MONITORING VERTICAL LAND MOVEMENTS AT TIDE GAUGES IN THE UK

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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 (U KGAUGE 111), which will begin in August 1997, for the continued monitoring of the vertical land movements at selected sites of the UK National 'fide 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 ct al, 1995), originally using the fiducial GPS technique and latterly using the I GS 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).

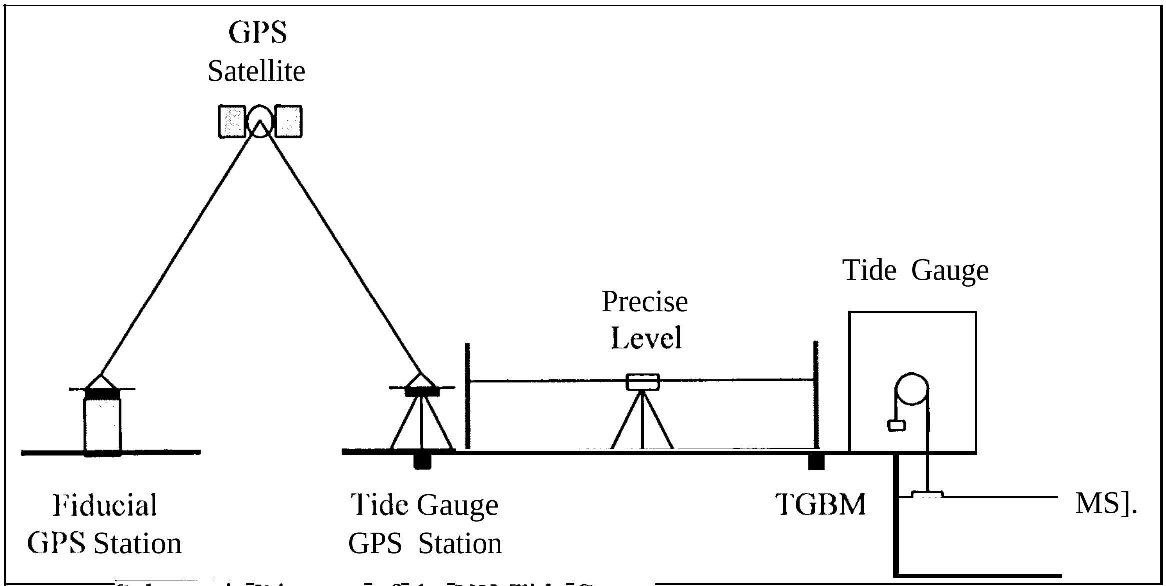

Fig. 1. Schematic Diagram of the UK Tide Gauge Monitoring Strategy

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 SSi 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.

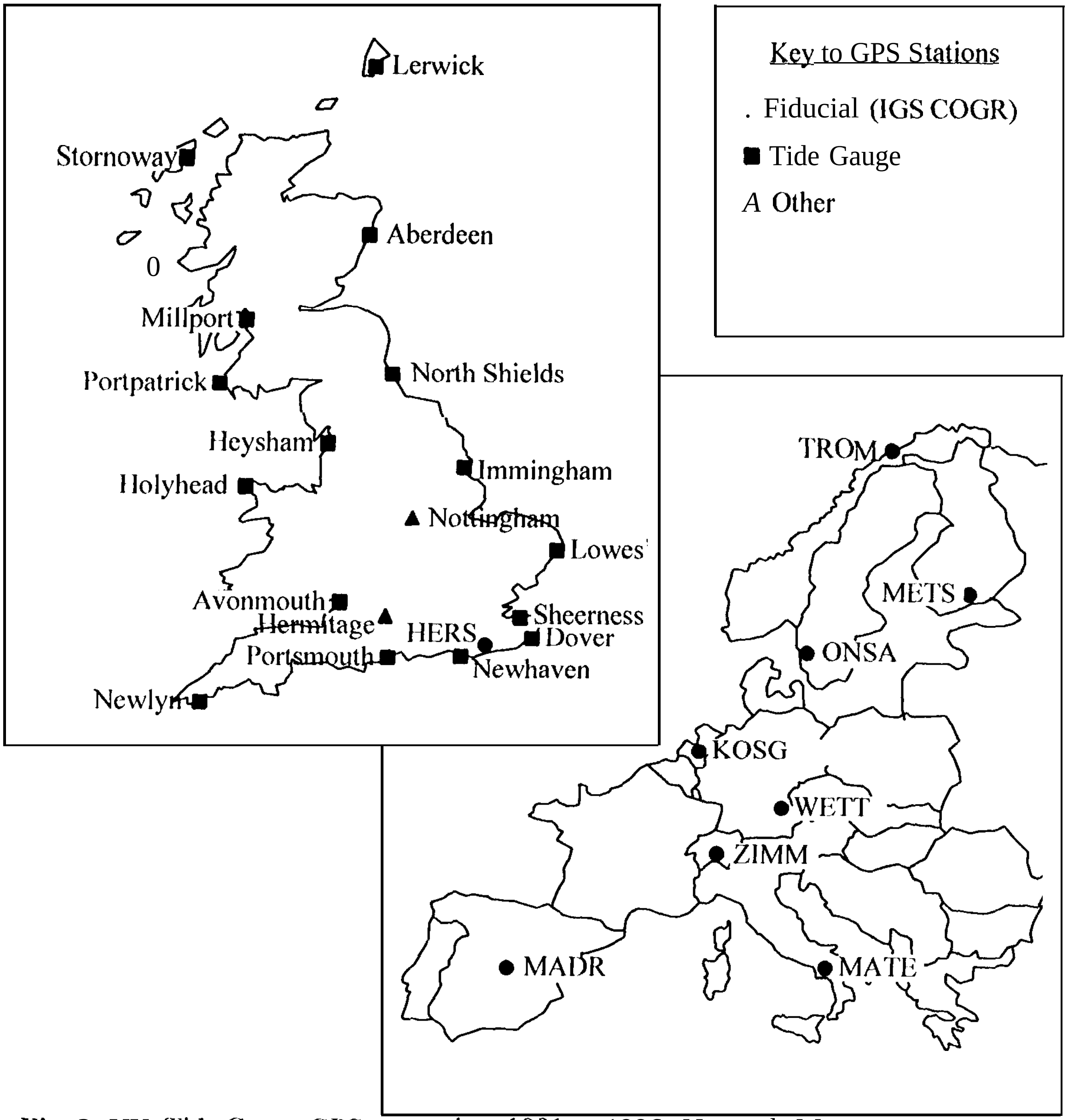

Fig. 2. UK Tide Gauge GPS ampaigns 1991 to 1996: Network Map

Only one TGGS (Portsmouth) was observed in all eight, one TGGS (Newlyn) and one other stat ion (Nottingham) were observed in seven, tw-o 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 (Avon mouth, Ho] yhead, Heysham and Mill port) 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	UK91 1991.70	UK92 1992.60	UK93 1993.61	EC93 1993.88	EC94 1994.21	UK95A 1995.68	UK95B 1995.91	UK96 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 SSI 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 / SSI 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.

