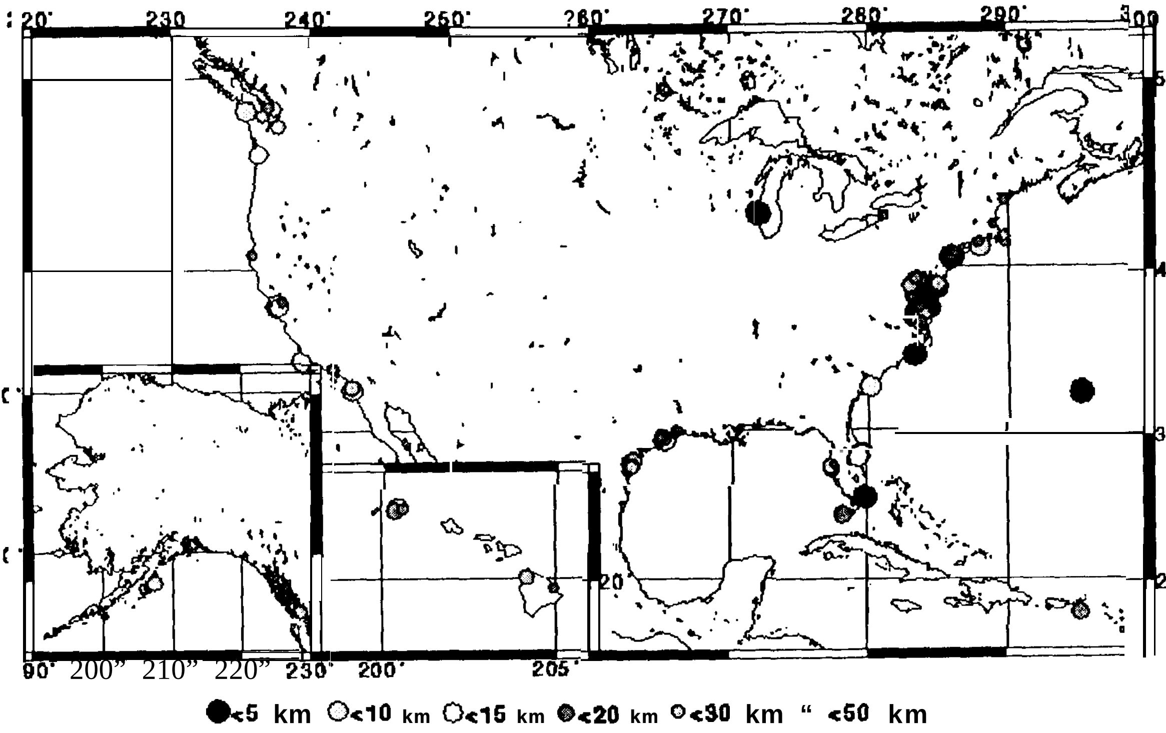


Figure 2: Proximity of Tide Gauges to CORS.

LAND UPLIFT / SUBSIDENCE AS INFERRED FROM GEODETIC SURVEYS IN THE SOUTHWESTERN PACIFIC ISLANDS

S. Turner
National Tidal Facility
GPO Box 2100
Adelaide 5001
steve@pacific.ntf.flinders.edu.au

Concerns of Pacific island nations to the widely publicised issue of sea level rise associated with global warming are being addressed through an Australian initiative funded by the Australian Agency for International Development (AusAID). An array of high resolution sea level stations has been established in eleven countries of the South Pacific Forum with data transmission by satellite technology to the National Tidal Facility (NTF) in Adelaide. An extensive geodetic survey monitors the stability of these stations,

The stations are supported by networks of deep bench marks established at coastal and inland sites where possible. Repeat high precision levelling and GPS connections are undertaken to monitor the stability of the sea level sensor. Surveyors from the NTF carry out these surveys, assisted by their counterparts in the national survey agencies. It is essential to use techniques capable of matching the size of the expected sea level rise in the order of 1.5mm/year.

The geodetic monitoring program at this stage enables sea level change to be determined relative to the adjacent land. While this is of prime importance to the communities, the project has plans to monitor absolute sea level rise through the separation of eustatic sea level change from tectonic movement of the islands.

GEODETIC SURVEY

Although the precision required to determine any trend in sea level due to the Greenhouse Effect is very close to the threshold of what is physically possible, the SEAFRAME measuring equipment used in this Project has been specifically designed with the special and rare quality of datum stability. This datum can be monitored with respect to a Tide Gauge Bench Mark (TGBM).

In early 1992, a four-phase, 20-year, Geodetic Survey Plan was prepared for the geodetic monitoring of the stability of the stations. The plan was prepared based on recommendations from the IAPSO committee which met in 1988 at Woods Hole, USA, to investigate the geodetic fixing of tide gauge bench marks.

Phases 1 & 2

Arrays of up to 7 deep bench marks, with at least one satisfying the requirements for a GPS site, have been established at each site. A regular program of precise differential levelling is undertaken between these bench marks and the tide gauge using a digital level and a pair of bar coded invar staves.

The precise differential levelling monitors the stability of the tide gauge in relation to the TGBM in the coastal zone of the island. However, it does not determine whether the coastal zone is moving in relation to the main body of the island.

Wherever possible, a second array of 3-4 bench marks has been established approximately 10 kilometres inland from the tide gauge in either stable ground or, more preferably, bedrock.

Precise differential levelling of the inland array of bench marks is done in conjunction with the survey of the coastal bench mark array. These surveys monitor the relative stability of the two arrays in isolation.

GPS observations or precise differential levelling are carried out between the arrays in conjunction with the levelling of the coastal and inland arrays. The GPS observations are done simultaneously with the levelling.

Phase 3

Phases 1 and 2 help to establish the relative difference between sea level and tectonic motions at one point on the main island in each country. The magnitude of tectonic movements in the Pacific can vary over small distances between islands within a PIC whereas sea level signals over similar distances are assumed to be the same. Of specific importance to the people of other islands in each nation group are the movements of sea level relative to their island.

in Phase 3 bench marks will be installed in other major islands and regular GPS connections will be made to the main island. From these observations relative movement between the main island and the outer islands can be deduced. Similarly, trends in sea level can also be deduced for these outer islands.

Phase 4

The sea level movements this Project is aiming to detect are small and require the use of the latest geodetic techniques. Of importance in understanding the variance of sea level in a regional sense is the detection of small vertical movement over large distances.

It is proposed to carry out inter nation GPS observations between each SEAFRAME tide gauge. Furthermore, it is proposed that this network be tied to core GPS stations established by the IGS.

RESULTS

To date, regular Phase 1 and Phase 2 surveys have been carried out by NTF staff in association with staff from the in-country national survey organisations. In comparison to Phases 1 and 2, Phases 3 and 4 are very expensive and a watching brief is being kept on international developments in GPS, especial] y collocating permanent trackers with tide gauges, before proceeding with this part of the survey. Also, other similar international projects are being identified in the area with the aim of sharing resources.

The rigorous survey techniques followed in the field enable the Project's levelling specifications to be satisfied. Internal consistencies of better than 1 mm√K are regularly achieved while the 2mm√K specification is easily attained.

This Project, by the very nature of the signal it is endeavoring to measure, is planned to extend more than 20 years, Therefore it will be some time before any trends become apparent from the data,

However, even at this early stage, with a maximum of four surveys at any particular site, movement between the TGBM and the SEAFRAME Sensor Bench Mark has been detected at several sites. After three surveys, spread over three years, a relative movement of more than 7mm has been measured in Western Samoa while movements greater than 2.5mm have been measured at other sites,

Further regular surveys are required before any further comment can be made about the relative stability of the SEAFRAME stations.

FUTURE DIRECTIONS

The Project is maintaining a watching brief on developments in space-based geodetic techniques. Since the Woods Hole workshop, geodetic techniques and precision have improved substantially, especially over the long distances expected to be measured in this Project.

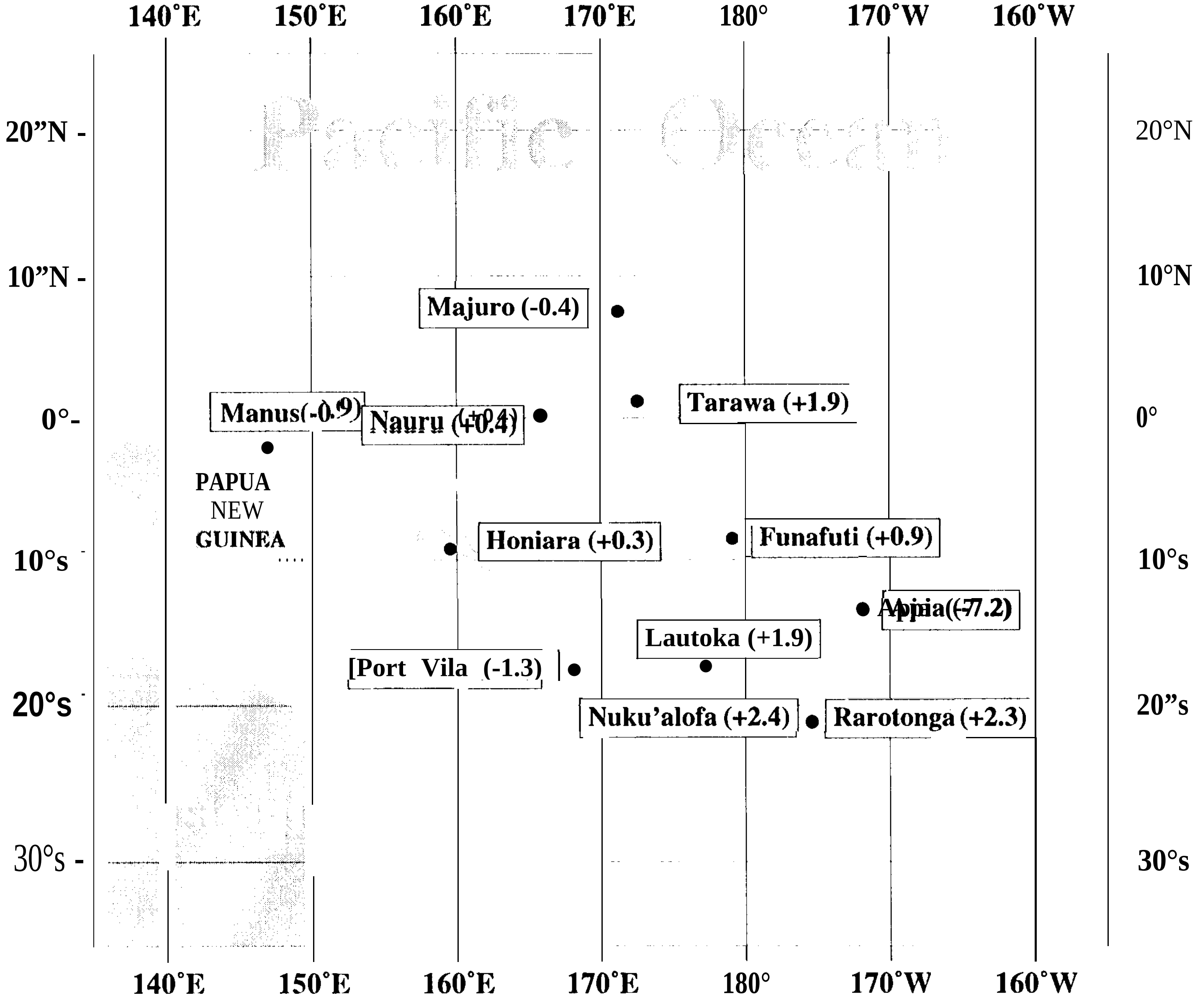
In 1993, the same group of experts again met to discuss advances in geodetic techniques for monitoring tide gauges and recommended that:

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

Unfortunately the installation of permanent GPS receivers at the SEAFRAME stations is expensive and logistically difficult in remote locations such as the Pacific. This part of the Project remains unfunded and will remain so until the logistical problems and set up costs are reduced.

in the meantime developments in this field are being closely monitored while observations using current techniques continue.

Relative Movement(mm) between SEAFRAME Sensor Bench Mark and Nearest Deep Bench Mark 1992-1996



GEODETIC CONTROL OF TIDE GAUGES IN THE ANTARCTIC AND SUBANTARCTIC

Summerson, R.M.V.(1), Brolsma, 11.(2), Govind, R.(3), and Hammat, J.(4)

(1) National Resource information Centre, Bureau of Resource Sciences, PO Box E I I,
Kingston, ACT 2600, Australia.
(2) Australian Antarctic Division, Channel Highway, KINGSTON,
TAS 7050, Australia,
(3) Australian Surveying and Land Information Group, PO Box 2, BELCONNEN,
ACT 2617, Australia.
(4) National Tidal Facility, Flinders University of South Australia, GPO Box 2100,
ADELAIDE, SA 5001, Australia.

ABSTRACT

The Australian Antarctic Division operates tide gauges at six sites in the Antarctic and Subantarctic. The tide gauge at Macquarie Island is an Aquatrak timed acoustic pulse sensor with a differential pressure sensor as back up. The other tide gauges are Platypus Engineering bottom mounted pressure gauges. The Australian Surveying and land Information Group (AUSLIG) operates permanent TurboRogue GPS stations at four of those locations.

The locations of the tide gauge installations is dependent on a number of factors such as water depth and accessibility, The locations of the GPS stations and antennae are dependent on a different set of factors such as unrestricted horizon, freedom from multipath and accessibility to power and communications. At no location has it been possible to co-locate tide gauge with GPS. Connections between the tide gauges and the GPS antennae are made annually by either spirit levelling or GPS baseline, or both

The results of four years of GPS and sea level observations at Mawson, Davis and Macquarie island will be presented together with the results of attempting to correlate relative vertical motion of sea level.

INTRODUCTION

The Australian Antarctic Division operates tide gauges at six sites in the Antarctic and Subantarctic. At four of these sites, the Australian Surveying and Land Information Group (AUSLIG) operates, in collaboration with the Australian Antarctic Division, a permanent GPS tracker. The locations of these sites are shown in figure 1.

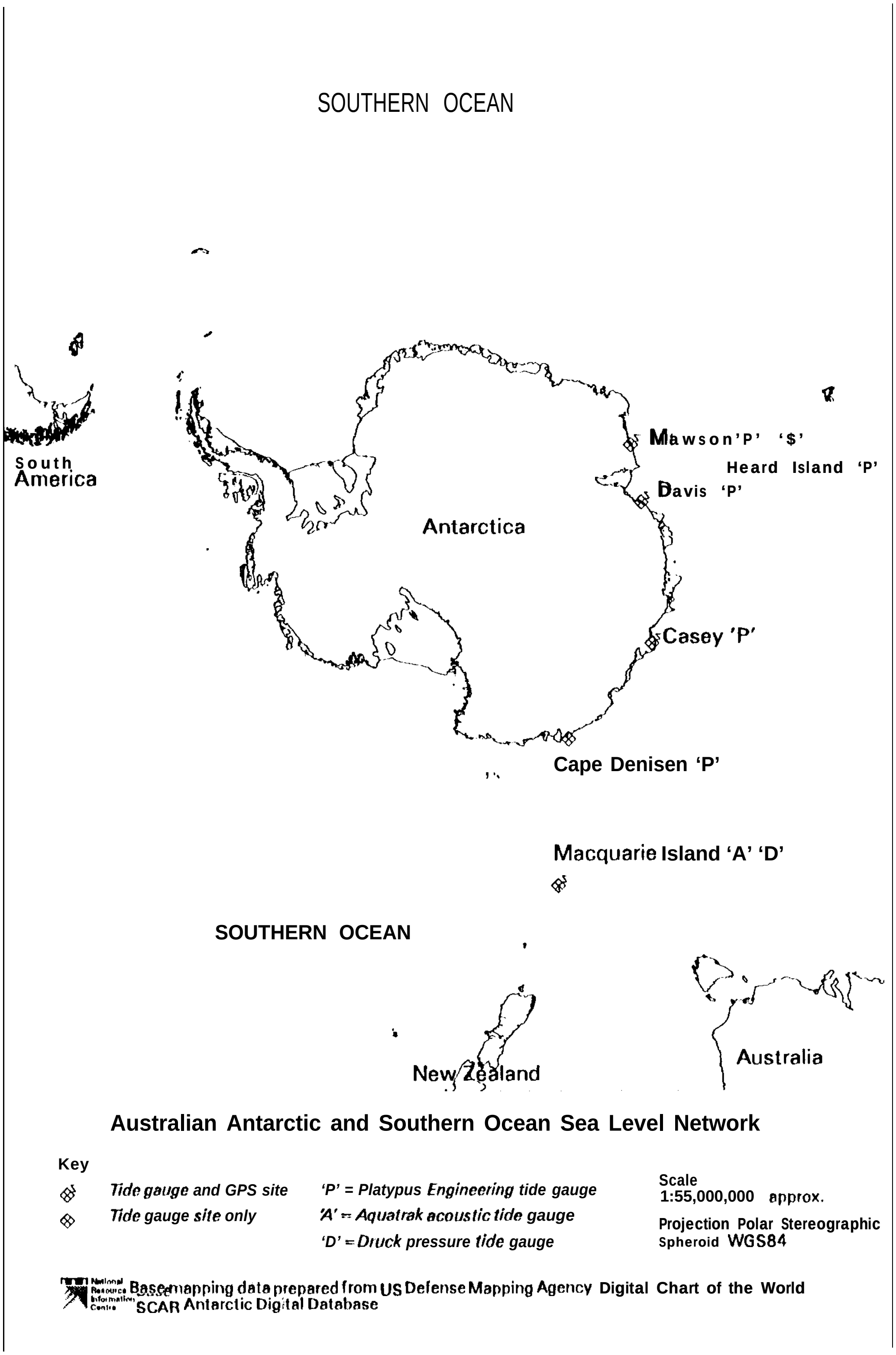


Figure 1. Location map.

A summary of the types of tide gauges and the GPS and dates of their deployment are in table 1.

'1'able 1. Types of tide gauges and GPS and dates of their deployment by location.

Location	Tide gauge	Date installed	Data to	GPS
Macquarie Island	Aquatrak acoustic Druck pressure	Aquatrak 12/93 Druck 12/94 ,,,,	1/97	TmboRogucSNR8100 Dorne Margolin Antenna
Heard island	Platypus Engineering	8/93	No data to date,	None
Mawson	Platypus Engineering	3/93	1/97	Tutt)oRogIlcSNR8100 Dorne Margolin Antenna
Davis	Platypus Engineering	4/93	1/97	Tutt)oRogacSNJt8100 Dorne Margolin Antenna
Casey	Platypus Engineering	3/96	No data to date	TurboRogue SNR 8100 Dorne Margolin Antenna
Cape Denison	Platypus Engineering	12/94	No data to date	None

Details of the designs of tide gauge in use are in Summerson and Handsworth 1995, Illustrations of the instruments and installations are in Plates 1-3.