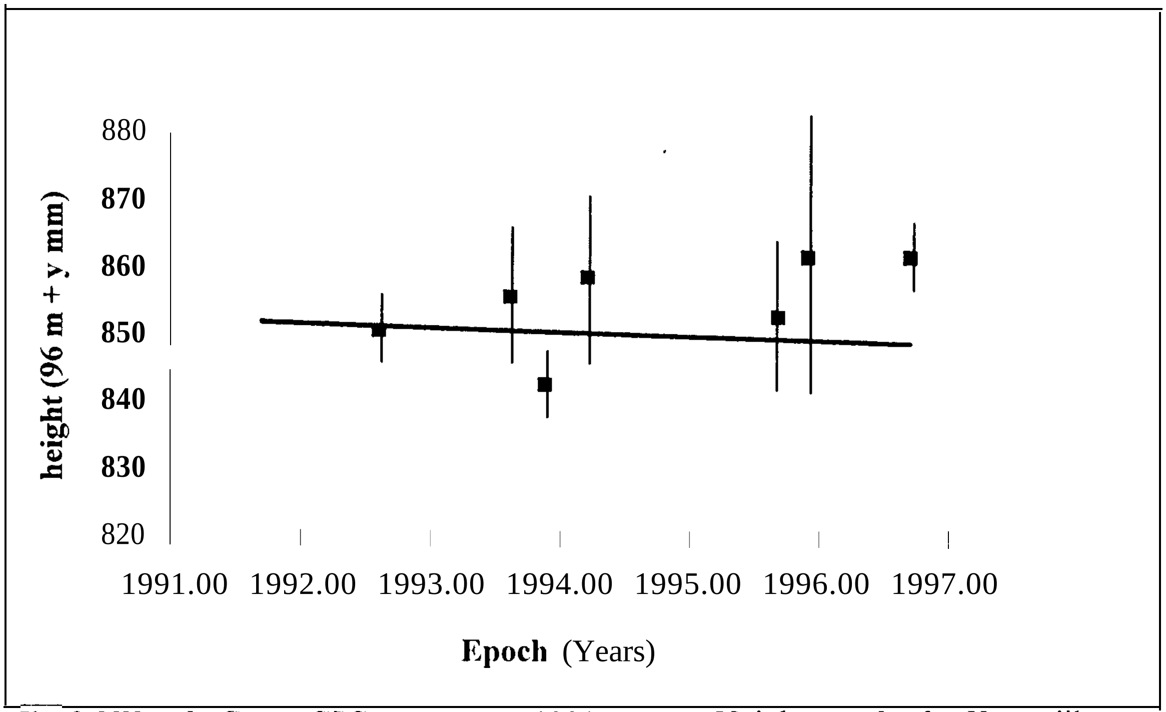

Fig. 3. UK Tide Gauge GPS Campaigns 1991 to 1996: Height Results for Kootwijk

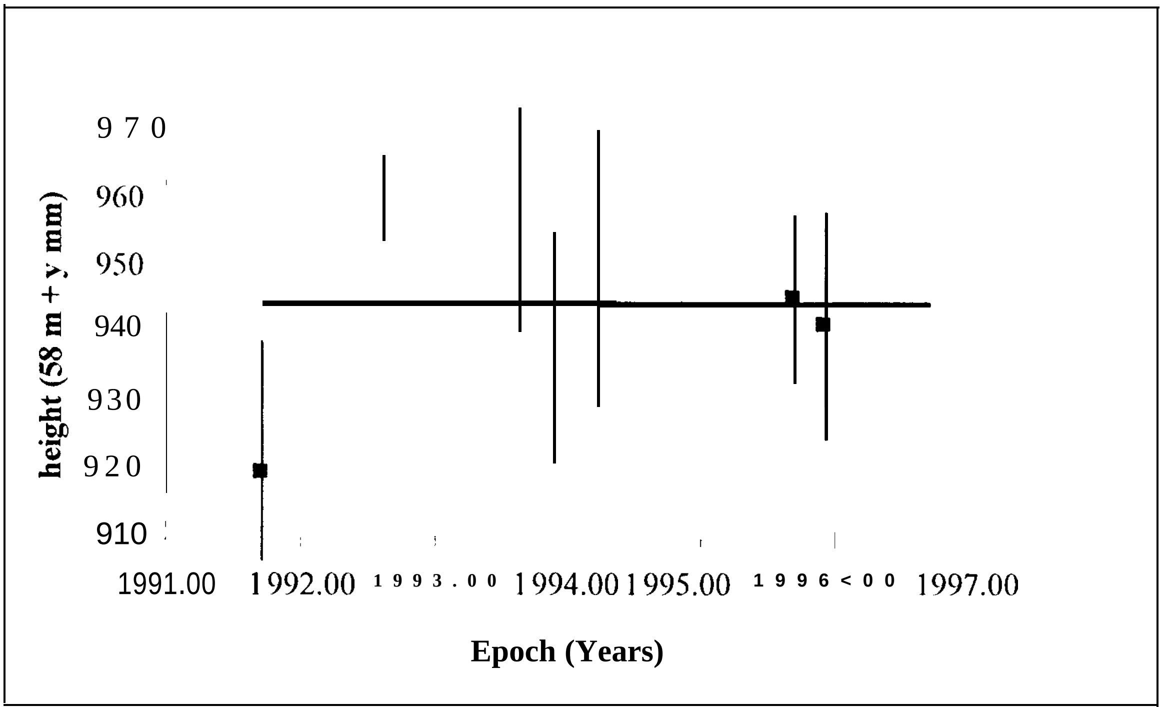

Fig. 4. UK Tide Gauge GPS Campaigns 1991 to 1996: Height Results for Newlyn

Figure 4 shows the height results obtained for the TGGS at Newlyn, with the thick line being the mean from the seven episodic G]% 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 (1 994), 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.

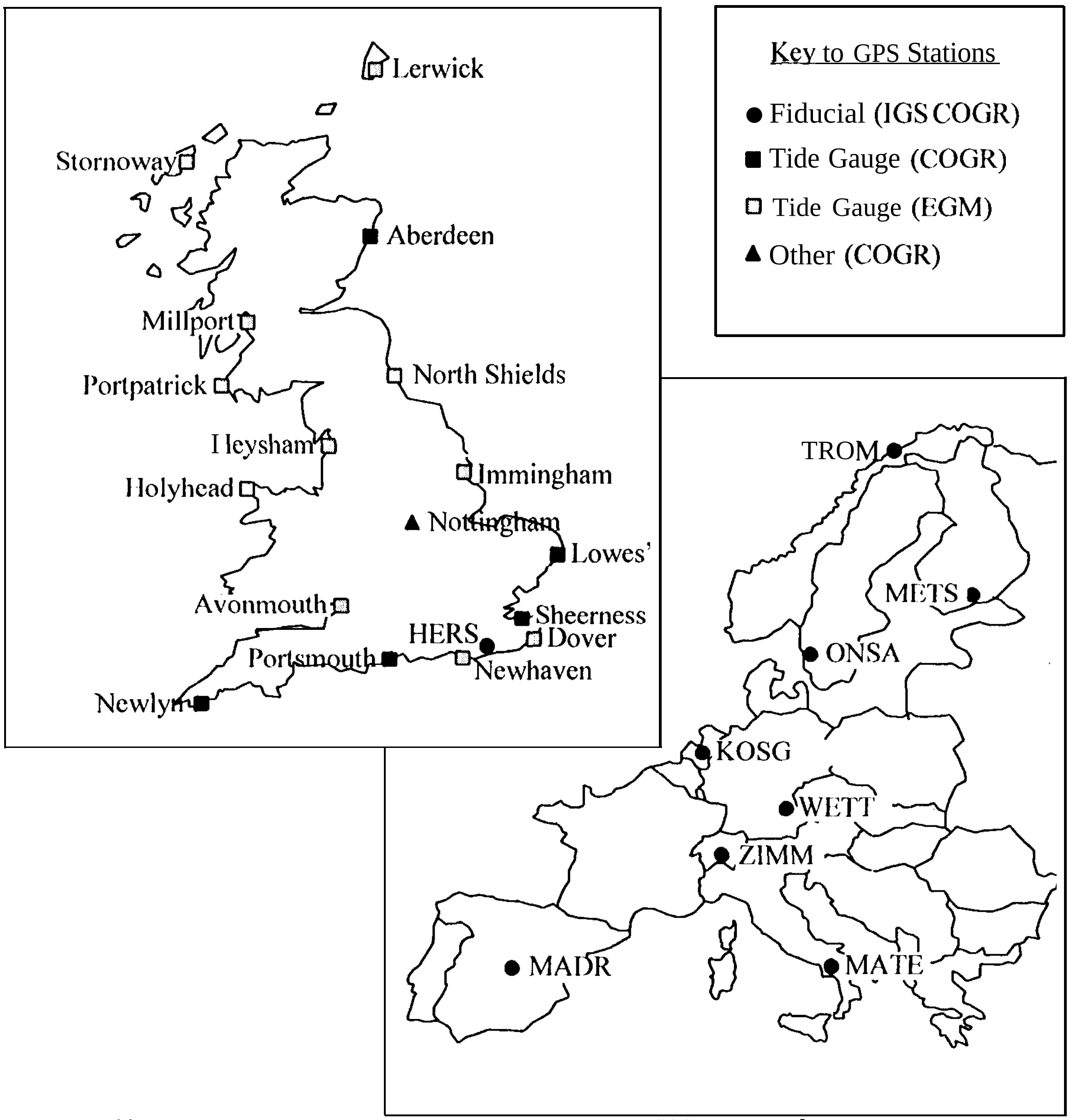

Fig. 5. UK Tide Gauge GPS M asurements 1997 to 2000: Network Map

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.

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

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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 sca 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

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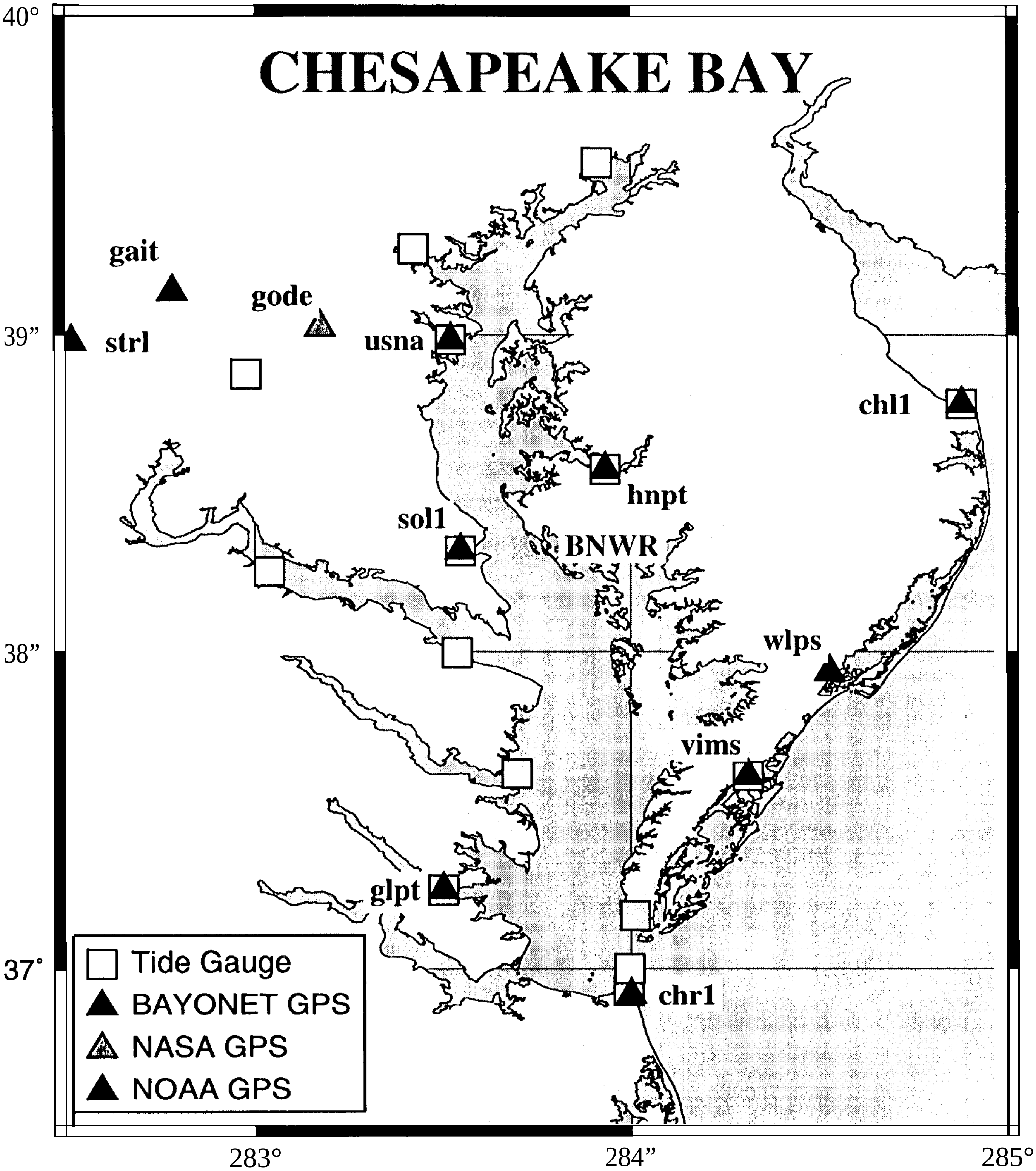
CHESAPEAKE BAY
40°
39”
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284”
285°
gait
gode
strl
usna
chl1
hnpt
sol1
BNWR
wlps
vims
glpt
chr1
Tide Gauge
BAYONET GPS
NASA GPS
NOAA GPS

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 *[Tush ingham 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
Lewisetta, 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.

'Cl'he 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

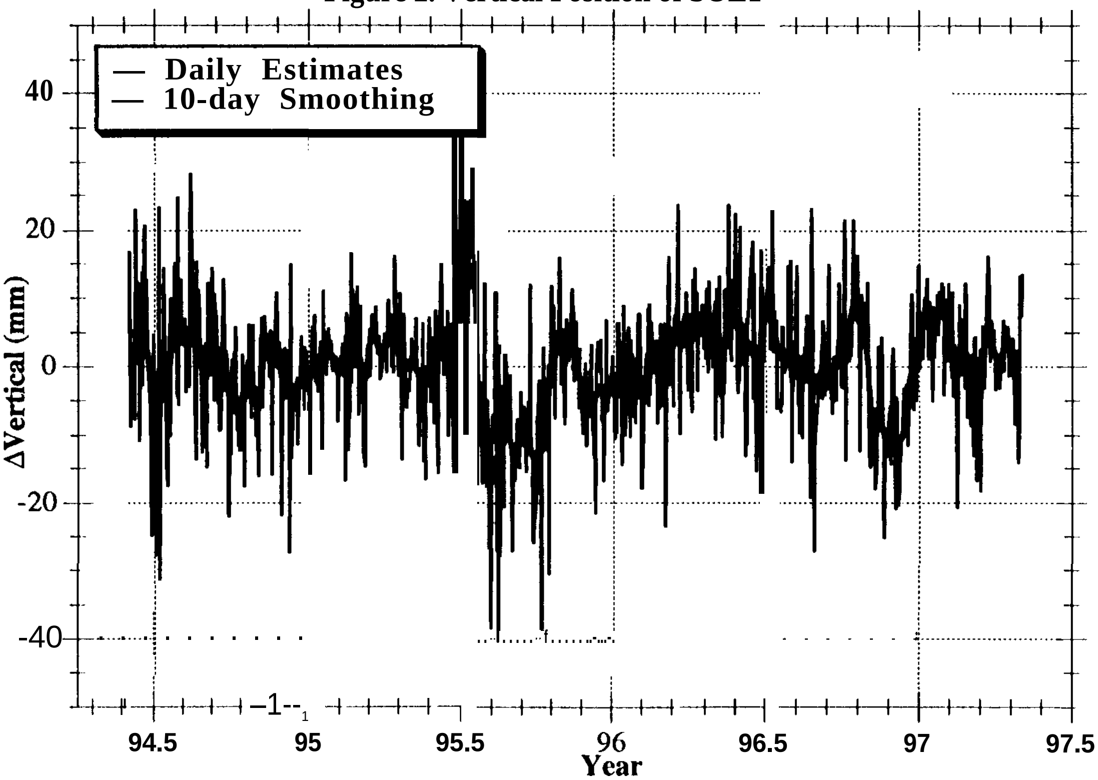

Table 1 shows the vertical rate estimates for the BAYONET sides, all with respect to GODE. The data from GLPT show some anomalous behavior, possibly due to radio interference, and have thus been omitted. With the exception of SOL 1, the remaining sites tend to suggest subsidence relative to GODE (which 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