MEAN SEA LEVEL RESULTS

Mean sea level is calculated monthly (as the arithmetic mean of the filtered hourly sea levels over one month) for each of the tide gauges for which there are data - Mawson, Davis and Macquarie island. A plot of mean sea level for Davis and Mawson from March 1993 to March 1997 is at figure 2. Conversion of water column pressure to metres of water has been carried out using the Fofonoff and Millard equation:

$$z = \frac{C_1p^1 + C_2p^2 + C_3p^3 + C_4p^4}{g(\O) + {}^1/_2\gamma' p} + \frac{\Delta D}{9{,}8} \qquad (1)$$

z =- water depth in metres

C_1 .,. =- coefficient of pressure from the least squares method of analysis

Mean vertical gradient of gravity
$\gamma' = +2.184\ E\text{-}6\ m/s^2/decibar$

Gravity expression
$g(0) = 9.780318\ (1.0 + 5.2788\ E\text{-}3 \sin 2\O + 2{,}361 \sim\text{-}5 \sin 40)$

ΔD = geopotential anomaly

(Fofonoff and Millard 1983)

It can be seen that these two sites are highly coherent despite being 640 km apart. This forms a useful check that the instruments are operating correctly and that they are recording true sea level signals. A seasonal cycle can be detected in that sea level begins to rise at the beginning of each summer, about in November, reaching a peak in about March and then falling during the winter. The seasonal cycle appears to follow, in reverse, a seasonal cycle in atmospheric pressure. Other features are apparent in the plots and are probably related to the incidence of low-pressure features and related storms.

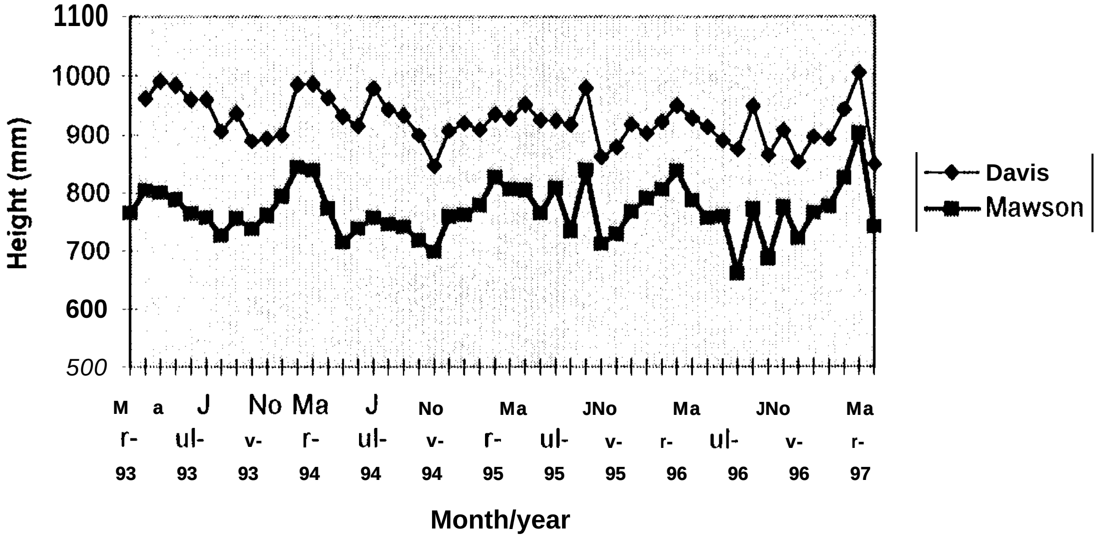


Figure 2. Monthly means for Mawson and Davis. Height values are in millimetres above lowest astronomical tide.

The monthly means for Macquarie Island from the installation of the Aquatrak acoustic sensor in December 1993 to December 1995 are in figure 3. No comparison between the sea level data and atmospheric pressure has been carried out to date. While there are no stations with which to make a direct comparison and to make a check on the quality of the data; a comparison has been made with data from Spring Bay, Tasmania, for the purposes of conducting a feasibility study into 'large scale variance of the (Antarctic Circumpolar) Current using the integrating power of the geostrophic gradient over a transect of the ACC' (Tait et al 1996).

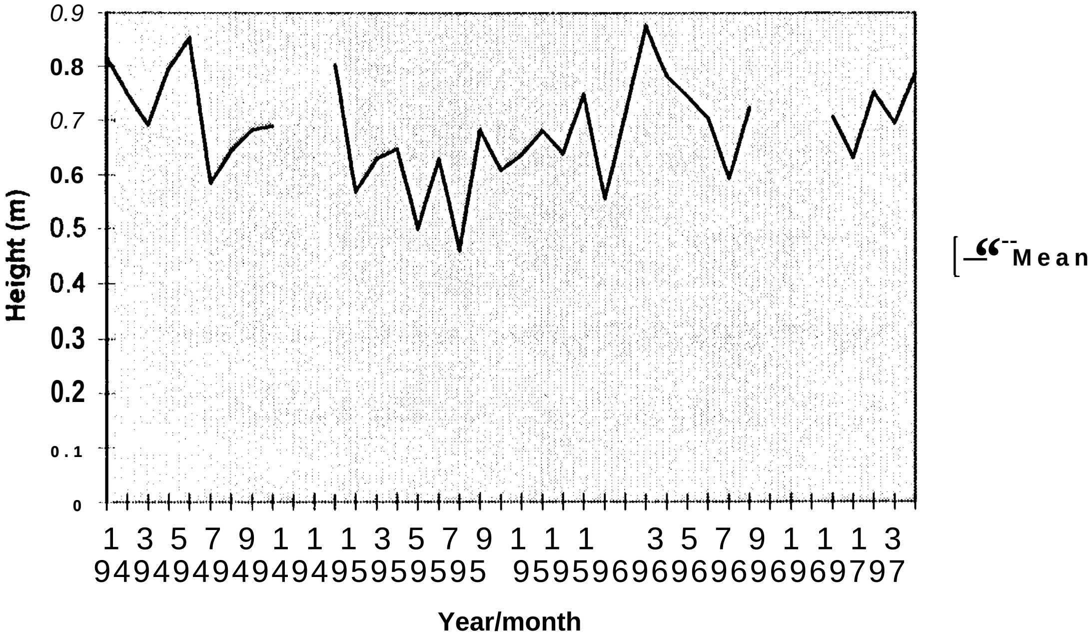


Figure 3. Monthly means for Macquarie Island. Height values are in metres above an arbitrary datum (3.3 m below the Aquatrak reference point). The data is principal y from the primary (Aquatrak) acoustic sensor with some of the gaps filled with data from the secondary (Druck) pressure sensor.

GPS DATA

The long time series GPS processing is performed using the Bernese GPS Software Version 4.0. Data from all Australian Regional GPS Network (ARGN) sites in addition to data from Tidbinbilla and Yaragadee is processed in twenty four hour sessions. The network design is based on observation optimisation and varies from day to day. See Govind et al 1996 for a complete description of ARGN data processing.

Site specific tropospheric delay parameters are estimated at a two hourly interval using the SAASTAMOINEN tropospheric model. Linear Combination phase observations are utilised to eliminate ionospheric delay effects.

IGS products including the precise combined Ephemerides and Earth Rotation Parameters are used and held fixed. A daily Normal Equation file is produced and is later incorporated into a seven day combined solution. Site coordinates and velocities for Tidbinbilla and Yaragadee are held fixed at this stage. Site coordinates for all other sites are estimated giving a seven day mean coordinate value for each site in effect.

No correction has been made for site deformation due to ocean tide loading which may be in the order of 0 - 5 mm depending on the site. This may be corrected for using

Microcosm GPS software to process the data. Bernese was used for this project in order to be compatible with other IGS products. Plots of east, north and up (ENU) coordinates of data from Mawson and Macquarie Island are shown in figures 4 and 5 respectively. Results prior to 1996,5 were produced in ITRF93 and later transformed into ITRF94. Results after 1996.5 are in terms of ITRF94 at date of survey.

These data sets are considered to be too short from which to draw meaningful conclusions, but a comparison of the ENU coordinates indicates that the data are of high quality and, with longer time series, will yield useful information on vertical motion,

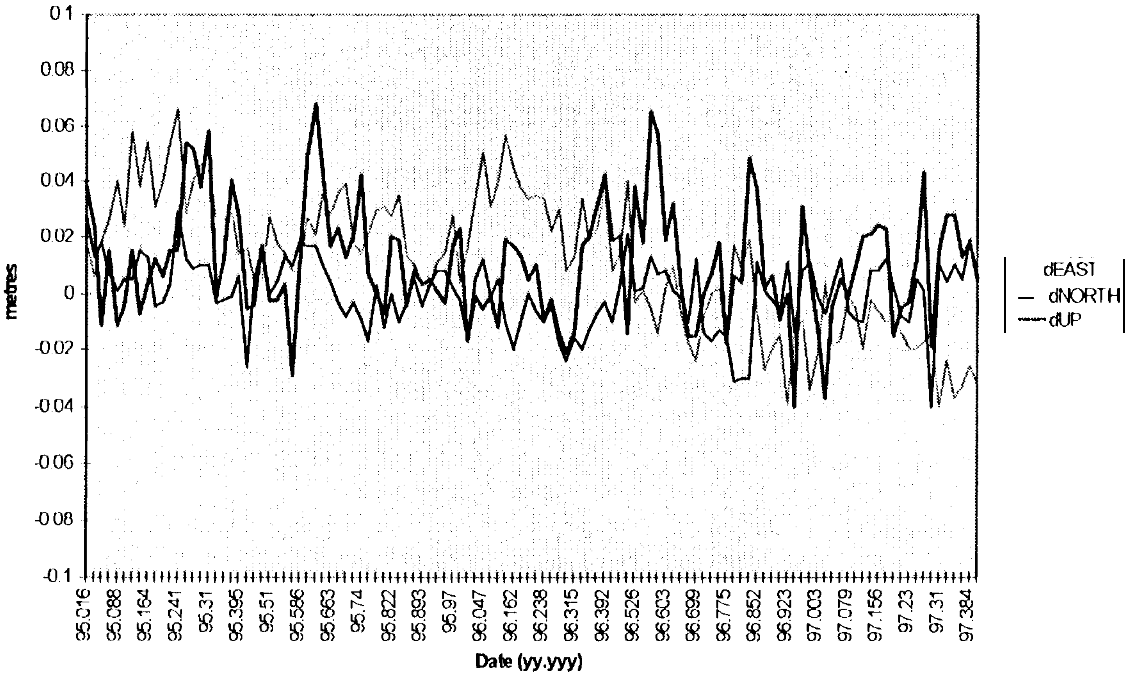


Figure 4. ENU plot of GPS data from Mawson.

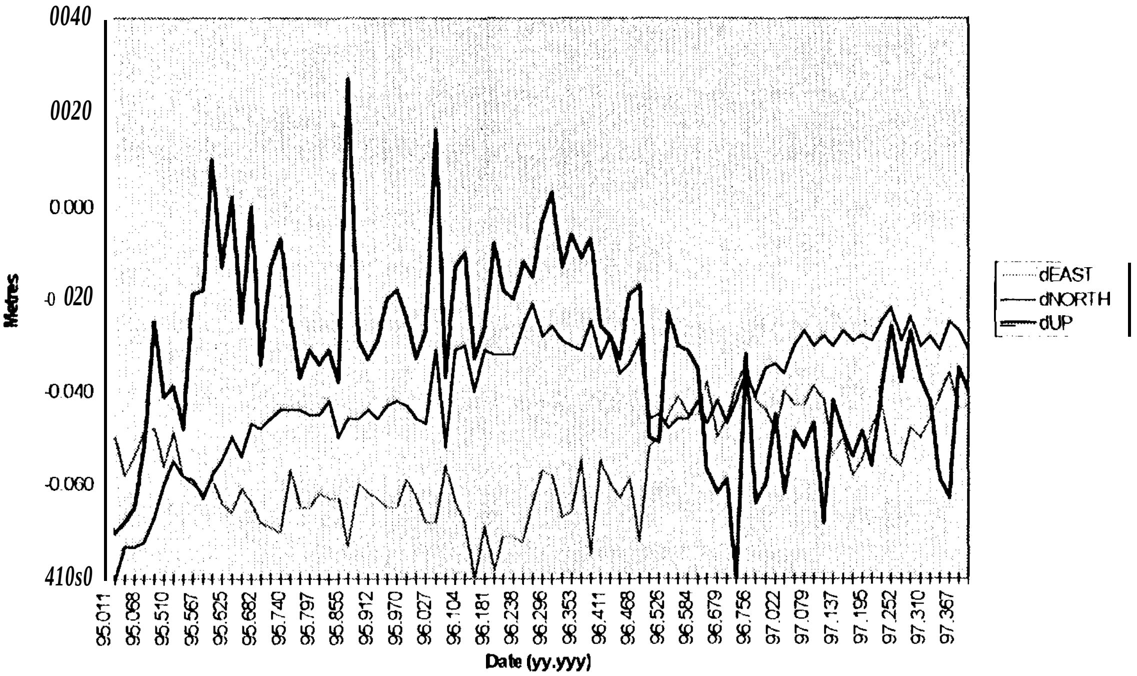


Figure 5. ENU plot of GPS data from Macquarie island.

GEODETIC CONNECTIONS - TIDE GAUGES TO GJ'S

Thee o-location of GPS and tide gauge would be impossible at either Macquarie Island on at any of the Antarctic stations. The tide gauge at Macquarie Island is submerged from time to time and the logistics of connecting a GPS receiver to the local area network and power supply at its present location would be extremely difficult. The Antarctic tide gauges are bottom-mounted and it would therefore be impossible to co-late with a GPS ! Connections between the title gauges at Macquarie island and the GPS have, however, been effected both by optical levelling and by GPS baseline. The results arc in Table 2.

Making geodetic connections to the tide gauges at the Antarctic stations, such as Mawson, and the tide gauge at Macquarie island involve quite different problems. The tide gauge at Mawson, f'or example, is of the bottom-mounted pressure type. The height of the tide gauge at Mawson below tide gauge bench mark (TGBM) AUS 258 was determined in 1995-6 as -8.269 m and in 1996-7 as -8.445 m. The tide gauge is in about 7 m of water and is about 70 m offshore. In 1995-96 the height of the tide gauge was determined by using a staff lowered from the surface which was then levelled to AUS 258 TGBM. The 1996-7 value was acquired by means of timed water level measurements at high and low water levelled to AUS258 TGBM. The value this obtained is more accurate as water level heights are measured by the tide gauge at the centre of the pressure transducer whereas the staff measurement was to the top of the tide gauge itself. The pressure transducer is about 175 mm below the top of the tide gauge which accounts for the difference.

Table 2. Geodetic connections from GPS stations to tide gauge bench marks

Station	1994-5	1995-6	1996-7
Macquarie Island			
All AUS 2 1 (Rogue) - AIJS 092 (Ashtech Z12), (DMT ants)	-9.463 (G)	-9.461 (G)	-9.465 (G)
All AUS 2 1 (underside of antenna) - AUS 092 (TG BM)	-9.502 (S)	Not done	Not done
A}I AUS 21 RM2* - AUS 092 (TG BM)	-8.186 (s)*	-8.186 (s)*	-8.186 (s)*
Mawson			
All AUS 064 RM2 - AUS 258 (TG BM)	Not done	-30,s51 (s3)	-30.551 (s2)
All AUS 064 (Rogue) - AUS 258 (Ashtech Z12). (DMT ants)	Not done	Not processed	Not done
All AUS 064 - AUS 258	Not done	?	-31.013 m (S2)
All AUS 258- Tide gauge	Not done	-8.269	-8.445
Davis			
All AUS 099 - AUS 186 (TG BM)	-23.161 (s)	-23.2(KJ (s)	-23.155 (s2)
All AUS 186 - Tide gauge	Not done	-11.280	Not yet done
Casey 1993-4			
All AIJS 100 - HBM3 (TG BM) 38.923	Not done	Not done	Not done

Notes
All heights are in metres
G = GPS baseline. Using Bernese processing package. ITRF93 reference frame. Epoch 1995.64.
S = Optical levelling. * = from reference mark, not from antenna.
2/3 = Order levelling.

The tide gauge at Macquarie Island is shore-mounted so it is possible to level directly to the reference point of the Aquatrak sensor. The Aquatrak is, however, installed at an angle of 33 ° from the horizontal so this must be taken into account.

Both GPS baselining and optical levelling have been carried out at both Mawson and Macquarie island. While there are some advantages in the former technique in that levelling is done implicitly to the phase centre of the antenna while in optical levelling it is usually most convenient to level to a reference mark and leave the antenna undisturbed. It can be seen from Table 2 that optical levelling at Macquarie Island, a distance of under I km, has produced a consistent value over three years while there has been some variation in the GPS baselining results.

CONCLUSIONS

These tide gauges and GPS stations have not been operating for a sufficiently long period for any firm conclusions to be drawn on absolute sea level change. Operating these instruments in extremely hostile continues to pose its challenges but we are confident that the results obtained are of high quality and that, with the passage of time and longer time series of data, useful information will be produced. While it has not been possible to co-locate the GPS receivers with the tide gauges, the consistent heights achieved, especially by optical levelling, show that this is not necessary.

REFERENCES

Fofonoff, N.P. and Millard, R.C. 1983. Algorithms for computation of the fundamental properties of sea water. UNESCO Technical papers in Marine Science No 44. UNESCO, Paris.

Govind, R., Johnston, G., and Luton, G. 1996. Geodetic fixing of tide gauge benchmarks of the Australian Baseline Sea Level Monitoring Array: results of the May 1995 GPS campaign. In Aung, T.H. (Ed). *Proceedings of the Ocean and Atmosphere Pacific International Conference.* 23-27 October 1995, Adelaide. 345-351.

Summerson, R.M.V. and Handsworth, R.J. 1995. Instrumentation for sea level measurement in Antarctica and the Southern Ocean. In Bellwood, O. *et al (Eds) Recent Advances in Marine Science and Technology '94.* PACON International and James Cook University. 375-383.

Tait, M.E., Summerson, R. M. V., Lennon, G.W. and Handsworth, R.J. 1996. Macquarie Island: a platform for monitoring sea level and its role in climate variability? In Aung, T. H. (*Ed*). *Proceedings of the Ocean and Atmosphere Pacific International Conference.* 23-27 October 1995, Adelaide. 77-91.

The Baltic Sea Level Project - History, Present and Future

Juhani Kakkuri and **Markku Poutanen**
Finnish Geodetic Institute, Masala
Janusz B. Zielinski
Space Research Institute, Warsaw

Introduction

The Baltic Sea level project was initiated as an *ad hoc* working group at the General Meeting of the IAG in Edinburgh in 1989. After the IUGG General Assembly in Vienna 1991, it received the status of a Special Study Group (No. 5.147), and after the IUGG General Assembly in Boulder in 1995, the status of Subcommission (No. 8. 1). All countries around the Baltic Sea have participated in the project.