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Precise Sea Surface Measurements Using DGPS Buoys

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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

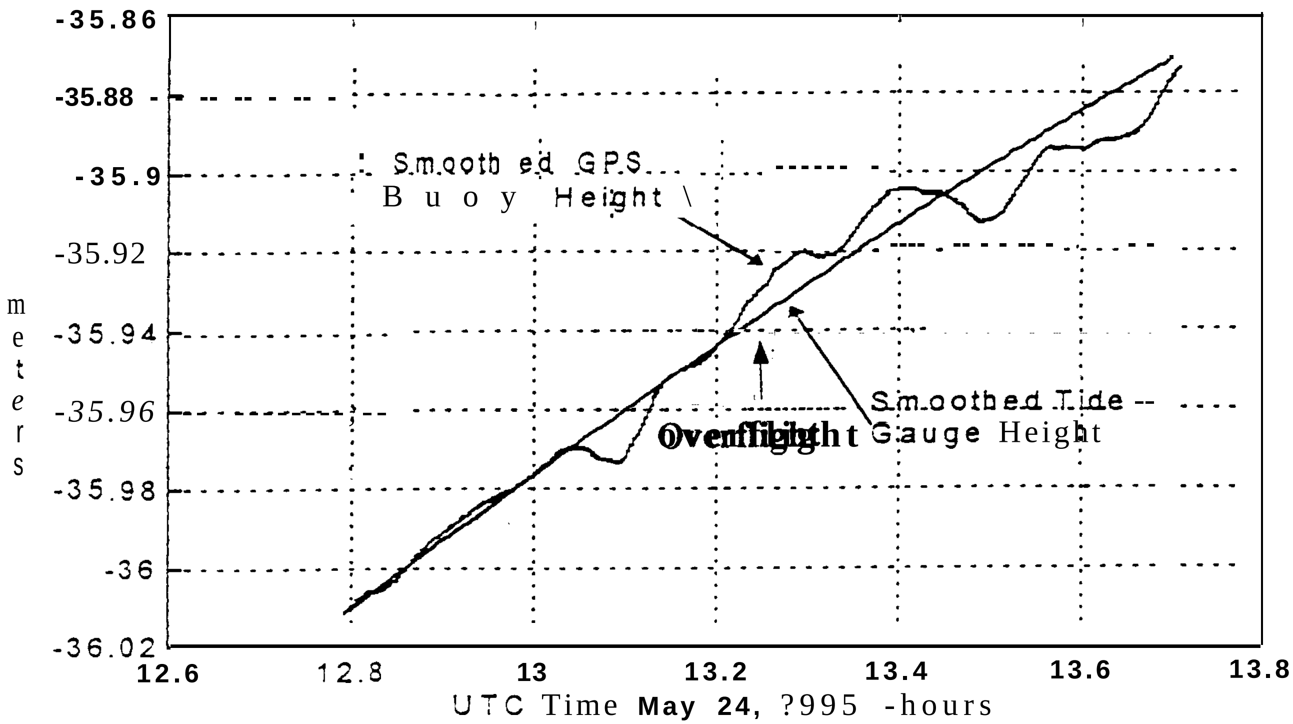


Figure 1: A comparison of double pass filtered DGPS sea level with NOAA acoustic tide gauge data at Texaco's platform Harvest on 24 May 1995. The mean difference is -0.03 cm with a standard deviation of 0.7 cm.

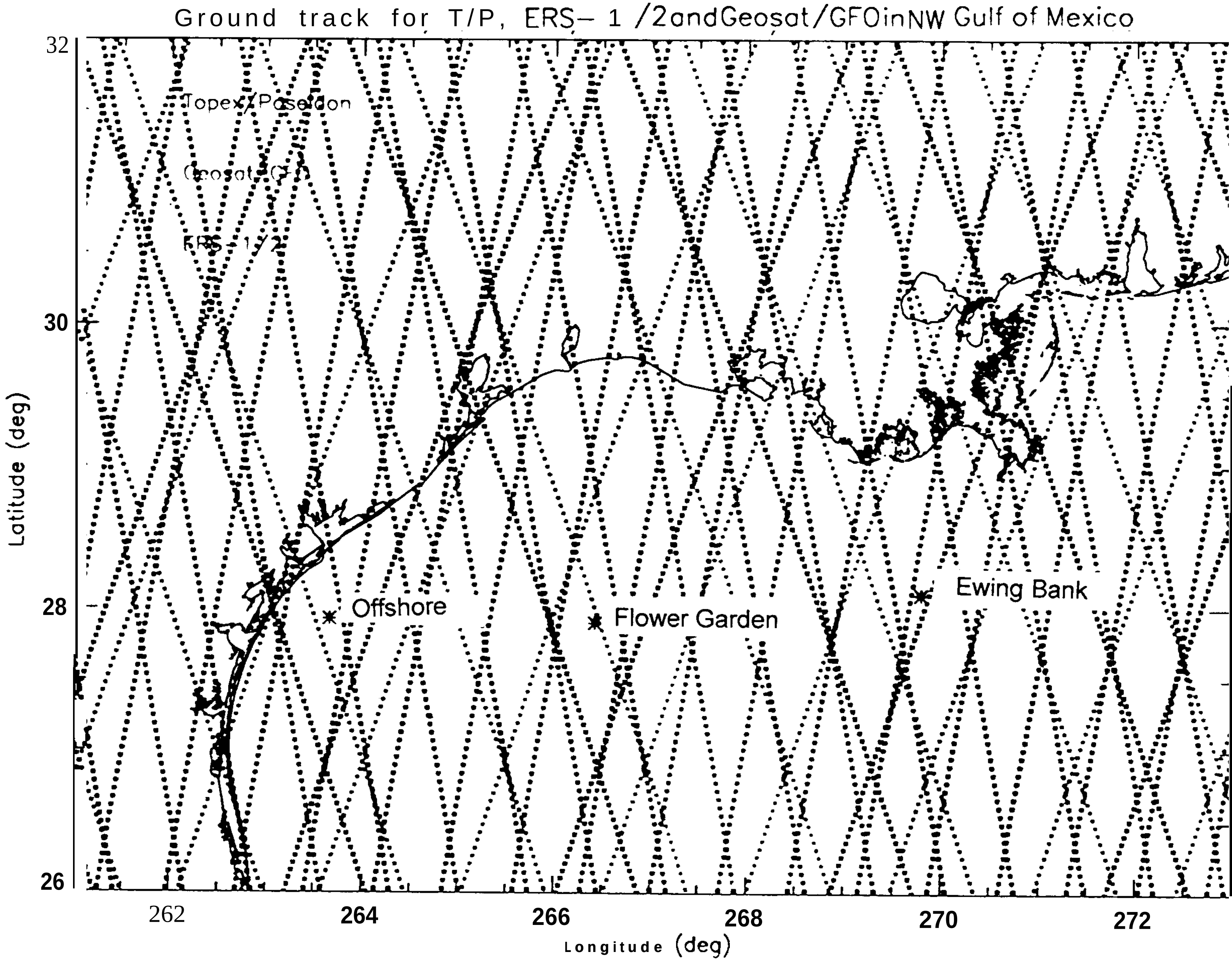


Figure 2: Ground tracks for ERS- 1/2, TOPEX/POSEIDON, and GFO-1 over the northwest Gulf of Mexico

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.

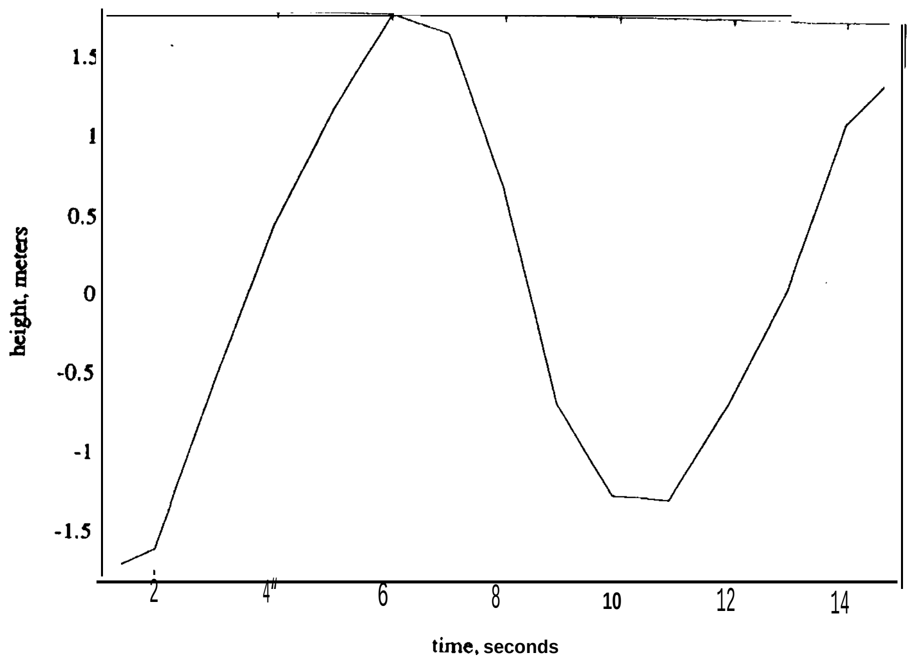
Other calibration sites are being considered. If cooperative arrangements can be made with coastal colleges and universities for local offshore calibration sites, then the latitude dependence of the altimeter error can be investigated. One of limitations of the Harvest/Lampedusa sites is that although 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,



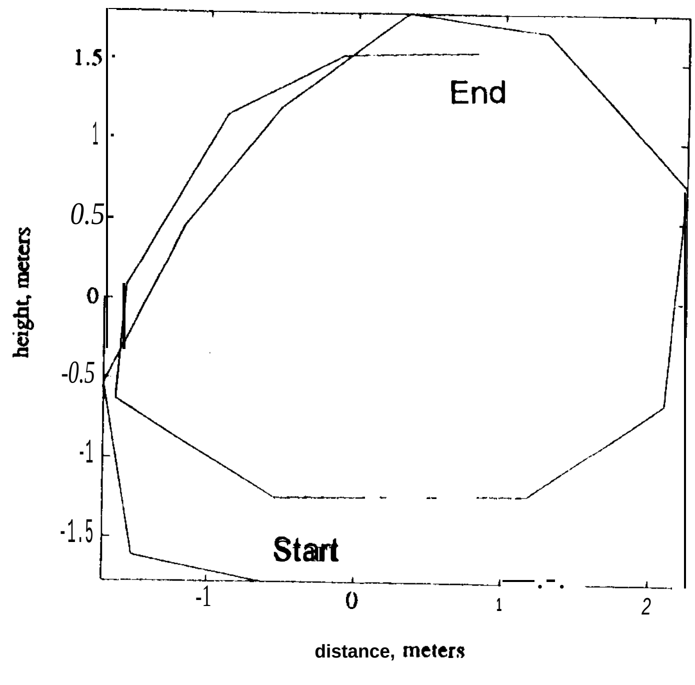


Figure 3: Top panel -once per second DGPS sea level for one wave period measured during the mapping exercise of Key et al., 1997. Bottom panel - vertical versus horizontal motions for the same period. A mean drift of the buoy has been removed and the coordinate system rotated to the direction of wave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

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BIFROST PROJECT: THREE YEARS OF CONTINUOUS GPS OBSERVATIONS

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ABSTRACT

We describe the operations within SWEPOS with geophysical purpose to detect crusts] motions in Fennoscandia. For this purpose a project named HIFROST was created; 1)1 FROST 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 G] 'S-based space geodesy were proposed to discern movements of surfaces in the course of postglacial rebound with

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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 dist antes between ten and several thousand kilometers [*BIFROST Project,* 1996].

in this report wc 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. ~'bus, it is possible to arrive at sing]c-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. 'l'able 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* [1 996].

The noise in tide gauge observations and the precision with which sca level rates can be determined (O. 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°0r 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 arc 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.

‘1’o 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 011 both 1,1 and 1,2 frequencics; carrier phase observations on L 1 and L2; Doppler frequency observations; and satellite broadcast ephemeris.

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 0S() from the SWEPOS stations directly.

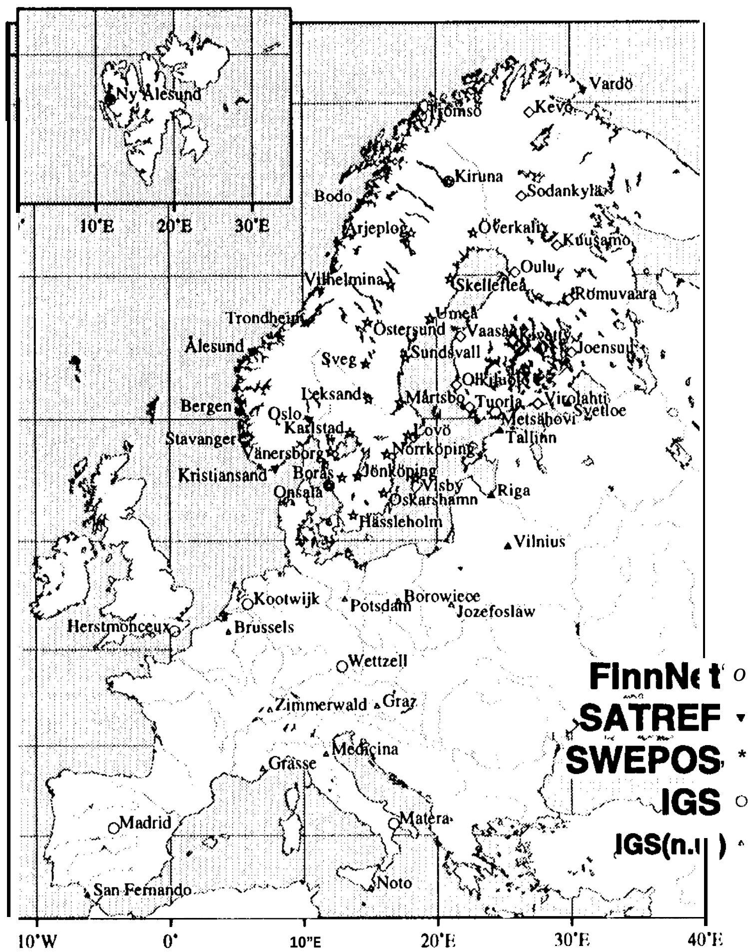

Figure 1: *Permanent GPS Stations in the area of Fennoscandia and Baltic and the European IGS sites regularly included (“n. ”- not included) in the solutions derived for the BIFROST project*

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 arc 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 (U]<), Kootwijk (Holland), Madrid (Spain), Matera (Italy), Wettzell (Germany). ‘l’his data is acquired regularly via Internet.

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

SOLVING GEODETIC PARAMETERS

The dual-frequency GPS phase and pseudorange data arc processed at the 0S0 regional processing center using the 2nd release of GIPSY software developed at Jet }’repulsion laboratory (JPL) [e.g., *Webb and Zumberge* 1993, and references therein]. Selected periods of the SW EPOS data are also processed using the Bernese Software ver. 4.0 [*Rothacher et al.*, 1996]. ‘l’his 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 lGS orbit determination is known to be approximately 10 centimeter, or better. In the standard BIFROST analysis wc adopt the combined IGS products and no further estimations of satellite orbits nor earth orientation parameters arc 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 arc estimated as bias terms with a priori uncertainties of 10 m (IGS sites with well determined coordinates) or 1 km (regional sites). Constraints arc thereafter applied to transfer the results into a terrestrial reference frame,

The zenith values, one for each site, of the propagation delay clue to water vapor (often referred to as the wet delay) are estimated as random walk bias terms. The signal propagation delay duc 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)