One of the goals of the Baltic Sea Level (BSL) Project was the unification of the vertical datums of the countries around the Baltic Sea. In order to achieve this, three GPS campaigns were organized: BSL I in 1990, BSL 11 in 1993 and BSL III in 1997. The Aland campaign in 1986 can be considered an early campaign (Kakkuri and Verrneer 1986). As a result of the campaigns, the heights of the non-tidal crust above the GRS-80 ellipsoid were computed for the tide gauges.

The BSI. I campaign was performed during unfavorable measurement conditions. Solar activity was high during the whole campaign, and, therefore, the ionosphere was rough and some receivers produced extremely noisy data (Poutanen 1994). Under these circumstances, the result of the BSL I was not as good as hoped for. The second campaign, BSL II, was performed under more favorable conditions than BSL I, and plenty of good observations were made (Poutanen 1995).

Final results of the BSL I and II campaigns were published in the *Reports of the Finnish Geodetic Institute* (Kakkuri 1994, 1995). Observations of BSL HI were made during the EUVN campaign (European Vertical GPS Reference Network) in May, 1997 and the computations will be made together with EUVN.

A brief account of the results of the E3SL H is given in the following paragraphs.

The Second Baltic Sea Level GPS Campaign

More than 30 tide gauges, which were connected to the national precise levelling networks, were included in the BSL 11 campaign. Its network consisted of two parts, one formed by reference stations and the other by tide gauge stations. The reference (or fiducial) stations were Tromsø and Trysil (in Norway), Metsähovi (in Finland), Furuögrund, Mårtsbo and

Onsala (in Sweden), Rigs (Latvia), Borowa Gora, Borowiec and Lamkowko (Poland), and Potsdam, Hohenbünstorf and Wettzell (Germany). The total number of tide gauges was 35 (Fig. 1).

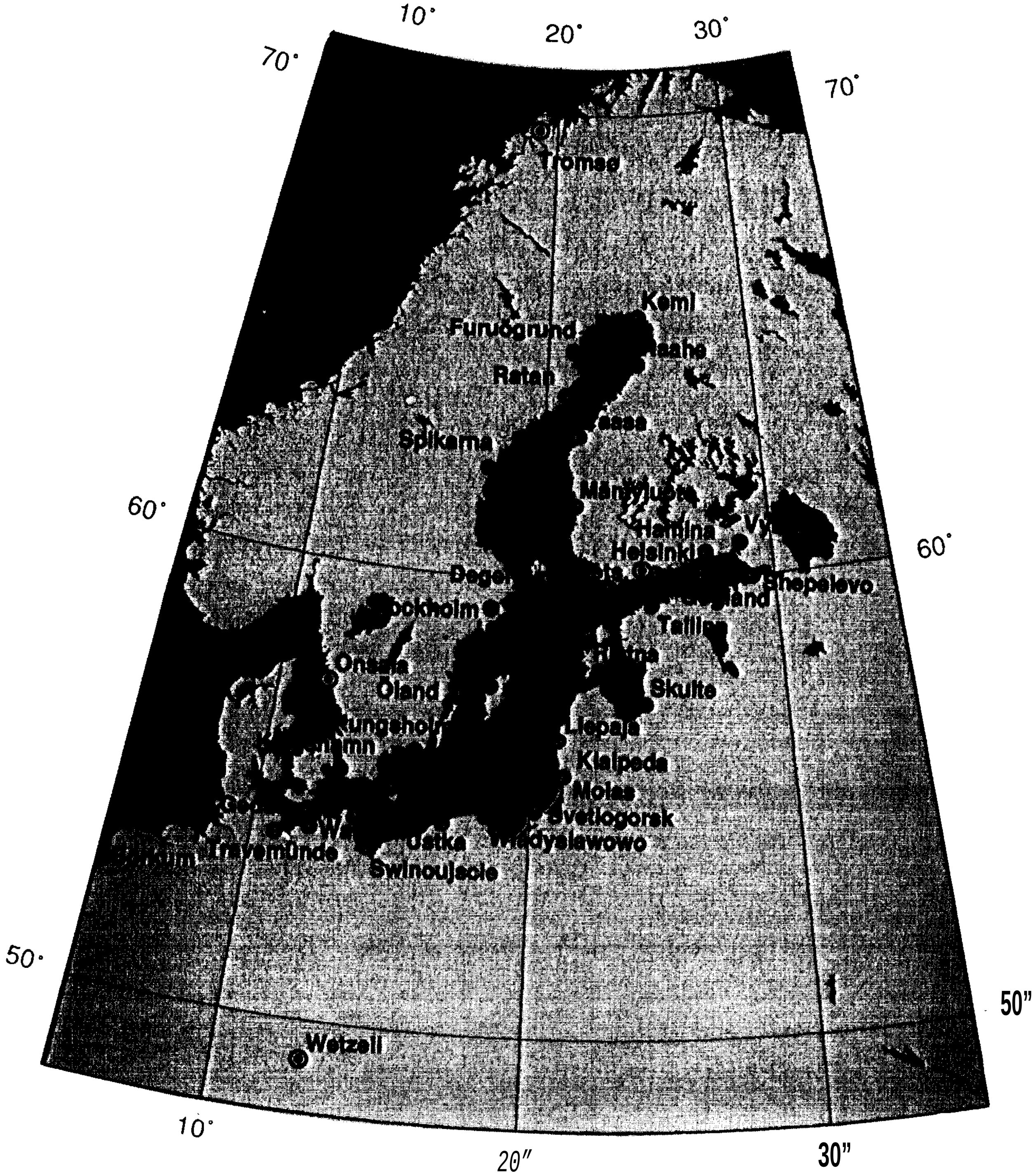


Figure 1. *The Baltic Sea Level network.*

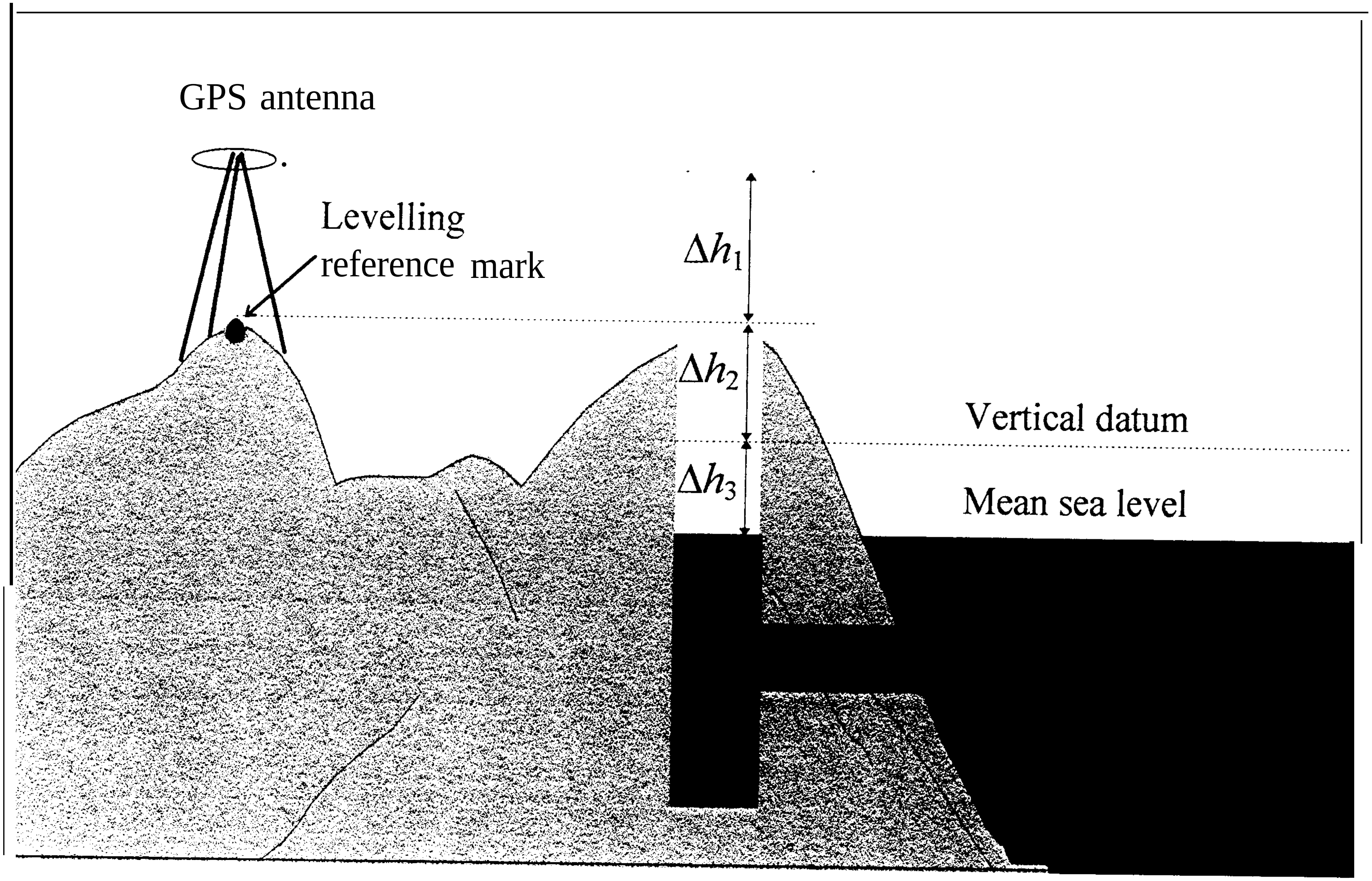


Figure 2. *Arrangements of the GPS observations at tide gauges.*

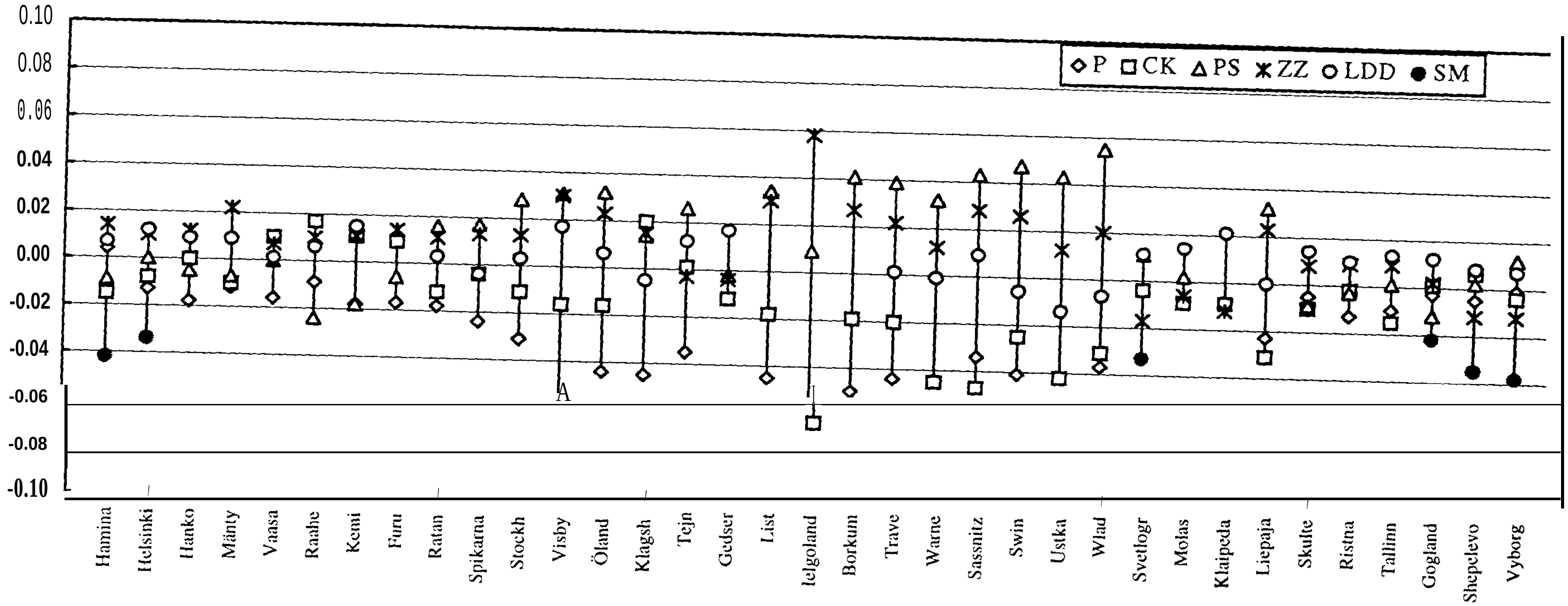


Figure 3. *Repeatability (in@ of the height component of the second Baltic Sea Level GPS Campaign obtained from the results of six separate computing groups.*

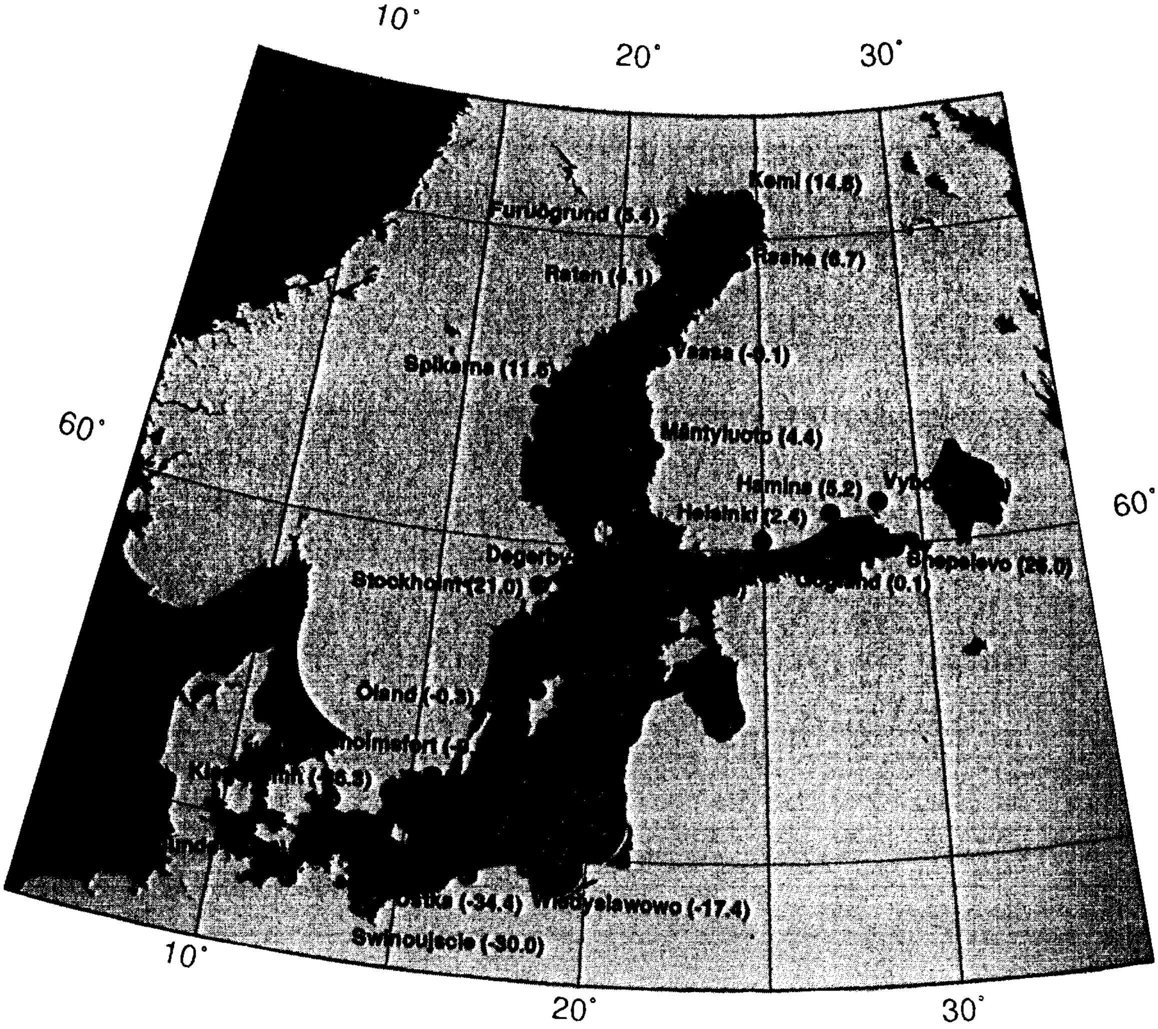


Figure 4. *Sea Surface Topography of the Baltic Sea.*

When fixing the tide gauges to the same geodetic frame, e.g. to ITRF-93, with the GPS-observations, the reference center of the GPS antenna at each gauge is to be tied to the levelling reference mark of the tide gauge station (Δh_1), the reference mark to the vertical datum (Δh_2), and the vertical datum to the present-day mean sea level (Δh_3) as shown in Fig. 2, One value which is then obtained is the height of the levelling reference mark above the reference ellipsoid, denoted here with h^{gps}. It is further converted into the orthometric height, H_o^{gps}, with the equation

$$H_o^{gps} = h^{gps} - N \tag{1}$$

where N is the height of the mean geoid above the ellipsoid.

In Fig. 3 the repeatability of the height component from the BSL 11 is shown. The RMS of the height component here is 2.3 cm. The *internal* repeatability, i.e. repeatability obtained by an individual computing group, is better than the ***external*** repeatability, i.e. when results of all computing groups are put together. This means that some systematic errors may still exist, the magnitude of which is unknown, Especially, a part of the error seems to be receiver dependent (or, in fact, antenna dependent). This may indicate an incomplete treatment of the antenna phase center shift in the Bernese software which was used in these computations by all groups. Using more modern tables than those from 93/94, one possibly could improve the accuracy slightly.

Sea Surface topography

The orthometric heights of the GPS benchmarks in national height systems are known, as well as the height differences between the benchmarks and mean sea level at the epoch of the observations. Because of the land uplift and the eustatic rise of the sea surface, this difference changes with time, The yearly variation is so large that the mean sea surface cannot be taken from the yearly mean, but a least squares fit of tide gauge readings over several decades must be performed.

Fig. 4 illustrates the sea surface topography of the Baltic, i.e. the height of mean sea level relative to the gravimetric geoid of the Baltic Sea (Kakkuri and Poutanen 1997). The topography was computed with the formula

$$SST = (h^{GPS} -- iv) - (\Delta h_2 +- \Delta h_3) \tag{2}$$

As can be seen, the surface of the Baltic Sea rises towards the north, the northern and eastern parts of the Sea being about 40 cm higher than the southern part. Oceanographic studies (e.g. Lisitzin 1965) show the same trend, the sea level being at the northernmost and eastern corners of the Baltic Sea (the North of the Gulf of Bothnia and the East of the Gulf of Finland, respectively) about 25 cm higher than at the North Sea entrance to the transition passage, Lisitzin (1965) concludes that the final difference from the Baltic proper to the Gulf of Bothnia is 36 cm. The sea surface topography derived from the precise levelings of the tide gauges (Ekman and Mäkinen 1996) shows also the same trend.

The sea level topography illustrated in Fig. 4 is based on the observations made at 23 tide gauges, some of them being at islands of the Baltic. Tide gauges on the coast. of the Baltic States were not included in this study, due to lack of the values for $\Delta h_2 + \Delta h_3$. The inaccuracy of each *SST* may be about 6 centimetres (i.e. inaccuracy of geoid undulations) which is sufficient for this study of sea surface topography. Some outliers discovered, e.g. in Sassnitz, may be due to incorrect determination of Δh_3 which requires further studies,

Future of the BSL

The results of the BSL 111 will be available together with EUVN computations. In this, the goal for vertical accuracy of ± 1 cm is already realistic. The most dramatic improvement since BSL 11 is the establishment of permanent GPS networks. There are currently country-wide netwoks in Finland, Sweden, Germany and Poland, and individual stations in Lithuania, Latvia, Estonia and Russia. In future, these stations can be used as permanent references ("backbones") for various observation campaigns.

The permanent networks also give a good connection between separate campaigns, even so that a need for large GPS campaigns becomes smaller in the future, Individual measurements can be connected using the background of the permanent stations. One task of the, possible projects in the future is to improve connections to the islands of the Baltic Sea. Horizontal movement studies, either by using permanent station data only or together with old triangulation observations, are also possible. There are also other projects like BIFROST (1996) which has some goals in common with the BSL.

References

131 FROST Project (1996). GPS measurements to constrain geodynamic processes in Fennoscandia, *EOS Trans. AGU, 77,* p. 337 &341, 1996.

Ekman, M. and J. Mäkinen (1996). Mean sea surface topography in the Baltic Sea and its transition area to the North Sea: a geodetic solution and comparisons with oceanographic models. *J. Geoph. Res.* Vol. 101, No. C5, Pages 11,993-11,999.

Kakkuri, J. and M. Vermeer (1986). The Åland GPS levelling experiment. Proceedings 2: Experiments, applications and numerical results of integration of GPS, inertial technics and photogrammetry, integration of terrestrial and satellite networks, 4D integrated geodesy. GGR1 of Hungarian Academy. Sopron.

Kakkuri, J. (cd.) (1994). Final Results of the Baltic Sea Level 1990 GPS Campaign. Research Works of the SSG 5.147 of the International Association of Geodesy. Rep. Finn. Geod. Inst. **94:2**.

Kakkuri, J. (cd.) (1995). Final Results of the Baltic Sea Level 1993 GPS Campaign, Research Works of the SSG 5.147 of the International Association of Geodesy. Rep. Finn. Geod. Inst. **95:2**.

Kakkuri J. and M. Poutanen (1997). Geodetic Determination of the Surface Topography of the Baltic Sea. *Marine Geodesy, 20,* no *4* (in press).

Lisitzin, E. (1965). The Mean Sea Level of the World Ocean. Sot. Sci. Fenn., Comm. Phys. Mat. XXX 7. Helsinki.

Poutanen, M. (1994). Accuracy, Repealability and Reliability of the First Baltic Sea Level GPS Campaign Results. In *Final results of the Baltic Sea Level 1990 GPS Campaign* (Ed. J. Kakkuri). Rep. Finn. Geod. Inst. **94:2**, 49–57.

Pouts.nen, M. (1995). A combined solution of the Second Baltic Sea Level GPS Campaign. in *Final results of the Baltic Sea Level 1993* ***GPS*** *Campaign* (Ed. J. Kakkuri). Rep. Finn. Geod. Inst. **95:2,** 115–123,

The results of the BSL III will be available together with EUVN computations. In this, the goal for vertical accuracy of ± 1 cm is already realistic. The most dramatic improvement since BSL II is the establishment of permanent GPS networks. There are currently country-wide netwoks in Finland, Sweden, Germany and Poland, and individual stations in Lithuania, Latvia, Estonia and Russia, In future, these stations can be used as permanent references (“backbones”) for various observation campaigns.

The permanent networks also give a good connection between separate campaigns, even so that a need for large GPS campaigns becomes smaller in the future, Individual measurements can be connected using the background of the permanent stations. One task of the possible projects in the future is to improve connections to the islands of the Baltic Sea, Horizontal movement studies, either by using permanent station data only or together with old triangulation observations, are also possible. There are also other projects like BIFROST (1996) which has some goals in common with the BSL.

References

131 FROST Project (1996]. GPS measurements to constrain geodynamic processes in Fennoscandia, *EOS Trans. AGU, 77,* p. 337 & 341, 1996,

Ekman, M. and J. Makinen (1996). Mean sea surface topography in the Baltic Sea and its transition area to the North Sea: a geodetic solution and comparisons with oceanographic models. *J. Geoph. Res.* Vol. 101, No. *C5,* Pages 11,993-11,999.

Kakkuri, J. and M. Vermeer (1986). The Åland GPS levelling experiment. Proceedings 2: Experiments, applications and numerical results of integration of GPS, inertial technics and photogrammetry, integration of terrestrial and satellite networks, 4D integrated geodesy. GGRI of Hungarian Academy. Sopron.

Kakkuri, J. (ed.) (1994). Final Results of the Baltic Sea Level 1990 GPS Campaign. Research Works of the SSG 5.147 of the International Association of Geodesy. Rep. Finn. Geod. Inst. **94:2**.

Kakkuri, J, (ed.) (1995). Final Results of the Baltic Sea Level 1993 GPS Campaign. Research Works of the SSG 5.147 of the International Association of Geodesy. Rep. Finn. Geod. Inst. **95:2**.

Kakkuri J. and M. Poutanen (1997). Geodetic Determination of the Surface Topography of the Baltic Sea. *Marine Geodesy, 20,* no **4** (in press).

Lisitzin, E, (1965). ‘l’he Mean Sea Level of the World Ocean. Sot. Sci. Fenn., Comm. Phys. Mat. XXX 7. Helsinki.

Poutanen, M. (1994). Accuracy, Repeatability and Reliability of the First Baltic Sea Level GPS Campaign Results. In *Final results of the Baltic Sea Level 1990 GPS* ***Campaign*** (Ed. J. Kakkuri). Rep. Finn. Geod. Inst. **94:2**, 49–57, Poutanen, M. (1995). A combined solution of the Second Baltic Sea Level GPS Campaign. In *Final results of the Baltic Sea Level 1993 GPS Campaign* (Ed, J. Kakkuri). Rep. Finn. Geod. Inst. **95:2**, 115–123.

European Vertical GPS Reference Network - EUVN

Concept, Status and Plans

EUVN-working group:

Josef Adam
Technical University of Budapest
Department of Geodesy
Müegyetem rkp.3.I.61
HU-I 111 Budapest, Hungary

Werner Gurtner
Astronomisches Institut der
Universität Bern
Sidlerstraße 5
CH-3012 Bern, Switzerland

Björn G. Harsson
Statens Kartverk
N-3500 Honefoss, Norway

Johannes Ihde
Institut fur Angewandte Geodäsie
Außenstelle Leipzig
Karl-Rothe-Straße 10-14
D-041 05 Leipzig, Germany

Wolfgang Schlüter (Chairman)
Institut fur Angewandte Geodäsie
Fundamentalst.ation Wettzell
Sackenrieder Str. 25
D-93444 Kötzting, Germany

Guy Wöppelmann
Institut Geographique national
2 Avenue Pasteur B.P. 68
F-941 60 St. Mandé, France

1. Objectives

GPS-techniques will be a very effective tool for the determination of the height component provided the geoid is known precisely for the conversion of the geometrical height into a physical height.

For the evaluation of a precise geoid, a first step is the establishment of a reference network consisting of points for which the coordinates

- Latitude,
- Longitude,
  ellipsoidal height and
- physical height

are known. For Europe the establishment of a Vertical GPS Reference Network has been started.

The goals of the European Vertical GPS Reference Network - EUVN are

contribution to the unification of the European height datum (centimeter level),

provision of fiducial points for the determination of the European Geoid, based on GPS-observation,

connection of the European tide gauge stations at different coastlines for the unification of the national levelling networks

support of the investigations on sea level variations and to

provision of the basis for an European geokinematic height reference system.

The basic idea for the realisation is the combination of the existing geodetic reference network EUREF with the levelling networks and the tide gauge network.

The EUREF-network consists of more than 200 sites covering the whole area of Europe for which precise coordinates derived with GPS on the centimeter level in ITRF resp. ETRF are available. Some of the stations are operating as permanent GPS stations today.

Two precise levelling networks have been established in the past decades. The Unified European Levelling Network (UELN) for the western part of Europe and the Unified Precise Levelling Network (UPLN) for the eastern part of Europe. Some of the tide gauges at the various coastlines have been regarded as reference for the national levelling networks (e. g. tide gauge Amsterdam for Germany).

2. Realisation

The EUVN-GPS-campaign will be the basis for the combination of the different networks. The campaign will be carried out in the frame of EUREF which is an IAG-Subcommission. During the EUREF-Symposium in Warsaw/Poland, June 1994 and the Symposium in Helsinki/Finland, Mai 1995 resolutions have been adopted to promote the work. During a meeting of the EUREF-Technical Working Group in Paris, October 1995 the EUVN working group has been established for the preparation of the EUVN-GPS-campaign.

The EUVN-campaign makes use of the cooperation within the European states provided by the national survey agencies and supported by related agencies. The coordination of the EUVN has to be organized by the EUVN-working group.

The network design and the site selection has been worked out in close cooperation of the working group with the national agencies. The proposed network design has been reviewed by the national agencies, some proposed sites have been replaced, deleted or some new sites have been added in agreement of the individual countries with the working group in order to optimize the design in respect with the national requirements. More than 190 stations will finally be observed (figure 1). The working group has set up guidelines and distributed circular letters to inform all involved groups.

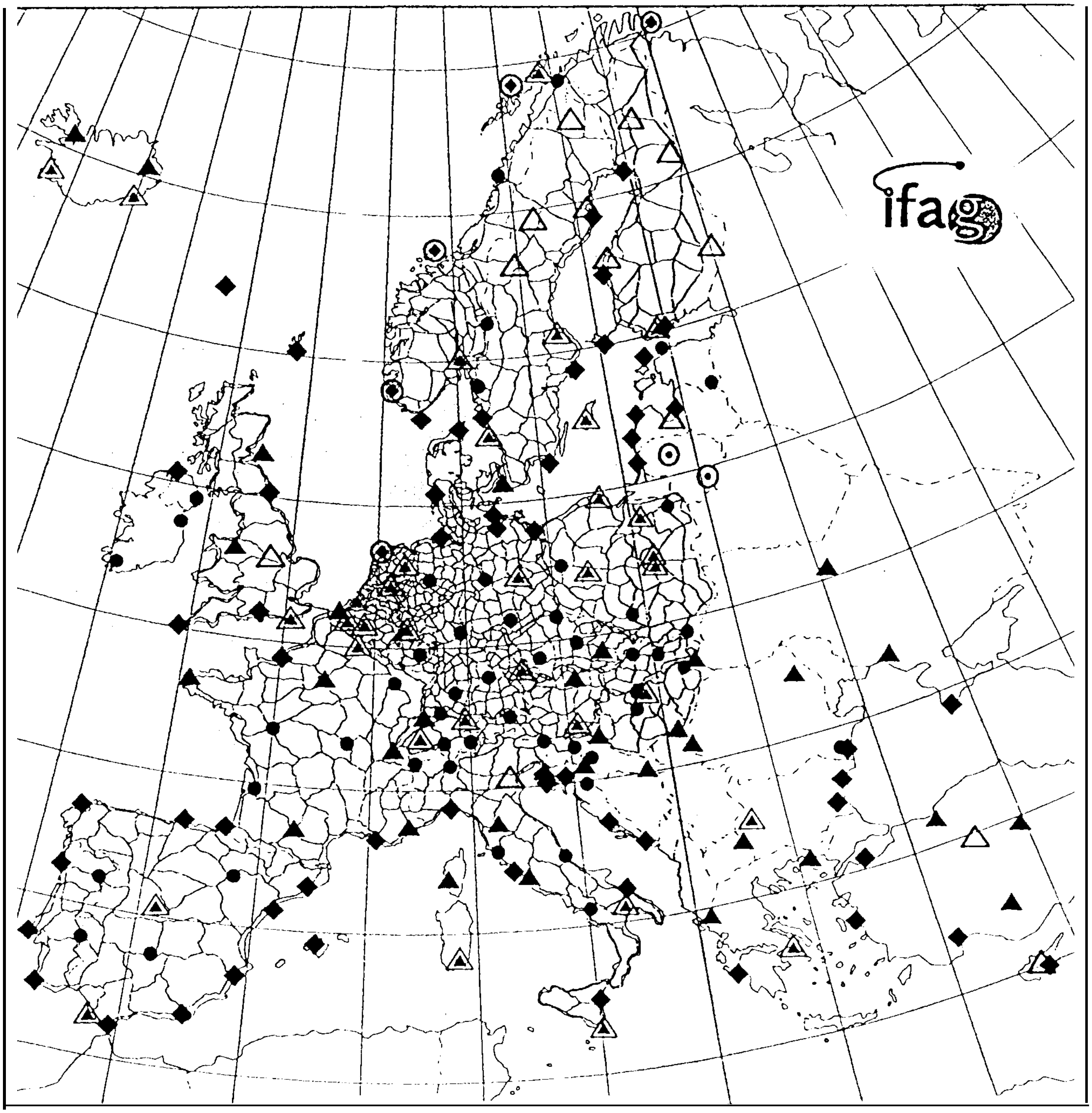
3. Schedule of the EUVN-activity

The GPS-observation campaign called EUVN97 is scheduled from May 21/1 8:00 UT to May 29/06:00 UT. The observations will be carried out over more than 8 full days mainly to contribute to the height component.

Preprocessing which covers the format conversion of the observation data format into the RINEX format, the quality control of the observations and the controll of the log sheets. The deadline for preprocessing is set to September 1, 1997, in order to start the analysis of the observations in September 1997. Around 10 analysis centers will perform the data reduction of 10 selected data blocks to distribute the workload to more agencies and to accelerate the data reduction phase.

The total network will be computed by the Institut fur Angewandte Geodäsie, in Leipzig and the Astronomische Institut Bern as a combination of the blocks.

The deadline for data reduction is spring 1998 in order to present the results at the EUREF-Symposium (June 1998).



28. May 1997

▲ EUREF sites

◬ GPS permanent stations - EUREF

△ GPS permanent stations

● UELN & UPLN nodal points

⊙ GPS permanent stations - nodal points

◆ Tide gauge sites

◉ GPS permanent stations - tide gauge

∼ UELN lines

Figure 1. European Vertica GPS Reference Network (EUVN

MONITORING TIDE GAUGES USING DIFFERENT GPS STRATEGIES AND EXPERIMENT DESIGNS

D Ugur Sanli and G Blewitt
Department of Geomatics, University of Newcastle
Newcastle upon Tyne, NE1 7RU, UK

ABSTRACT

In order to study absolute sea level variations in a global reference frame, an experiment has been designed in the Northeast of England. Two tide gauges (Blyth and North Shields) have been chosen, and a high precision permanent GPS station has been installed in Morpeth. Vertical crustal motions of the tide gauges is monitored by frequently repeated (every two weeks at each station) GPS measurements carried out at the tide gauge GPS sites. GPS data is processed by using precise and relative point positioning techniques. Processing results of the five-day data (6 hour observation window) show that daily precise positioning and relative positioning height repeatabilities of the tide gauge GPS benchmarks are at 1.2 and 1.3 cm level respectively. Precise point positioning results improve if data span is more than 12 hours.

METHODOLOGY

The experiment design for monitoring absolute sea level variations in Northeast England considers the following points with the goal of improving the vertical positioning accuracy for tide gauge benchmarks: investigation of vertical crustal movements in detail by several methods; using IGS methods; data sampling and processing strategy.

Vertical crustal movements at the tide gauge stations will be monitored by GPS. For this purpose, a new permanent high precision GPS station has been installed at MORP, about 6 km north of Morpeth. Tide gauge GPS benchmarks have been installed at BLYT and NORT (in Blyth and North Shields respectively) (Figure 1).

The cause of the vertical crustal movements can be twofold: the effects of the regional movements and local subsidence or instability (Baker 1993). Regional effects can be studied by applying the IGS Densification Initiative (Blewitt et al., 1996a). In our example, reference station MORP, which is set up in IGS standards, will be incorporated in the analysis of European Regional Network by a Regional Network Associate Analysis Centre (RNAAC). By looking at the history of the levelling results carried out in the region we can have same kind of information about regional movements. As part of this project, possible local subsidence will be monitored by precise levelling from a light house built on a stable surface. Comparison of sea level analysis results from the two tide gauges might reveal such a local movement as well.

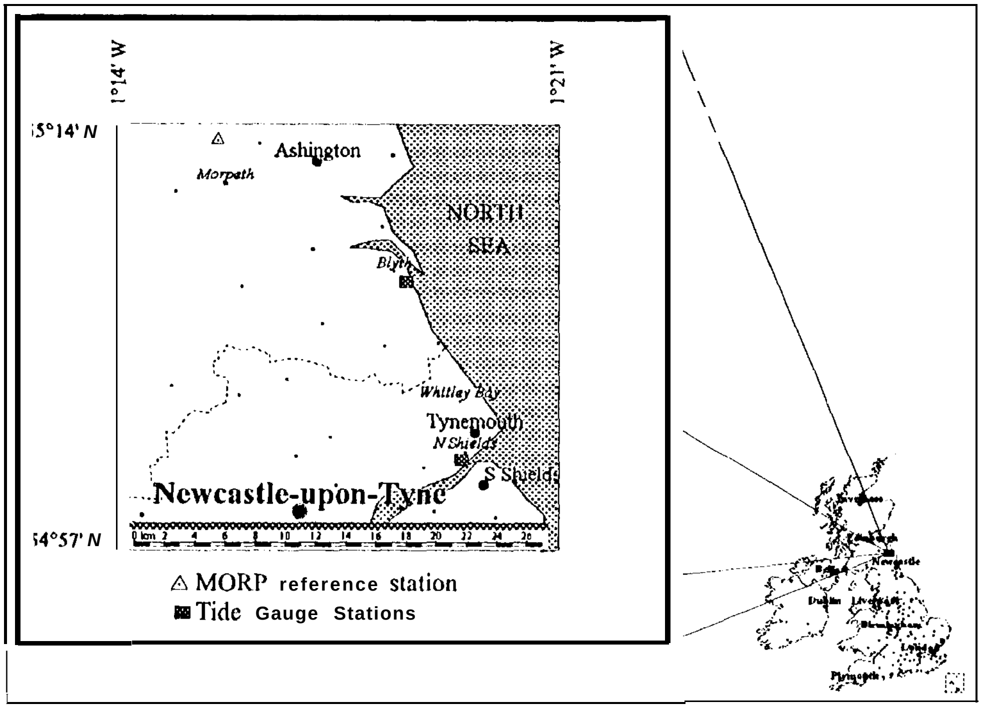


Figure 1. Location of the permanent GPS station MORP and the Tide Gauges

Both tide gauge GPS benchmarks will be occupied every two weeks for a couple of years in order to construct a height time series. It is hoped that this will lead to a better assessment of strategies and errors, and reveal various possible types of vertical signal. Coordinates of the GPS benchmarks will be derived using global IGS products and solutions, Another method that will be tested is precise point positioning using precise ephemerides and satellite clocks from the Jet Propulsion Laboratory (JPL) (Zumberge et al., 1997). Relative positioning between MORP and the tide gauge GPS benchmarks will also be applied in an attempt to separate regional and local crustal movements. Moreover, we know that tropospheric zenith delays are highly correlated over short distances. In our example, reference station is not far from the tide gauge GPS stations (16 km from Blyth and 28 km from North Shields). Therefore, by applying relative point positioning, height estimates are expected to be improved due to reduced zenith delay error.