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

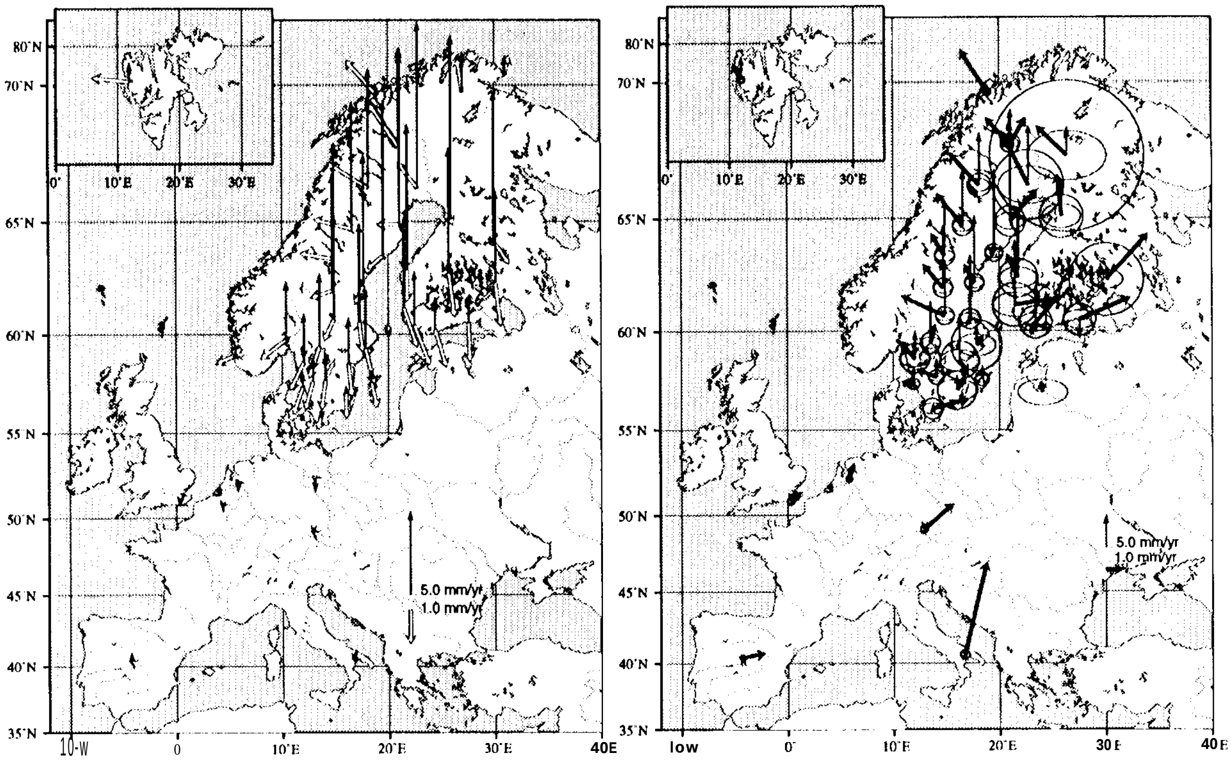

Figure 2: Modelling results (left) and observations (right) in the form of vectors of motion, Horizontal motion is shown as wide vectors, vertical as narrow vectors pointing up.

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. BI F'}{OS'l' 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/covari ance bet ween 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 [1995]* ?

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 assembly, implying 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 systematic offsets of the phase centre 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

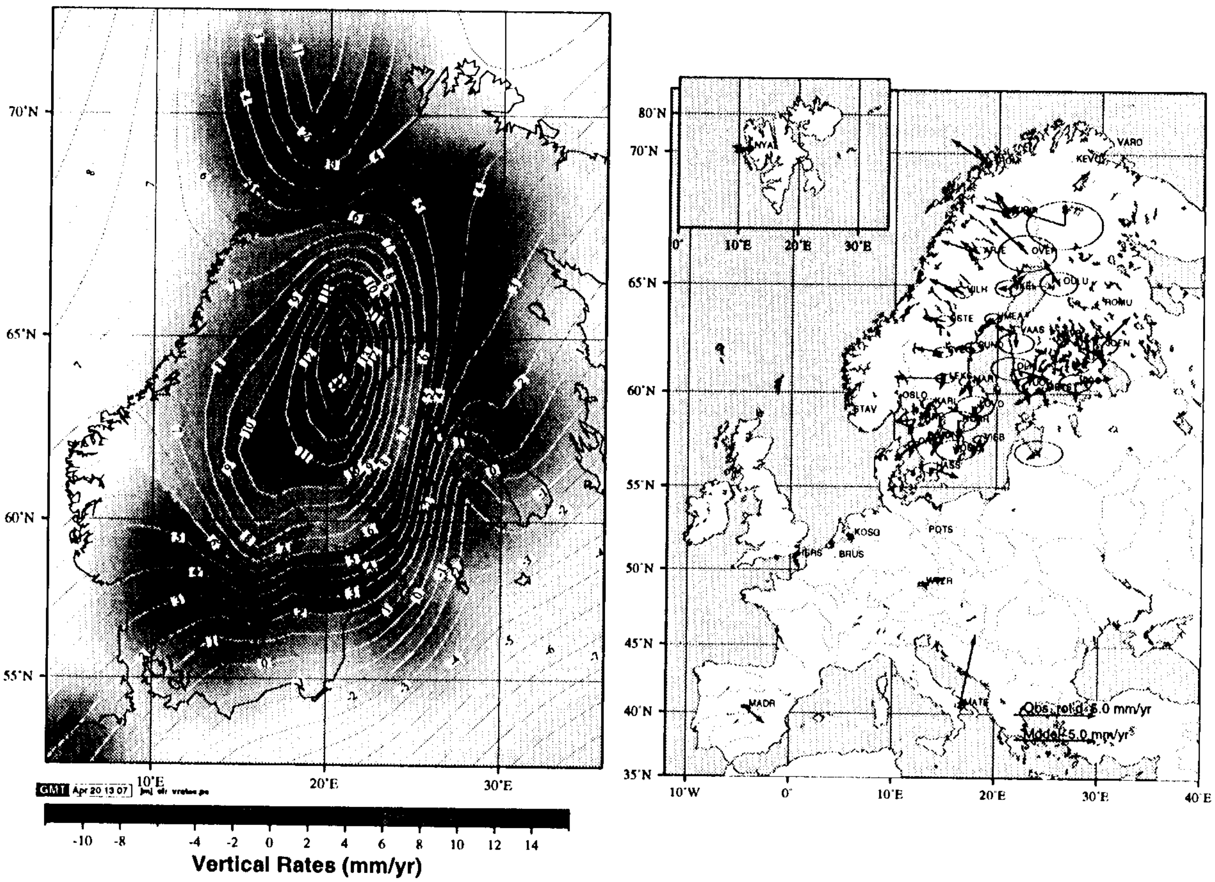

Figure 3: Left frame shows a contour plot of vertical rate estimates based on more than 1000 days of BIFROST GPS operation and data analysis. About 50 stations are regularly included in the BIFROST GPS solutions. Outside Sweden, observations at reference stations of the network of the other nordic countries 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].