GPS processing and sea level analysis results from the two tide gauges will enable us to study regional correlations. Thus, vertical crustal movements, tropospheric zenith delay effects, geographical location differences might be interpreted better. Conclusions drawn from such comparisons should direct us towards an optimal approach for sea level monitoring.

A HIGH PRECISION GPS STATION: MORP

A new permanent high precision GPS station, MORP, has been installed in the Northeast of England (Blewitt et al., 1996b). It is aimed to provide three dimensional control with 1 mm stability over decades. It is located 32 km north of Newcastle and 6 km north of Morpeth. The station is away from multipath sources; has good satellite visibility; supported by electricity and telephone lines; and has a shallow bedrock depth. To assure high stability monumentation the GPS antenna is situated on a pyramid shape stone pillar weighing 4.5 tones and closely matching the properties of the underlying bedrock (Figure 2). A choke-ring antenna is used and connected to a TurboRogue SNR-12 GPS

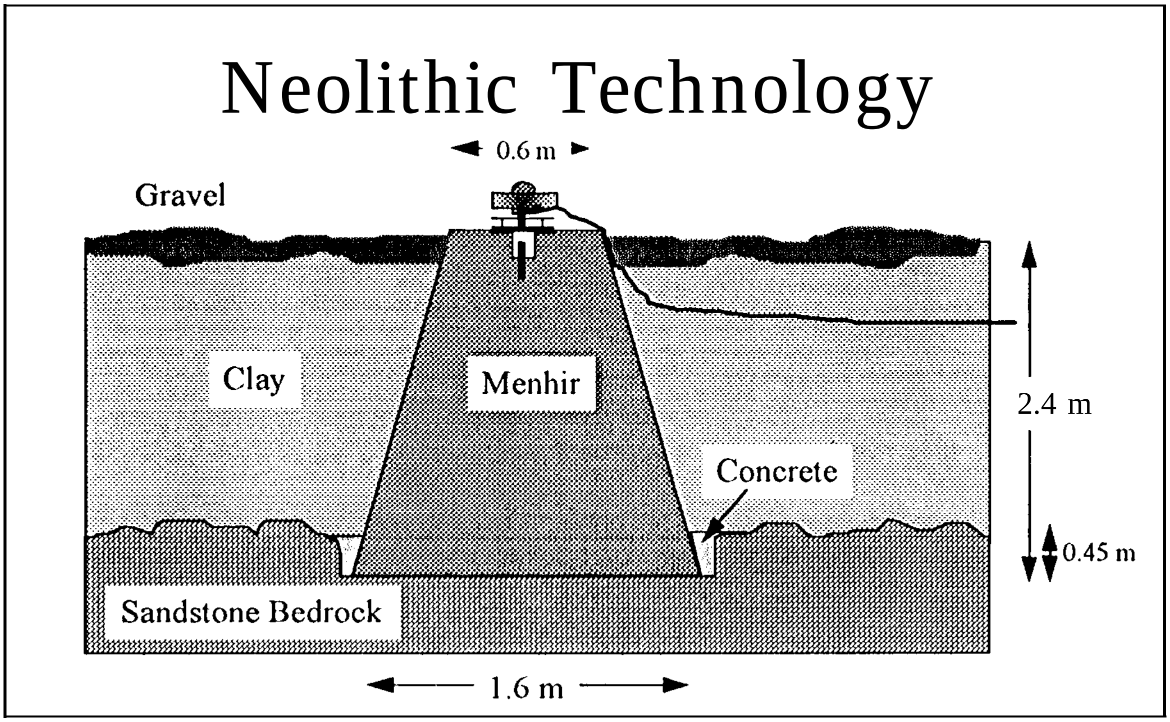


Figure 2. Cross section showing the ground structure of MORP (Blewitt et al.,1996b)

receiver located in a hut 45 m away from the antenna. Currently the station is in operation collecting observations every 30 seconds, and the data are downloaded every 24 hours to Newcastle University via modems and telephone lines,

TIDE GAUGE INFORMATION

Blyth tide gauge, situated beside the North Sea, has 32 years of sea level record. Sea level recording device is electronic, and the data obtained from this device is loaded directly to a PC. The distance from the reference station MORP is about 16 km. GPS benchmark BLYT is set up less than hundred meters from the tide gauge hut.

North Shields tide gauge is located by the Tyne River about 1.5 km from the river delta. It has 95 years of sea level record which is very suitable to study sea level changes. GPS benchmark NORT is situated about hundred metres away from the tide gauge shed since the multipath environment is extremely poor at the tide gauge site. The distance to the reference station MORP is about 28 km.

The ground where both tide gauges are located does not appear to be stable (sites which are attached to the sea bottom by wooden columns). So it is worthwhile studying vertical movements,

Plot of North Shields sea level data shows 2 mm/yr rising trend which matches global sea level rise given in the literature (Baker, 1993) (Figure 3). High correlation between the two tide gauge sea level variations can be seen from the comparison of corresponding 20 years of sea level data (Figure 4).

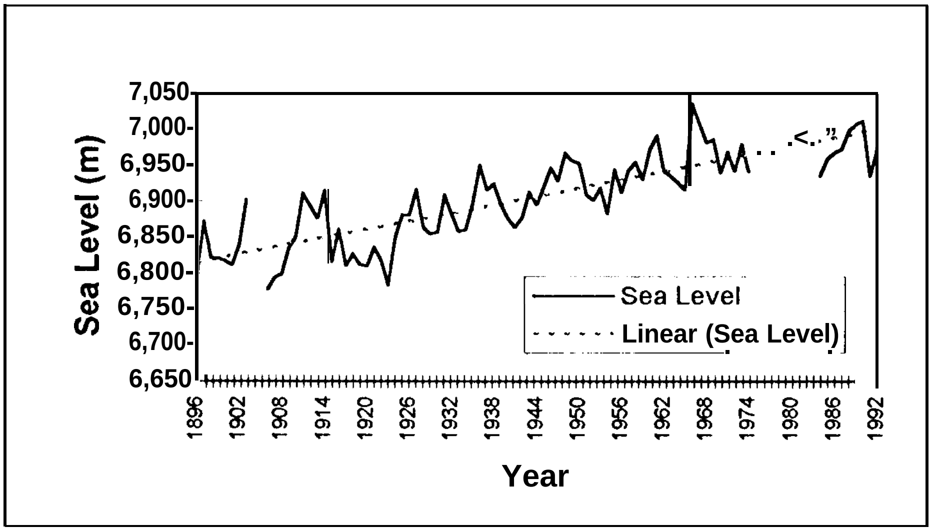


Figure 3. North Shields Sea Level Trend

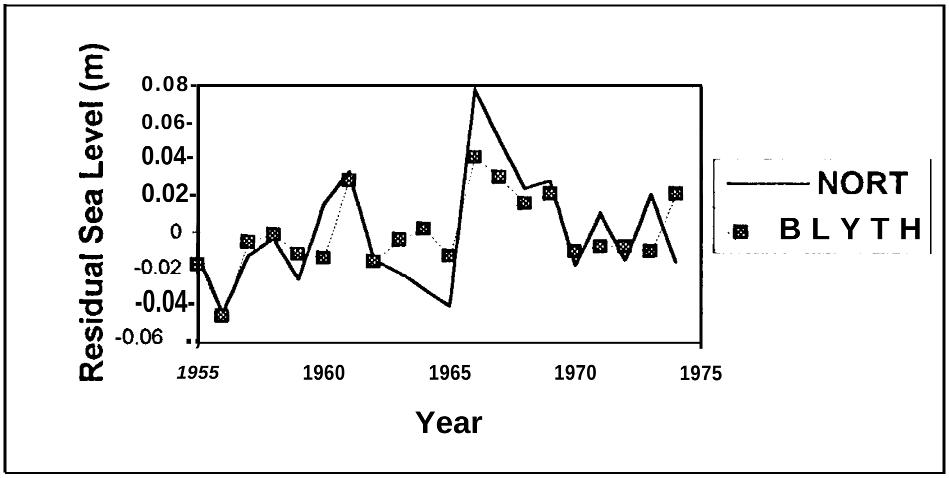


Figure 4. Sea Level Correlation Between Blyth and North Shields

PRELIMINARY RESULTS

GPS data, collected at tide gauge sites, have been processed by using relative and precise point positioning (PPP) techniques (Zumberge et al. 1997). For relative positioning MORP is held fixed. Trimble's GPSurvey and JPL's GIPSY OASIS 11 softwares have been used for processing. Comparison of five-day BLYT data indicates that commercial GPSurvey results are less precise (Figure 5). The PPP technique has been applied for both the reference station and the tide gauge GPS data, and daily repeatabilities have been compared (Figure 6). 24-hour MORP PPP results are more precise than 6-hour tide gauge GPS PPP results.

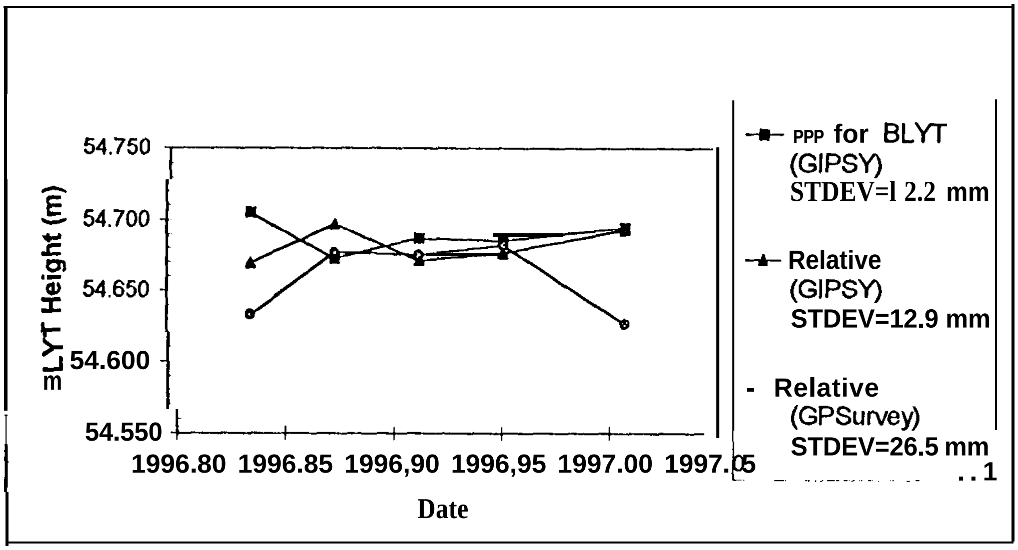


Figure 5. Software/Technique For Point Positioning: BLYT-MORP(16 km)

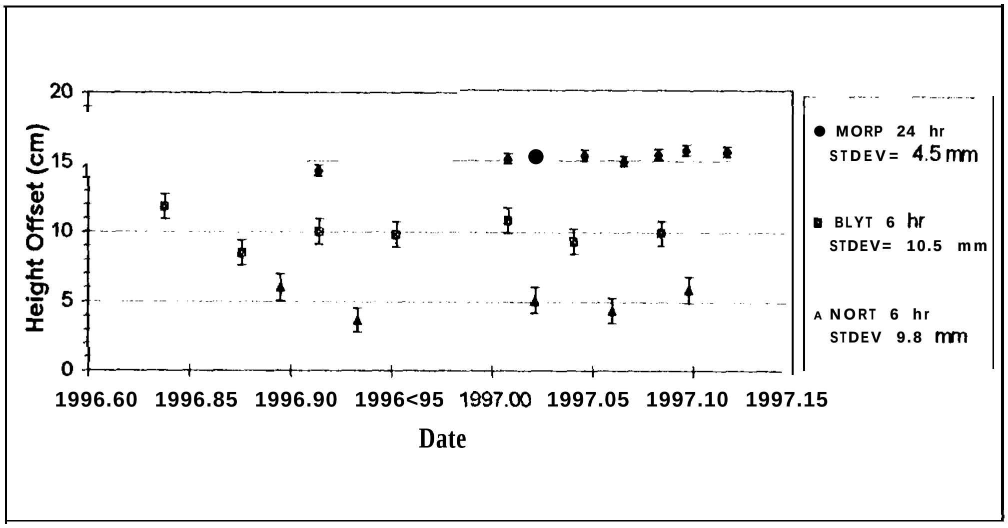


Figure 6. Precise Point Positioning (GIPSY, 30 sec data)

Multipath environment at the tide gauge sites is not good, therefore permanent GPS antennas can not be placed on the tide gauges. Places chosen for GPS benchmarks are not suitable for permanent antenna set up due to the fishing industry at the harbour and security reasons.

Since height errors are believed to be dominated by tropospheric errors, and tropospheric conditions are strongly correlated over several days, we are testing the idea that measurements made every two weeks might produce comparable precision as for permanent stations, for studies of long-term change in height. Tide gauge GPS benchmarks are occupied every two weeks with 6-hour observation window. Observations are carried out by one person, so it is difficult to routinely spend more than 6 hours doing measurements.

In order to study the effect of different data spans on PPP precision some tests have been applied for MORP data. 24-hour data were divided into 12, 8, 6, 4, and 3-hour periods. Weighted repeatabilities have been calculated for each period, and then results have been compared (Figure 7). It is seen from Figure 7 that, as expected, precision decreases with the decreasing data span, In addition, the effect of different data epoch on the PPP has been tested. 30 second epochs have been applied for 3,6, and 24-hour time spans. When epoch is increased computation time is a little bit decreased, but the change in results is not statistically significant (Figure 7).

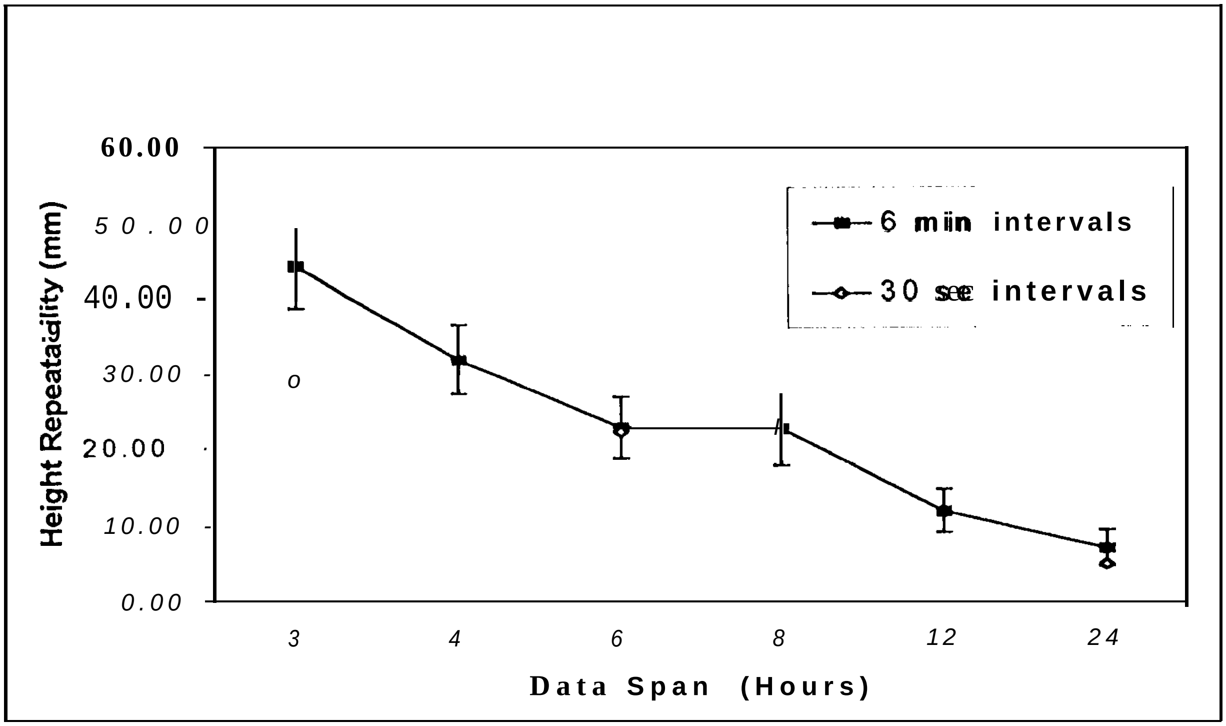


Figure 7. Effect of Data Span on Precision (MORP Precise Point Positioning, GIPSY)

CONCLUSION

We have recently initiated an investigation of absolute sea level change in the Northeast of England. Results presented above are the first impressions of the study and very preliminary, For example, due to some GPS data collection failure encountered in practice and incomplete processing, we only have a few corresponding data spans for software/technique comparison. The same comparison will be repeated once a long term complete set of estimated heights has been derived.

In addition, more robust results for the sea level trend in North Shields and for the sea level correlation between the two tide gauges await a more thorough analysis of the sea level data.

One aspect of future work will be to overcome common problems experienced in the data collection procedure. In addition, if regional meteorological data can be obtained, it is possible that tropospheric correlations can be analysed and a methodology implemented to improve regional relative positioning.

ACKNOWLEDGEMENT'S

We would like to thank Chris Pinal, Ozsen Corumluoglu, and Yung-Lung Tsou for their help in performing the levelling measurements.

REFERENCES

Baker, T. F., 1993, Absolute Sea Level Measurements, Climate Change and Vertical Crustal Movements: Global and Planetary Change, volume. 8, p. 149-159.

Blewitt, G., P. Davies, and U SanIi, 1996a, GPS Strategies for Measuring Absolute Sea-level Change, Wegener 96: Vila Nova de Gaia, Hotel Solverde, June 3-7, Portugal.

Blewitt, G., Kawar, R., Handgraaf, J., 1996b, Neolithic technology: Lesson for Space Geodesy, In EOS, Transactions, American Geophysical Union, Spring Meeting Supplement, 72-74, (5)

Zumberge, J. F., M.B. Heflin, D. C. Fefferson, M.M. Watlins, F. H. Webb, 1997, Precise point positioning for the efficient and robust analysis of GPS data from large networks, Journal of Geophysical Research, volume 102, No B3, pp. 5005-5018.