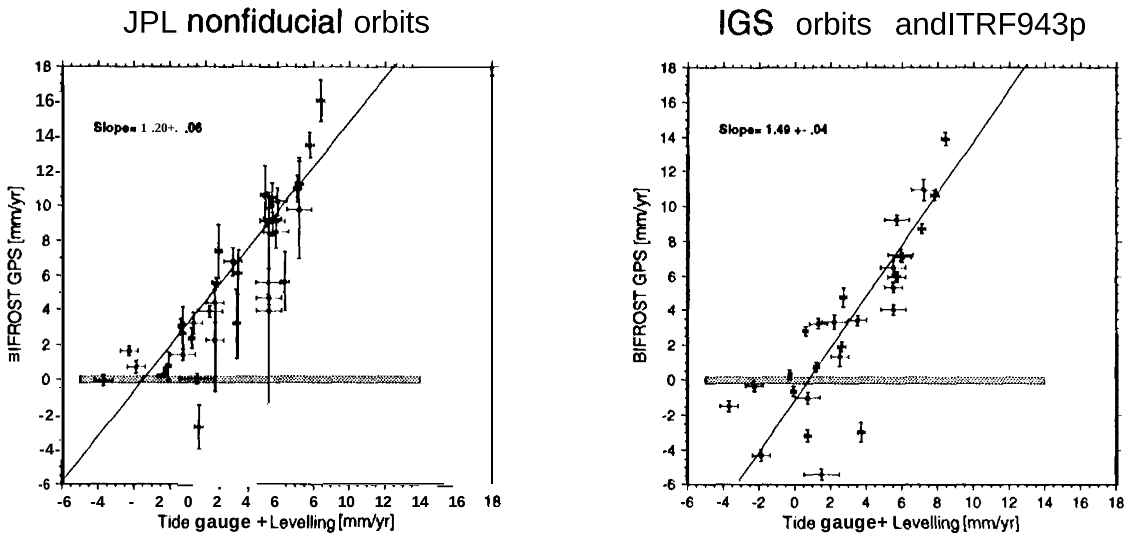

Figure 4: GPS vertical crusts] rates from SWEPOS analysis versus rates of land emergence determined by Ekman (1995) using Mareograph and Precise Levelling data. Nonfiducial orbits (left frame) and IGS orbits (right frame). A line of regression (solid) is fit considering onc sigma limits in both data 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.,* 1 996a].

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 arc 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, 'I'his 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 be determined exactly, than this system would be most suitable as it avoids rebound signatures at the tracking stations to be 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 does 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

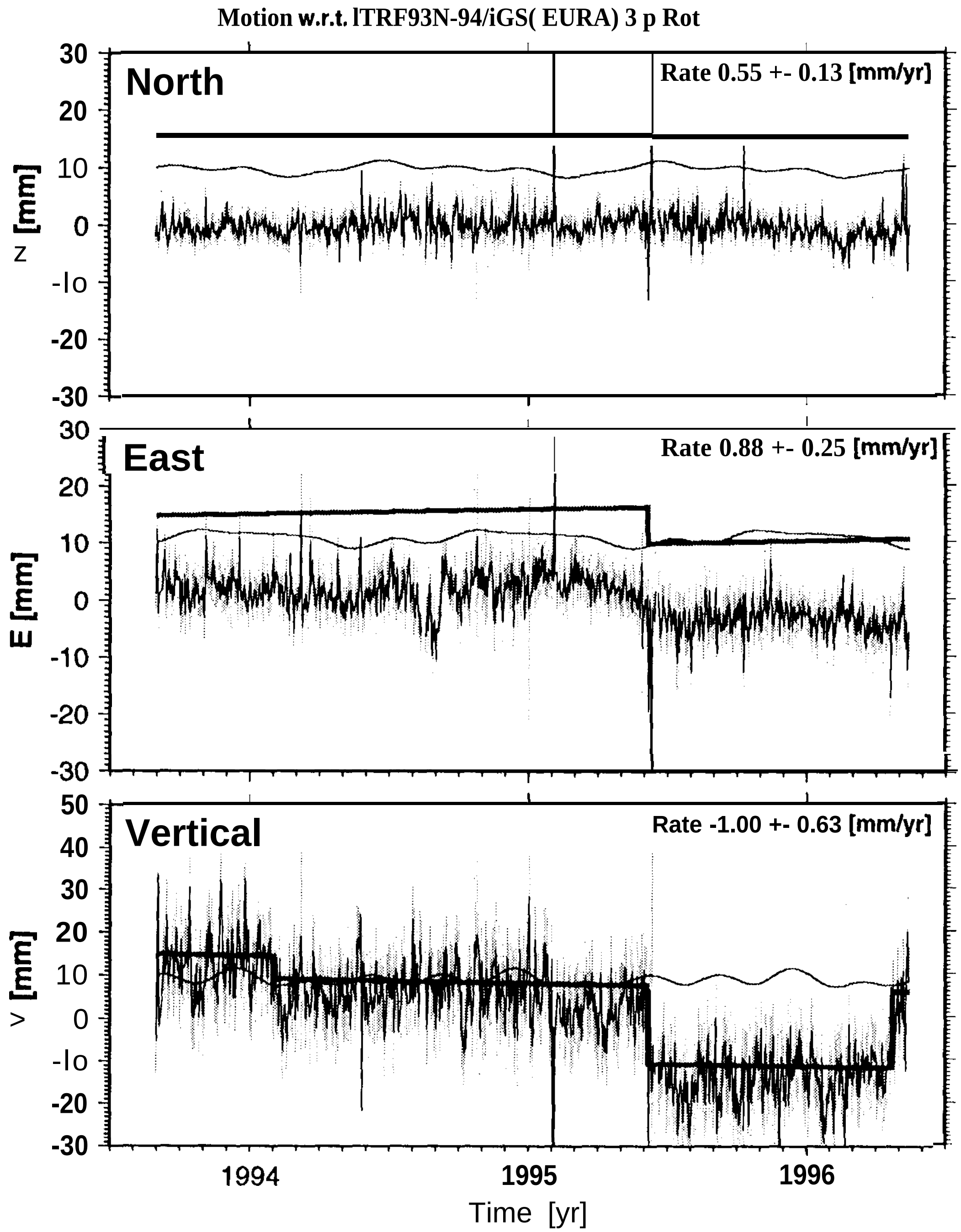

Figure 5: Single site solution, Hässleholm. Results from daily solutions arc shown as the noisy thin line on a grey background signifying the 95% confidence limit. The positions arc shown after free network adjustment and alignment with a rigid frame that corotates with the the European subset of the 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 arc included, i.e.,. if we restrict the comparison to mareographs and G] 'S, 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 specifics a **subsidence** of 1.2 mm/yr while postglacial rebound would suggest a rise of 0.86 mm/yr. Likewise, at Wettzell (Tromsø) 1'1'1{1{'94 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 vertical] y reduced motion (i .e. pure geocentric rotation) would be a more stable frame than a frame moving together with the regional reference sites in