VARIATIONS IN SEA LEVEL CHANGE ALONG THE CASCADIA MARGIN: COASTAL HAZARD, SEISMIC HAZARD AND GEODYNAMICS

M. Meghan Miller, Dan Johnson,
Department of Geology, Central Washington University
Ellensburg, Wa 98926 USA

Ray Weldon, Randy Palmer,
Department of Geological Sciences, University of Oregon
Eugene, Or 97403 USA

A fortuitous combination of long history tide gauges and regional GPS resources make the Pacific Northwest an ideal location for sorting out the relative contributions of regional and global processes to historic sea level rise, using a new technology approach to tide gauge - GPS integration. In addition to adding fundamental new constraints to the processes of global sea level rise and solid earth deformation, relative changes in sea level drive a variety of regional natural hazards including seismic risk, co-seismic subsidence and differential sea inundation, tsunami hazard, and accelerated coastal erosion.

Determinations of global sea level rise rely on a small fraction of available tide gauge records because so many instrumented coastlines experience tectonic or isostatic crustal deformation, and thus have necessarily been deleted from datasets used to infer historic sea level rates (Douglas, 1991). Adding six to eight newly corrected records from the Pacific Northwest that span nearly 100 years each would substantially enhance the data set used to determine rates and possible temporal variations in global sea level rise. Substantial existing GPS infrastructure in the Pacific Northwest and a new experiment design makes this a cost effective pilot study.

Both tectonic processes and global changes in sea level contribute to the observed sea level rise in the Pacific Northwest, The strongest tectonic signal along the coast comes from elastic strain accumulation above the locked and transitional parts of the Cascadia subduction zone (e. g., Hyndman and Wang, 1995), In southern Canada, this results in nearly a centimeter per year of horizontal shortening orthogonal to the subduction zone (Dragert and Hyndman, 1995); concomitant vertical interseismic uplift is probably several mm/a based on vertical releveling data (Mitchell et al., 1994), In addition, some permanent deformation also accumulates during the interseismic interval, but has not been estimated in detail, In addition to global sea level rise, meteorological and oceanographic events, although transient, may contribute to or contaminate the historic record.

In this context, tide gauges in the Pacific Northwest measure an undifferentiated combination of eustatic sea level rise, interseismic (elastic and permanent) deformation, adjustments to the geoid, meteorological and oceanographic events, as well as any motion of the pier or structure upon which the gauge is mounted. Isostatic deformation is thought to be negligible in this region, based on the relatively old age of the Puget lobe of the Cordilleran ice sheet in this area (Beget et al., 1997). These very long but undifferentiated records could contribute substantially to understanding of historic sea level rise through characterization of the various components using several integrated observational and modeling approaches. GPS that will simultaneously measure the interseismic deformation, and isolate the motion of the pier or hut in which the gauge is mounted. TOPEX data can be used to independently monitor sea level rise and oceanographic or meteorological events (Weldon, unpublished data, 1996). Geologic evidence provides understanding of coseismic deformation, long term estimates of permanent deformation, recurrence intervals, role of crustal structures in spatial variations in sea level rise, Finally, modeling that relies on the input of these data can characterize interseismic elastic deformation, coseismic elastic deformation, isostatic rebound, and adjustments to the geoid that result from both interseismic and co-seismic deformation. Thus, nearly all the parameters measured by tide gauges can be independently measured or estimated, some in more than one way, to characterize the total sea level rise budget that contributes to the tide gauge record. The new technique potentially renders the long record usable for estimates of global sea level rise, in addition to characterizing important processes of geodynamics.

Mitchell et al (1994) present careful analyses of the integrated tide gauge and vertical leveling record from the Pacific Northwest. Their results indicate that differential vertical motions characterize the Cascadia margin. These data sets are limited because they determine only relative vertical motions, which are partly constrained near the coast by ties to tide gauges. The absolute motions of the inland ends of the releveling lines are unconstrained; GPS could further add constraints to these historic data sets. Such constraints would substantially enhance the accuracy and power of models that describe interseismic deformation in the Pacific Northwest and thus substantially enhance our understanding of seismic risk along the Cascadia margin. Another important aspect of our previous work is the demonstrable variation in vertical uplift rates along the margin. This points to several possible explanations: along strike variation in the geometric character of the subduction zone and the possible role of crustal faults and folds in controlling the spatial variation of uplift. These provide important information on the character of the subduction zone and the forces that drive deformation of the lithosphere.

The March 1997 Sea Level Workshop at JPL witnessed considerable discussion of whether GPS monitoring efforts should be directed towards monitoring vertical deformation of land near tide gauges or the motion of the tide gauge itself. In order to best unravel the tide gauge history, monitoring the gauge itself or the hut or pier where it was mounted was advocated. This approach gives the best chance of deciphering the long history tidal record, particularly if the motion of the pier is systematic. On the other hand, this approach commits expensive resources to monitoring an unstable structure rather than directly observing earth phenomenon, and was difficult for crustal deformation investigators to support. Further, it gives no indication of relative sea level rise at a particular location, for instance if the pier is subsiding; such information is of critical importance from a hazards perspective. There is an inexpensive solution to this problem, that would allow careful monitoring of both vertical crustal motions and relative motion of the tide gauge. We propose an approach that uses a high precision geodetic quality dual frequency receiver on a drilled braced monument on bedrock, where possible, to monitor vertical crustal motions. A less expensive system, using a single frequency receiver could then be connected to an antenna mounted on the tide gauge structure itself, or as close as possible to it. The tide gauge position could then be solved for in a static or differential mode and precise solutions for it's motion would rely on constraints generated by monitoring of the bedrock site, This allows cost effective evaluation of the relative vertical motions of the tide gauge which provide the correction to the historic tidal record. It also allows careful estimation of crustal deformation and assessment of relative sea level rise on a regional scale, which ultimately drives coastal hazard. We call this approach Differential Vertical Motion Estimation (DiVE).

Under the auspices of a recently formed consortium (PANGA, Pacific Northwest Geodetic Array) of workers interested in regional GPS monitoring for earth science applications, we (Miller, Johnson, Rubin, Qamar, and Humphreys) currently hold NSF funding for a GPS network designed to monitor horizontal deformation and for a data analysis facility at Central Washington University. The PANGA network and facility provide a backbone regional network that would development and verification of the DiVE application at a relatively small incremental cost to the project. Thus, data analysis and network coordination come at no cost to the proposed pilot study.

We propose to monitor the Cascadia convergent margin, which has the assets of long history tide gauge records that, if corrected, could substantially enhance estimates of global sea level change, densely populated areas that are exposed to seismic risk and coastal hazards, and an ideal setting to address questions concerning the driving forces of continent-ocean subduction and deformation, This pilot study will verify the utility of integrated tide gauge and DiVE GPS studies, enhance the historic global sea level record, characterize natural hazards such as seismic risk, sea level inundation, tsunami hazard and coastal erosion acceleration that are intimately related to global and regional sea level rise, and better constrain crustal dynamics in the Pacific Northwest. Integration of tide gauge records, DiVE GPS observations, TOPEX/POSEIDON data when available, vertical releveling data, validation by consistency with geologic evidence for uplift or subsidence, and modeling provide an integrated and robust approach to understanding these interrelated processes.

REFERENCES

Beget, J. E., M. J. Keskinen, and K. P. Severin, Tehprochronologic **constraints on the Late Pleistocene history of the southern margin of the** Cordilleran **ice-sheet, Western Washington,** ***Quarternary Research, 47, 140-146, 1997,***

Douglas, B. C., Global Sea Level Rise, *Journal of Geophysical Research, 96,6981-6992, 1991.*

Dragert, H., and R. D. Hyndman, Continuous GPS monitoring of elastic strain in the Northern Cascadia subduction zone, ***Geophysical Research Letters, 22, 755-758, 1995.***

Hyndman, R. D., and K. Wang, Constraints on the zone of potential great earthquakes on the Cascadia subduction thrust from deformation and the thermal regime, *Journal of Geophysical Research,* ***in press,*** 1995.

Mitchell, C. E., P. Vincent, R. J. Weldon, and M. A. Richards, Present day vertical deformation of the Cascadia margin, Pacific Northwest, United States, *Journal of Geophysical Research Solid Earth, 99, [B6],* 12257-12277, **1994.**

IGS-PSMSL

DATA HANDLING

Co-chairs:

Carey E. Nell
NASA Goddard Space Flight Center
Greenbelt, Maryland, U.S.A.

Mark Merrifield
University of Hawaii
Sea Level Center
Honolulu, Hawaii, U.S.A.

SUMMARY OF SESSION 5 — DATA HANDLING

Carey E. Nell, Mark Merrifield, Co-Chairs

The purpose of this session was to familiarize the IGS and sea level communities with how data and products were handled by these groups.

Carey Nell, manager of the Crustal Dynamics data Information System (CDDIS), a global data center for the IGS, described the flow of data and data products within the IGS framework,

Mark Merrifield from the University of Hawaii Sea level Center discussed tide gauge data product flow

Phil Woodworth of the PSMSL provided an overview of the sea level data centers and presented any outstanding concerns raised during the previous sessions of the workshop.

Michael Bevis from the University of Hawaii discussed the need for situating the GPS receivers and tide gauge sensors as close as possible at collocation sites,

The papers following this introduction discuss these topics in detail,

Recommendations which resulted from this session included:

1. Approximately thirty tide gauge sites will be selected to collocate with GPS receivers. The data from sites not already part of the IGS network should be available at athe global data center level in order to be redily accessible to IGS analysis centers.
2. New products required to support tide gauge analysts, as well as formats, data flow paths, and timelines, need to be identified, Data centers should be notified of new products required for archiving.

FLOW OF GPS DATA AND PRODUCTS FOR THE IGS

Carey E. Noll
NASA Goddard Space Flight Center
Greenbelt, MD 20771 USA

INTRODUCTION TO THE IGS

The International GPS Service for Geodynamics (IGS) was formed by the International Association of Geodesy (IAG) to provide GPS data and highly accurate ephemerides in a timely fashion to the global science community to aid in geophysical research. This service has been operational since January 1994. The GPS data flows from a global network of permanent GPS tracking sites through a hierarchy of data centers before they are available to the user at designated global and regional data centers. A majority of these data flow from the receiver to global data centers within 24 hours of the end of the observation day. Common data formats and compression software are utilized throughout the data flow to facilitate efficient data transfer. IGS analysis centers retrieve these data daily to produce IGS products (e.g., orbits, clock corrections, Earth rotation parameters, and station positions). These products are then forwarded to the global data centers by the analysts for access by the IGS Analysis Coordinator, for generation of the final IGS orbit product, and for access by the user community in general. To further aid users of IGS data and products, the IGS Central Bureau information System (CBIS) was developed to provide information on IGS sites and participating data and analysis centers. The CBIS, accessible through ftp and the World Wide Web (WWW), provides up-to-date data holding summaries of the distributed data systems. The IGS, its data flow, and the archival and distribution at one of its data centers will be discussed.

IGS DATA AND PRODUCTS

In general, eighty percent of the GPS tracking data are delivered, archived, and publicly available within 24 hours after the end of observation day. Derived products, including an official IGS orbit, are available within ten days.

GPS Tracking Data

The network of IGS sites is composed of GPS receivers from a variety of manufacturers. To facilitate the analysis of these data, raw receiver data are downloaded on a daily basis by operational data centers and converted into a standard format, RINEX, Receiver Independent EXchange format (Gurtner, 1994). GPS tracking data from the IGS network are recorded at a thirty second sampling rate[1]. The GPS data unit typically consists of two daily files, starting at 00:00:00 UTC and ending at 23:59:30 UTC; one file contains the

---

[1] Selected sites sample data at higher rates (e.g., one second) in support of other programs; the data are dessimated at operational data centers prior to submission to the **IGS** data flow.

range observations, a second file contains the GPS broadcast ephemerides for all satellites tracked. These two RINEX data files form the smallest unit of GPS data for the IGS and after format conversion, are forwarded to a regional or global data center for archival and distribution. For selected sites, meteorological data from collocated weather stations are available and submitted in the data flow with the observation and navigation data; these data are also in RINEX format. Each site produces approximately 0.6 Mbytes of data per day in compressed RINEX format.

The daily GPS data in RINEX format from a single site are approximately 2.0 Mbytes in size; with a network of over 140 sites, this over 250 Mbytes per day. Thus, to lessen electronic network traffic as well as storage at the various data centers, a data compression scheme was promoted from the start of the IGS test campaign, It was realized that the chosen software must be executable on a variety of platforms (e.g., UNIX, VAX/VMS, and PC) and must be in the public domain. After testing several packages, UNIX compression was the software of choice and executable for VAX/VMS and PC platforms were obtained and distributed to data and analysis centers. This data compression algorithm reduces the size of the distributed files by approximately a factor of three; thus daily GPS files average 0.6 Mbytes per site, or a total of 70 Mbytes per day at a typical IGS global data center (GDC).

IGS Products

Seven IGS data analysis centers (ACs) retrieve the GPS tracking data daily from the global data centers to produce IGS products. These products consist of daily precise satellite ephemerides, clock corrections, Earth rotation parameters, and station positions. The files arc sent to the IGS global data centers by these analysis centers in uncompressed ASCII (in general), using NGS SP3 format (Remondi, 1989) for the precise ephemerides and Software Independent Exchange Format, SINEX, (Blewitt et. al., 1995) for the station position solutions. The Analysis Coordinator for the IGS, located at NRCan, then accesses one of the global data centers on a regular basis to retrieve these products to derive the combined IGS orbits, clock corrections, and Earth rotation parameters as well as to generate reports on data quality and statistics on product comparisons (Beutler et. al., 1993). The time delay of the IGS final orbit products is dependent upon the timeliness of the individual IGS analysis centers; on average, the combined orbit is generated within two to three days of receipt of data from all analysis centers (typically within ten days). Furthermore, the lGS Analysis Coordinator produces a rapid orbit product, available within 24 hours and a predicted orbit, available within one hour UTC of the day for which this prediction was produced. The precise and rapid orbit products are available from the global data centers as well as the IGS Central Bureau.

Recently, associate analysis centers (AACs) have begun analyzing IGS data on a regional and global basis. To date, six groups regularly produce regionally-oriented analysis in SINEX format to global data centers, Three global network associate analysis centers (GNAACs) incorporate the weekly solutions provided by the analysis centers and the regional network associate analysis centers (RNAACs) to produce combined network solutions.

FLOW OF IGS DATA AND INFORMATION

The flow of lGS data (including both GPS data and derived products) as well as general information can be divided into several levels (Gurtner and Neilan, 1995) as shown in Figure 1:

- Tracking Stations
- Data Centers (operational, regional, and global)
- Analysis Centers
- Analysis Center Coordinator
- Central Bureau (including the Central Bureau Information System, CBIS)

The components of the IGS dealing with flow of data and products will be discussed in more detail below.

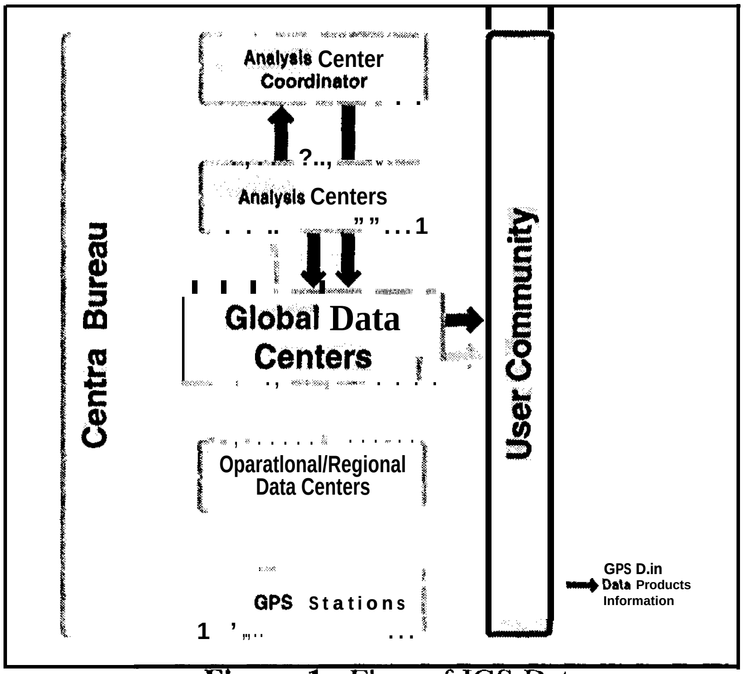


Figure 1. Flow of IGS Data

Tracking Stations

The global network of GPS tracking stations are equipped with precision, dual-frequency, P-code receivers operating at a thirty-second sampling rate. The IGS currently supports over 140 globally distributed stations, These stations are continuously tracking and are accessible through phone lines, network, or satellite connections thus permitting rapid, automated download of data on a daily basis. Any station wishing to participate in the IGS must submit a completed station log to the IGS Central Bureau, detailing the receiver, site location, responsible agencies, and other general information. These station logs are accessible through the CBIS. The IGS has established a hierarchy of these 140 sites since not all sites are utilized by every analysis center (Gurtner and Neilan, 1995). A core set of nearly seventy sites are analyzed on a daily basis by most centers; these sites are called global sites. Sites used by one or two analysis centers for densification on a regional basis are termed regional sites. Finally, sites part of highly dense networks, such as one established in southern California to monitor earthquake deformation, are termed local sites. This classification of IGS sites determines how far in the data center hierarchy the

data are archived. For example, global sites should flow to the global data center level, where regional sites are typically archived at a regional data center only.

Procedures have been developed by the IGS CB for new stations wishing to participate in the IGS (Gurtner and Neilan, 1995). These procedures include recommendations for installation of the site, identification of data flow paths and contacts, and creation of proper site documentation.

Data Centers

During the IGS design phases, it was realized that a distributed data flow and archive scheme would be vital to the success of the service. Thus, the IGS has established a hierarchy of data centers to distribute data from the network of tracking stations: operational, regional, and global data centers. Operational data centers (ODCs) are responsible for the direct interface to the GPS receiver, connecting to the remote site daily and downloading and archiving the raw receiver data. The quality of these data are validated by checking the number of observations, number of observed satellites, date and time of the first and last record in the file. The data are then translated from raw receiver format to a common format and compressed. Both the observation and navigation files (and sometimes meteorological data) are then transmitted to a regional or global data center within a few hours following the end of the observation day.

Regional data centers (RDCs) gather data from various operational data centers and maintain an archive for users interested in stations of a particular region. These data centers forward data from designated global sites to the global data centers ideally within one to two hours of receipt. IGS regional data centers have been established in several areas, including Europe and Australia.

The IGS global data centers (GDCs) are ideally the principle GPS data source for the IGS analysis centers and the general user community. GDCS are tasked to provide an on-line archive of at least 100 days of GPS data in the common data format, including, at a minimum, the data from all global IGS sites. The GDCS are also required to provide an on-line archive of derived products, generated by the IGS analysis centers and associate analysis centers; two of the three global data centers currently provide on-line access to IGS products generated since the start of the IGS test campaign (June 1992). These data centers equalize holdings of global sites and derived products on a daily basis (at minimum). The three GDCS provide the IGS with a level of redundancy, thus preventing a single point of failure should a data center become unavailable. Users can continue to reliably access data on a daily basis from one of the other two data centers. Furthermore, three centers reduce the network traffic that could occur to a single geographical location. The flow of GPS data from the current network of IGS tracking stations to global data centers is shown in Figure 2; Table 1 presents this information by GPS station name. Table 2 lists the data centers currently supporting the lGS.

IGS data and products are freely available to the public. Interested users can access the IGS CBIS in order to determine a convenient source to access and follow the procedures for connecting to the selected data center.

Analysis Centers

The seven IGS data analysis centers (ACs) retrieve the GPS tracking data daily from the global data centers to produce daily orbit products and weekly Earth rotation parameters and station position solutions; the nine associate Analysis Centers (AACs) retrieve the data

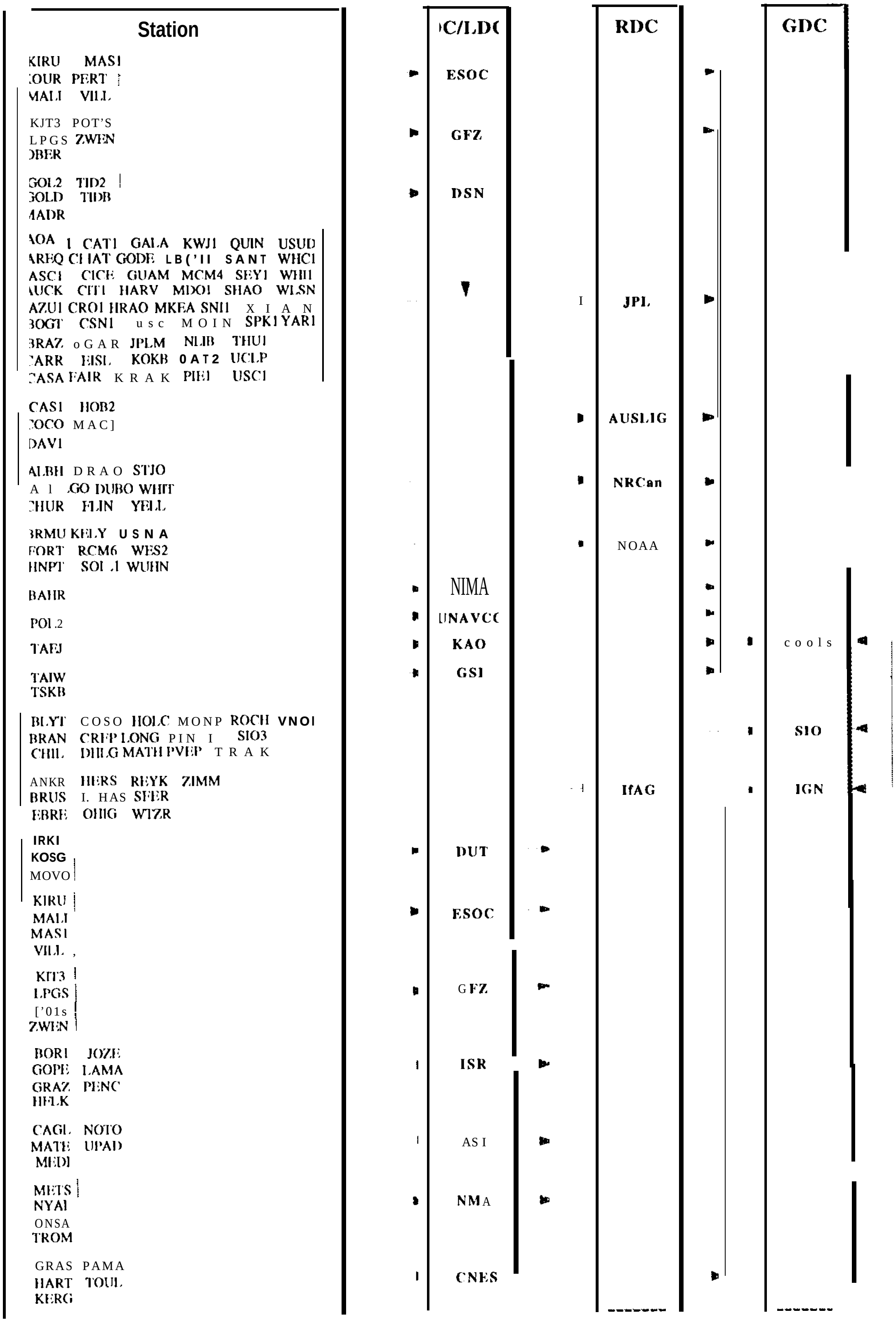


Figure 2. IGS Data Flow (by Data Center)

‘J’able 1. IGS Data Flow (by Station)

Station	OC/LDC	RDC	GDC
ALBH*		NRCan	CDDIS
ALGO*		NRCan	CDDIS
ANKR*		rfAG	IGN
AOAI		JPL	CDDIS
AREQ*		JP1.	CDDIS
ASC1•		JPL	CDDIS
AUCK*		JPL	CDDIS
AZU1		JPL	CDDIS
BAHR*	NIMA		CDDIS
BLYT			S1O
BOGT		JPL	CDDIS
BOR1	ISR	IfAG	rGN
BRAN			SIO
BRAZ*		JPL	CDDIS
BRMU*		NOAA	CDDIS
BRUS		lfAG	IGN
CAGL.	AS I	IfAG	IGN
CARR		JPL	CDDIS
CAS1*		AUSLIG	CDDIS
CASA		JPL	CDDIS
CAT1		JPL	CDDIS
CHAT*		JPL	CDDIS
CHIL			S1O
CHUR		NRCan	CDDIS
CICE		JPL	CDDIS
CIT1		JPL	CDDIS
COCO*		AUSLIG	CDDIS
COSO			SIO
CRFP			*SIO*
CRO1*		JPL	CDDIS
CSN1		JPL	CDDIS
DAV 1•		AUSLIG	CDDIS
DGAR*		JPL	CDDIS
DHLG			S1O
DRAO*		NRCan	CDDIS
DUBO		NRCan	CODIS
EBRE		IfAG	IGN
EISL*		JPL	CDDIS
FAIR*		JPL	CDDIS
FLIN		NRCan	CDDIS
FORT*		**NOAA**	CDDIS
GALA		JPL	CDDIS
GODE		**JPJ .**	CDDIS
GOL2	DSN	JPL	CDDIS
GOLD*	DSN	JPL	cools
GOPE	lSR	IfAG	IGN
GRAS	CNES		IGN
GRAZ	ISR	IfAG	IGN
GUAM*		JPL	CDDIS
HART	CNES		rGN
HARV		JPL	CDDIS
HERS		IfAG	rGN
HFLK	lSR	**IfAG**	IGN
HNPT		**NOAA**	CDDIS
HOB2*		AUSLIG	CDDIS
HOLC			SIO
HRAO		**JPL.**	CDDIS
IISC*		JPL	CDDIS
IRKT*	OUT	IfAG	IGN
JOZE	ISR	JfAG	IGN
JPLM		JPL	CDDIS
KELY*		NOAA	CDDIS
KERG*	CNES		IGN
KIRU	ESOC	(rime) | IfAG	CDDIS | IGN
KIT3*	GFZ	**(none)** I IfAG	CDDIS|IGN
KOKB*		JPL	CDDIS
KOSG*	DUT	IfAG	rGN
KOUR*	ESOC		CDDIS
KRAK		JPL	CDDIS
KWJ 1*		JPL	CDDIS
LAMA	ISR	IfAG	IGN
LBCH		JPL	CDDIS
LHAS*		IfAG	IGN
LONG			S1O
LPGS*	GFZ		COON I IGN
MAC1		AUSLIG	CDDIS
MADR*	DSN	JPL	CDDIS
MALI*	ESOC	(none) | IfAG	CDDIS | IGN
MAS1*	ESOC	(none) | IfAG	CDDIS | IGN
MATE*	AS I	rfAG	IGN
MATH			SIO
MCM4*		JPL	CDDIS
MDO1*		JPL	CDDIS
MDVO*	DUT	IfAG	IGN
MEDI	ASI	JfAG	IGN
METS*	NMA	rfAG	IGN
MKEA*		JPL	cools
MOJN		JPL	CODIS
MONP			SJo
M .IB*		JPL	CDDIS
NOTO	ASI	IfAG	IGN
NYAL*	NMA	lfAG	lGN
0AT2		JPL	*CDDIS*
OBER	GFZ	(none) | IfAG	CDDIS | IGN
OHIG*		IfAG	IGN
ONSA*	NMA	IfAG	JGN
PAMA*	CNES		IGN
PENC	ISR	IfAG	IGN
PERT*	ESOC		CDDIS
PIE1		JPL	CDDIS
PIN1			Slo
POL2*	UNAVCO		CDDIS
POTS	GFZ	(none) | IfAG	CDDIS | IGN
PVEP			S1O
QUIN		JPL	CDDIS
RCM6*		NOAA	CDDIS
REYK*		rfAG	IGN
ROCH			SIO
SANT*		JPL	cools
SEY1		JPJ.	CDDIS
SFER		lfAG	IGN
SHAO*		JPL	CDDIS
SIO3			SIO
SNI1		JPL	CDDIS
SOL1		NOAA	CDDIS
SPK1		JPL	CDDIS
STJO*		NRCan	corm
TAEJ*	KAO		CDDIS
TAJW*	GSI		CDDIS
THU1*		JPL	CDDIS
TID2	DSN	JPL	corms
TIDB*	DSN	JPL	CDDIS
TOUL	CNES		IGN
TRAK			SIO
TROM*	NMA	IfAG	IGN
TSKB*	GSI		CDDIS
UCLP		JPL	CDDIS
UPAD	ASI	IfAG	lGN
USC1		JPL	CDDIS
USNA		*GODC*	CDDIS
USUD*		JPL	CDDIS
VILL	ESOC	(none) | IfAG	CDDIS | IGN
VNOP			*SIO*
WES2*		NOAA	corm
WHC1		J PI	CDDIS
WHI1		JPL	CDDIS
WHIT*		NRCan	CDDIS
WLSN		JPJ.	CODIS
WTZR*		IfAG	[GN
WUHN*		NOAA	CDDIS
XIAN		Jr’l.	CDDIS
YAR1*		JPL	CDDIS
YELL*		NRCan	corm
ZIMM		IfAG	IGN
ZWEN*	GFZ	(none) | IfAG	CDDIS I IGN

67 global stations; 146 total stations

Notes: * indicates global stations
| notation indicates duplicate flow of data

Table 2. Data Centers Supporting the IGS

Operational **Data** Centers	
ASI	Italian Space Agency
AUSLIG	Australian Land Information Group
CNES	Centre National d'Etudes Spatiales, France
DSN	Deep Space Network, USA
DUT	Delft University of Technology, The Netherlands
ESOC	European Space Agency (ESA) Space Operations Center, Germany
GFZ	GeoForschungsZentrum Germany
GSI	Geographical Survey Institute, Japan
ISR	Institute for Space Research, Austria
JPL	Jet Propulsion Laboratory, USA
KAO	Korean Astronomical Observatory
NIMA	National Image and Mapping Agency (formerly DMA), USA
NMA	Norwegian Mapping Authority
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources Canada
SIO	Scripps institution of Oceanography, USA
UNAVCO	University NAVSTAR Consortium, USA
Regional Data Centers	
AUSLIG	Australian Land information Group
IfAG	Institut für Angewadte Geodäsie, Germany
JPL	Jet Propulsion Laboratory, USA
NOAA/GODC	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources Canada
Global Data Centers	
CDDIS	Crustal Dynamics Data Information System, NASA GSFC, USA
IGN	Institut Géographique National, France
SIO	Scripps Institution of Oceanography, USA

and products to produce station position solutions. These AC solutions, along with summary files detailing data processing techniques, station and satellite statistics, etc., are then submitted to the global data centers within one week of the end of the observation week; AAC solutions typically are submitted two to three weeks later.

Analysis Center Coordinator

The Analysis Center Coordinator, located at NRCan, retrieves the derived products and produces a combined IGS orbit product based on a weighted average of the seven individual analysis center results. The combined orbit is then made available to the GDCs and the IGS CBIS within ten days following the end of the observation week. Rapid and predicted orbits are also generated at NRCan; rapid orbits are available within 24 hours while the predicted orbits are available within one hour UTC of the day for which this prediction was generated.

Central Bureau

The Central Bureau, located at JPL, sees to the day-to-day operations and management of the IGS. The Central Bureau facilitates communication within the IGS community through several electronic mail services. The Central Bureau also has created, operates, and maintains the Central Bureau information System (CBIS) (Liu, et. al., 1995), designed to disseminate information about the IGS and its participants within the community as well as to other interested parties, The CBIS was developed to provide a central source for general information on the IGS as well as pointers to the distributed data centers, guiding users to the most efficient access to data and product holdings, Although the CBIS is a central data information system, the underlying data are updated via automated queries to the distributed data centers. These queries update the CBIS data holdings information as well as GPS status reports and IGS electronic mail archives several times per day, Other data, such as station configuration logs and the official IGS product archives, are deposited when new or updated information is generated.

CONCLUSIONS

The IGS has shown that near real-time availability of GPS data is a reality. The hierarchy that was established in both tracking stations and data centers has streamlined data flow. with the global data center serving as the main interface between the data and the user, Standards in data formats and compression software are essential to the successful operation of the IGS. Furthermore, automation in data archiving and retrieval is a necessity in order to provide near real-time access to data over an extended period of time, The IGS has found, however, that some data flow paths require optimization in order to prevent the flow of redundant data to data centers, as well as scheduling of data deliveries to avoid congestion over electronic networks, The IGS would also like to encourage the stations and operational data centers to upload the data to regional and global data centers even faster than the current 24 hour average. This schedule would permit the analysis centers to produce more rapid orbit products.

REFERENCES

Beutler, G. “The 1992 IGS Test Campaign, Epoch ’92, and the IGS Pilot Service: An Overview” in *Proceedings of the 1993 IGS Workshop.* Druckerei der Universitat Bern, 1993.

Blewitt, G., Y. Bock, and J. Kouba. “Constructing the IGS Polyhedron by Distributed Processing” in *Proceedings of the IGS Workshop on the Densification of the ITRF through Regional GPS Networks.* JPL. 1995.

Gurtner, W. “RINEX: The Receiver Independent Exchange Format” in *GPS World, v.* 5, no. 7. July 1994.

Gurtner, W. and R. Neilan. “Network Operations, Standards and Data Flow Issues” in *Proceedings of the IGS Workshop on the Densification of the ITRF through Regional GPS Networks.* JPL. 1995,

Liu, R., et. al.. “Introducing the Central Bureau Information System of the International GPS Service for Geodynamics“ in *Inter-national GPS Service for Geodynamics Resource Information.* January 1995.

Remondi, B. W. “Extending the National Geodetic Survey Standard Orbit Formats” in *NOAA Technical Report NOS 133 NGS 46.* 1989.

Sea Level Data Flow

Mark A. Merrifield
University of Hawaii at Man
Honolulu, HI 96822

Abstract

The flow of in situ sea level data from tide gauge stations to various data assembly and distribution centers is described. Emphasis is placed on the international sea level network known as the Global Sea Level Observing System, and on sources of near-real time sea level data. Quality control procedures, as typified by those used by the University Hawaii Sea Level Center, are briefly discussed.

The GLOSS Network

The primary organizational entity for international sea level measurements is the Global Sea Level Observing System (GLOSS) coordinated by the Intergovernmental Oceanographic Commission (IOC). The mission of GLOSS is to ensure that in situ sea level measurements are collected and processed in a standardized manner for use by various research and government programs. A global array of approximately 300 permanent stations constitutes the current GLOSS network (Figure 1). Monthly and annual mean sea level values from the GLOSS stations are archived at the Permanent Service for Mean Sea Level (PSMSL). Higher frequency and near-real-time data from a subset of GLOSS stations are archived at the University of Hawaii Sea Level Center (UHSLC).

To standardize the GLOSS database, the following criteria are recommended:

i) a sample interval of at least 1 hour
ii) a timing accuracy of 1 minute
iii) a level of accuracy of approximately 10 mm for an individual datum
iv) a specified benchmark, or gauge zero, to which the data are referenced
vi) the capability to transfer data automatically to data centers, preferably in near-real-time via satellite
vii) the availability of ancillary environmental data such as winds and atmospheric pressure.

In many cases these criteria are not all satisfied, however, GLOSS contributors are encouraged to upgrade existing stations with these goals in mind.

GLOSS is reviewed on a regular basis by the IOC Group of Experts on GLOSS and Secretariat to ensure coordination with other international research programs, such as the World Ocean Circulation Experiment (WOCE) and the Climate Variability and Predictability Program (CLIVAR).

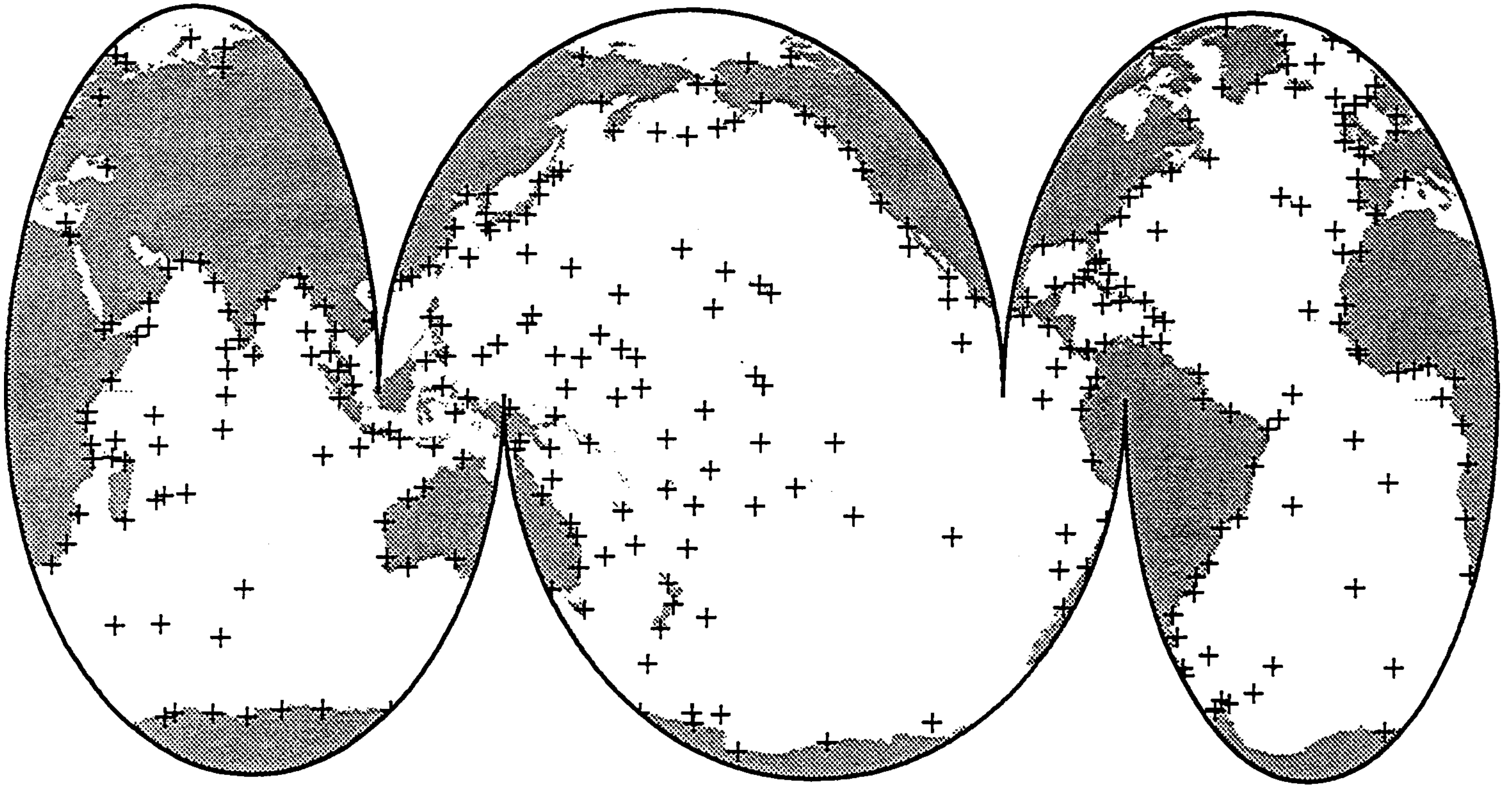


Figure 1. Projected Global Sea Level Observing System, 995.

Sea Level Data Centers

The Permanent Service for Mean Sea Level (PSMSL)

The PSMSL, located at the Proudman Oceanographic Laboratory, Bids ton Observatory UK, is the primary archive for monthly and annual mean sea level data for the majority of tide gauges from around the world, including the GLOSS network. As of 1996, 42,500 station-years of data were available in the PSMSL database for approximately 1,750 stations from over 170 national authorities, The PSMSL archive includes the longest time series of sea level on record in the so-called “Revised Local Reference” dataset. This dataset has been used extensively for trend and low frequency analyses.

The WOCE Sea Level Data Assembly

As part of the WOCE project, a high frequency (typically hourly) in situ sea level data base has been maintained to monitor geostrophic currents and to provide in situ data for joint analysis with satellite altimeters. The archive includes approximately 100 stations for which data are made available in fast mode (30-45 days) by the Data Assembly Center (DAC) at the UHSLC (described below), and 60 stations for which data are made available in delayed mode (1 year) by the British Oceanographic Data Centre (BODC). The delayed mode stations typically are remote sites that do not have satellite transmission capabilities or computer network access. Both the near-real-time and delayed mode data will be combined by the BODC into the final WOCE sea level data base which will be archived at PSMSL and the World Data Center-A for Oceanography.

The University of Hawaii Sea Level Center- Joint Archive for Sea Level (UHSLC-JASL)

The UHSLC maintains three databases: the near-real-time or “Fast Delivery” data which originated from the WOCE DAC activities, the Joint Archive for Sea Level (JASL), and monthly mean values which are used to produce the Integrated Global Services System (IGOSS) Sea Level Project in the Pacific (ISLP-Pat) data products.

The Fast Delivery dataset (Figure 2) was established to provide in-situ data on a time frame commensurate with altimeter data products. Data are typically obtained by direct satellite transmission or by electronic or surface mail. The Fast Delivery data are quality controlled at the UHSLC and made available approximately 6 weeks after collection. Select stations with near-real-time data flow capabilities are being added to the original WOCE network. The Fast Delivery data set is being maintained at the UHSLC beyond the WOCE project with support from the Office of Global Programs at NOAA.

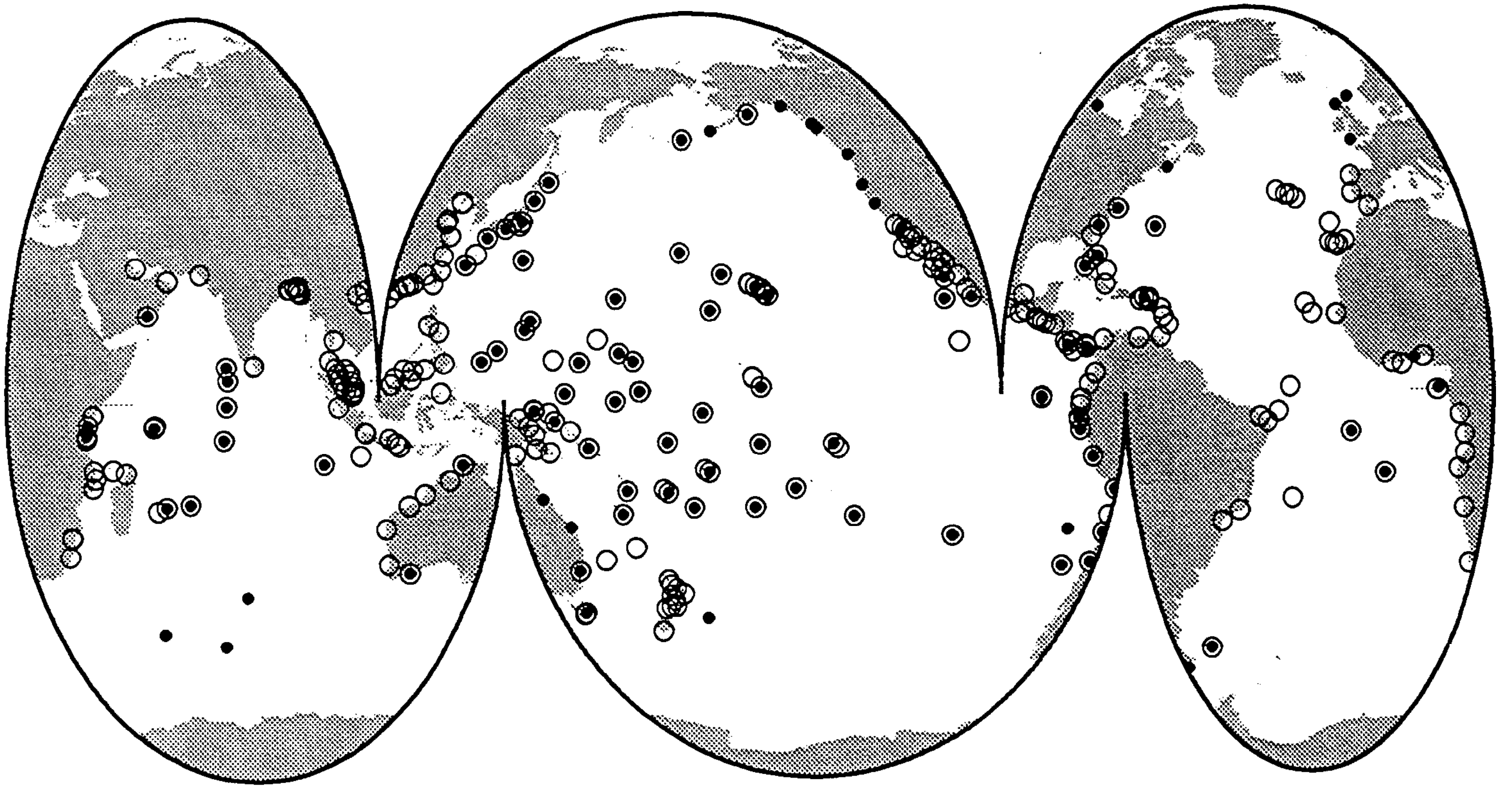


Figure 2. Joint Archive for Sea Level database, June 1997. Solid circle indicates “Fast Delivery” component.

High frequency sea level data (hourly, daily, monthly) are available from the JASL (Figure 2) which is maintained by the UHSLC and the National Oceanographic Data Center (NODC). The JASL, or Research Quality, dataset undergoes a higher level of quality control than the fast Delivery dataset with particular attention to reference level stability. The JASL includes data from 335 stations from over 60 agencies representing nearly 70 countries. The JASL dataset is also extended backward in time as historic high frequency time series become available.

Since 1985, monthly mean sea level values from various stations throughout the Pacific Ocean have been used to examine sea level deviations and anomalies, and to construct upper layer volume and geostrophic transport indices near the equator. This so-called ISLP-Pac dataset is available approximately 6 weeks after the measurements have been collected.

The **National Tidal Facility, Flinders University (NTF)**

The NTF, through support from the Australian Antarctic Division, maintains the Southern Ocean Level Centre (SOSLC) which collects sea level data from over 50 stations located poleward of 30°. In addition to providing sea level time series, the SOSLC will soon provide various sea level products including Antarctic Circumpolar Current indices and sea level anomaly maps for the Southern Ocean.

Data Flow and Quality Control

Sea level data acquisition and quality control procedures of the UHSLC are summarized in this section to provide an example of data flow from tide gauge station to data archive. The UHSLC is chosen because the center is involved at each level of the data flow from station operation and data acquisition, to quality control and data distribution. In addition, the UHSLC maintains a variety of databases which illustrate the different levels of data processing. The quality control procedures of the UHSLC are similar to those of the Bidston WOCE DAC and efforts are underway to formalize these procedures into one GLOSS standard.

Currently data from over 100 satellite-transmitting stations are received and processed at the UHSLC. Typically the data are received in both real-time via satellite, and in near-real-time (within a month) using on-site data loggers. Each month, the two redundant datasets are processed, merged, and incorporated into the Fast Delivery dataset. The UHSLC also receives near-real time data in varying formats and stages of processing from collaborating national agencies on a monthly cycle. Punch paper tape and analog rolls from gauges are collected and digitized inhouse. Processed data are obtained from other agencies via conventional and electronic mail. These near-real time data are available with a delay of 1-2 months.

The quality assurance of the UHSLC real-time data begins at the sea level station. Typically, each station has at least two instruments which measure sea level. This redundancy not only serves to improve data return, but provides a simple means for the detection and correction of data outliers, reference level shifts, timing errors, and data gaps. In addition, on-site observers perform routine maintenance duties and collect tide staff measurements which are used for reference level determination.

A daily review of the real-time data is conducted at the UHSLC and station observers and operators are notified as problems occur. After all the high frequency data (both real-time and near-real time) for a station have been collected each month, hourly mean time series are formed and gaps and errors in the primary data channel are replaced by data from redundant sensors when available. Data outliers are usually caused by telemetry, instrumentation, digitization, or processing errors. Timing errors are usually due to bad initialization of the instrument, processing errors, or clock drift. Other spurious signals may be associated with the blockage of the stilling well by sand or marine organisms, overgrowth of marine organisms on the float and in the well, faulty float cables, and leaky floats. These errors are handled on a case-by-case basis and corrections are applied if warranted.

For each site, a metadata file is maintained which accompanies the processed data in the final archive. This file contains pertinent information about the station, a quality assessment of the data, and a log of corrections made to the data.

The JASL database includes data from near-real-time stations as well as data received in delayed mode from various agencies, typically on an annual basis. In addition to the quality control applied to the near-real-time data, an assessment is made of the stability of the reference level for the JASL database. The UHSLC stations are equipped with specially designed switches that are surveyed to the tide staff. These reference level switches measure the exact time the sea level passes the switch, and can be used to determine the vertical location of the sensor. When available, tide staff readings and reference level switch data are compared with gauge-derived mean levels to obtain the zero reference level for each station. This level is assessed each year. The final JASL data are merged back into the Fast Delivery set replacing the preliminary data that had only the basic quality control.

Recommendations

For collocated tide gauge-GPS sites, we recommend that these tide gauge stations be included in the GLOSS network and that the GLOSS collection and processing standards are applied. In particular, we recommend that these stations be equipped with satellite transmission capability so that high frequency data can be quality controlled and made available in near-real-time. In this way, problems with the data acquisition or data flow can be assessed and corrected in a timely fashion. The high frequency sea level data from these stations should be made available to the community in near real-time (1 month) for joint use with altimeter data products. The UHSLC has been identified by the IOC Group of experts on GLOSS as a potential distribution center.

Appendix A: List of Acronyms

BODC	British Oceanographic Data Centre
CLIVAR	Climate Variability and Predictability Program
DAC	Data Assembly Center
GLOSS	Global Sea Level Observing System
IGLOSS	Integrated Global Ocean Services System Commission
ISLP-Pac	IGOSS Sea Level Project in the Pacific
JASL	Joint Archive for Sea Level
NODC	National Oceanographic Data Center
PSMSL	permanent Service for Mean Sea Level.
SOSLC	Southern Ocean Sea Level Centre
UHSLC	University of Hawaii Sea Level Center
WOCE	World Ocean Circulation Experiment

……

Appendix B: Sea Level Data Center Addresses

PSMSL	http://www.nbi.ac.uk/psmsl/psmsl.info.html
JASL/UHSLC	http://www.soest. hawaii.edu/UHSLC
BODC	http://www.pol.ac.uk/bodc/woce/dmsldac.html
SOSLC	http: //www.ntf.flinders. edu.au

ACRONYMS AND ABBREVIATIONS

AAc	(IGS) Associate Analysis Center
AC	IGS Analysis Center
ASI	Italian Space Agency
AusAID	Australian Agency for International Development
AUSLIG	Australian Surveying and Land Information Group
BAYONET	GPS Network for Monitoring Absolute Sea Level in the Chesapeake Bay
BIFROST	Baseline Inferences for Fennosccsndian Rebound Observations, Sea-Level and Tectonics
BODC	British Oceanographic Data Centre
BSL	Baltic Sea Level (Project)
CBIS	(IGS) Central Bureau Information System
CDDIS	Crustal Dynamics Data Information System
CIGNET	Cooperative International GPS NETwork
CLIVAR	Climate Variability and Predictability Program
CMSLT	Commission of Mean Sea Level and Tides
CNES	Centre National d'Etudes Spatiales, France
COGR	Continuously Operating GPS receiver
CORS	Continuously Operating Reference Station
DAC	Data Assembly Center
DGPS	differential GPS
DiVE	differential vertical motion estimation
DORIS	Determination of Orbit Radiopositioning integrated by Satellite (DORIS instrument on TOPEX/Poseidon)
DSN	Deep Space Network, U.S.
DUT	Delft University of Technology, the Netherlands
EGM	episodic GPS measurements
ENSO	El Niño Southern Oscillation
EOF	empirical orthogonal function
ERS-1	European Space Agency Remote Sensing Satellite-1
ESOC	European Space Agency (ESA) Space Operations Center, Germany
EUREF	European Reference Frame
EUVN	European Vertical Network
FAGS	Federation of Astronomical and Geophysical Data Analysis Services
FGI	Finnish Geodetic institute
FinnNet	Finnish Permanent GPS Network
GFZ	GeoForschungsZentrum, Germany
GLOSS	Global Sea Level Observing System
GNAAC	Global Network Associate Analysis Center
GPS	Global Positioning System
GSFC	Goddard Space Flight Center, U.S.
GSI	Geographical Survey Institute, Japan
IAG	International Association of Geodesy
IB	inverted barometer
IAPSO	International Association for the physical Sciences of the Ocean
IERS	International Earth Rotation Service
IESSG	Institute of Engineering Surveying and Space Geodesy, Univ. of Nottingham, U.K.
IfAG	Institut fur Angewandte Geodäsie, Germany
IGN	Institut Géographique National, France
IGOSS	Integrated Global Ocean Services System
IGS	International GPS Service for Geodynamics
IOC	Intergovernmental Oceanographic Commission
IOS	institute of Ocean Sciences (Canada)
IPCC	Intergovernmental Panel on Climate Change
ISLP-Pac	Integrated Global Services System Sea Level Project in the Pacific
ISR	Institute for Space Research, Austria

ITRF	IERS Terrestrial Reference Frame (often referred to as International Terrestrial Reference Frame)
JASL	Joint Archive for Sea Level
JPL	Jet Propulsion Laboratory, U.S.
KAO	Korean Astronomical Observatory
MAFF	(U. K.) Ministry of Agriculture Fisheries and Food
MORP	Morpeth geodetic station monument (in northeast England)
NCL	University of Newcastle upon Tyne, U.K.
NGWLMS	(NOAA] Next Generation Water Level Measurement System
NGS	National Geodetic Survey (U. S.)
NKG	Nordic Geodetic Commission
NIMA	National Image and Mapping Agency, U.S. (formerly DMA)
NLS	(Swedish) National Land Survey
NMA	Norwegian Mapping Authority
NOAA	(U. S.) National Oceanographic and Atmospheric Administration
NODC	National Oceanographic Data Center, Us.
NRCan	Natural Resources Canada
NRIC	National Resource Information Centre, Bureau of Resource Sciences, Australia
NTF	National Tidal Facility (Flinders Univ., Australia)
ODC	(IGS) operational data center
OSO	Onsala Space Observatory
PANGA	Pacific Northwest Geodetic Array
PGR	post-glacial rebound
POL	Proudman Oceanographic Laboratory (U. K.)
PPP	precise point positioning
PSMSL	Permanent Service for Mean Sea Level
RDC	(IGS) regional data center
RINEX	Receiver Independent Exchange (format)
RMS	root mean square
RNAAC	(IGS) Regional Network Associate Analysis Center
SATREF	SATellittbasert REFeransesystem (network of Norwegian GPS stations)
SELF	Sea Level Fluctuations in the Mediterranean
SINEX	Solution (software/technique) Independent Exchange (format)
SIO	Scripps Institute of Oceanography, U.S.
SLR	Satellite Laser Ranging
SOLC	Southern Ocean Level Center
SST	Sea Surface Temperature
SWEPOS	Swedish Permanent GPS Network (GPS network in Sweden)
TGBM	tide gauge benchmark
TGGS	tide gauge GPS station
TOGA	Tropical Ocean and Global Atmosphere
T/P	TOPEX/Poseidon
UB	University of Bologna, Italy
UELN	Unified European Levelling Network
UH	University of Hawaii at Manoa, U.S.
UHSLC	University of Hawaii Sea Level Center, Us.
UNAVCO	University NAVSTAR Consortium, U.S.
UPLN	Unified Precise Levelling Network
USCG	U.S. Coast Guard
USF	University of South Florida, St. Petersburg, U.S.
UTA	University of Texas at Austin, U.S.
UTC	Universal Time Coordinated
VLBI	very long baseline interferometry
VLF	very low frequency
WOCE	World Ocean Circulation Experiment