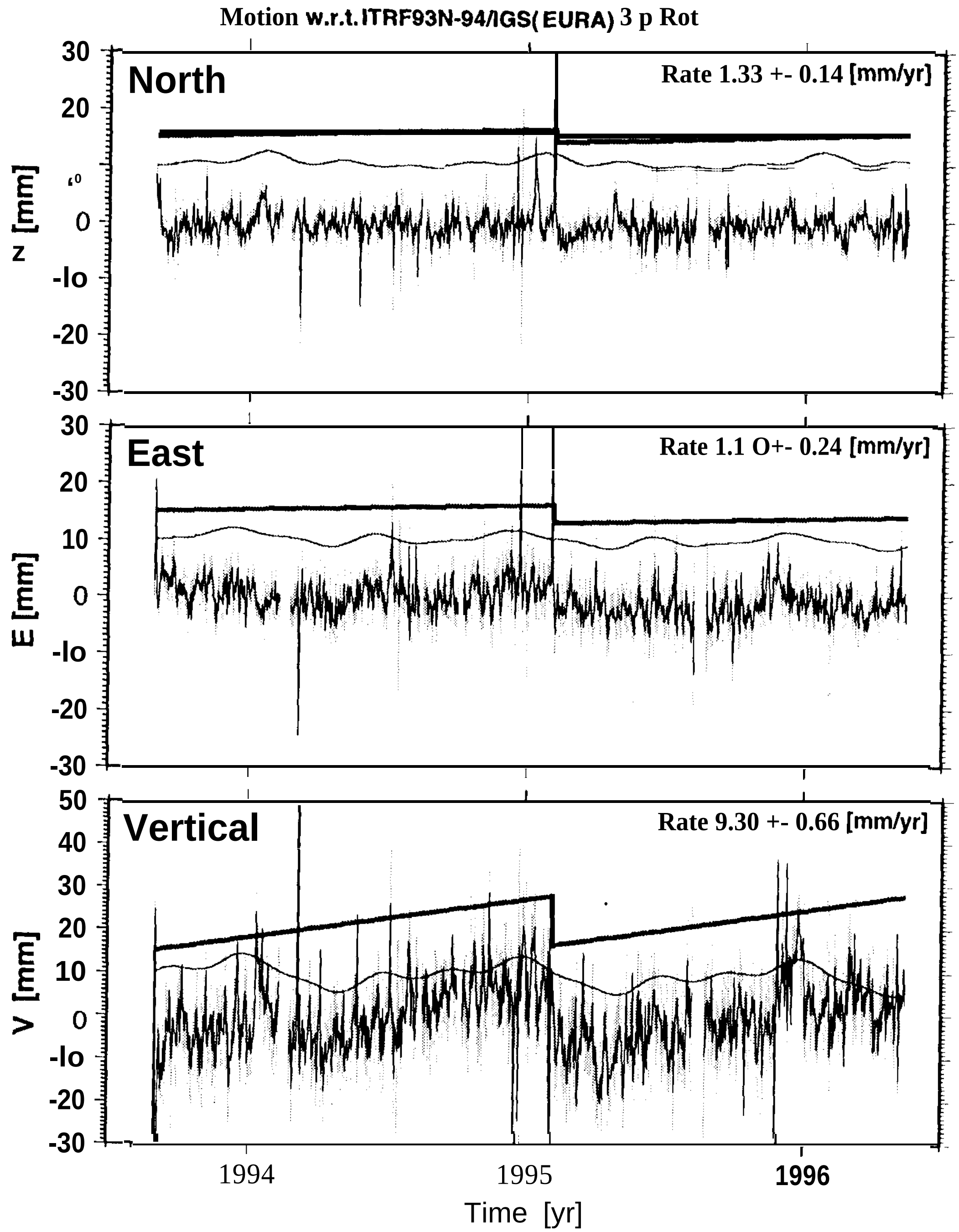

Figure 6: Single site solution, like in Fig. 5, for Umeå, however. (Cent'd from previous figure:)

Station mode] 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 wc assume a global sea level rise and in particular the North Sea value of *Douglas* [199]] 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 Tromsøis 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 usc 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. 'l'his 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* [1 995].

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The Applicability of CORS for Tide Gauge Monitoring

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(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.

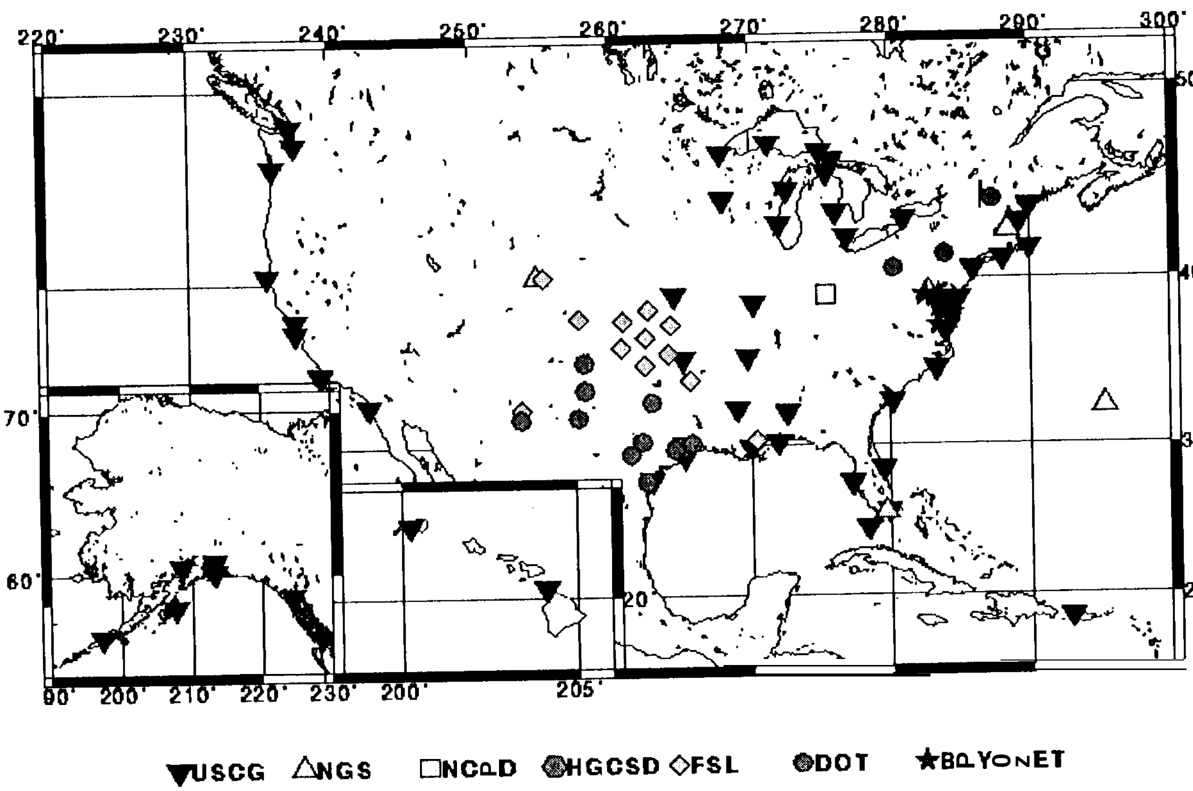

Figure 1: CORS Available Trhough NGS

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 Adtninistration 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.

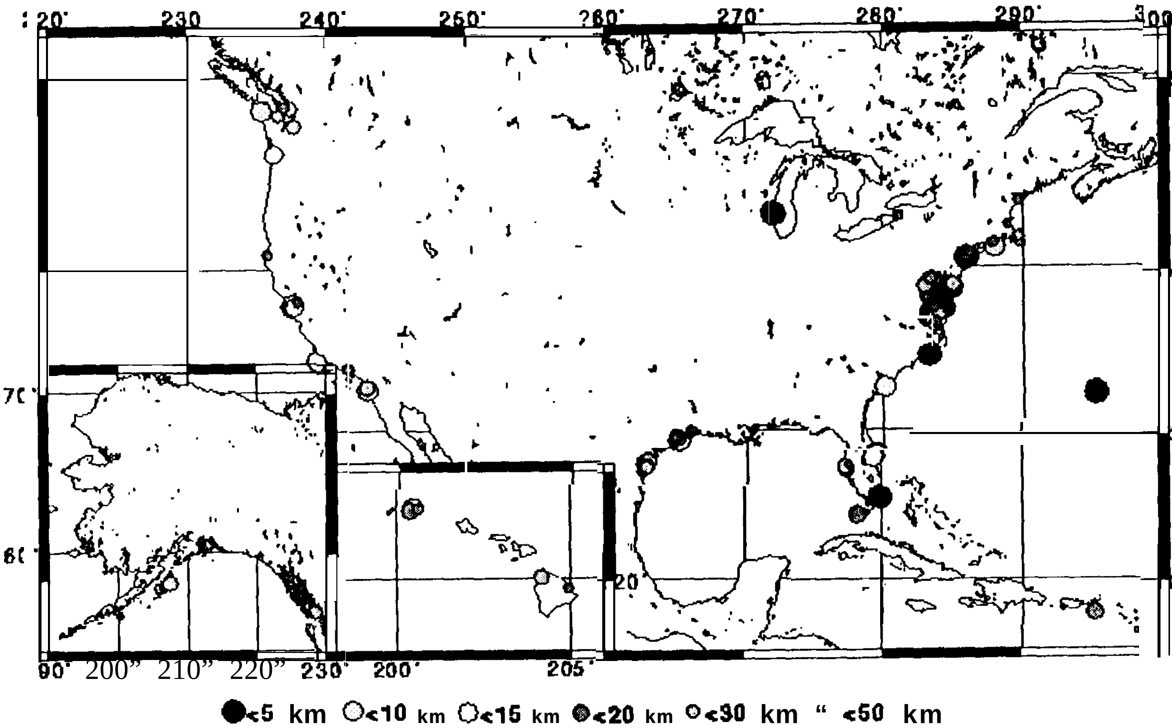

Figure 2: Proximity of Tide Gauges to CORS.

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

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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 bc 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 lAPSO 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 onc 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 $mm\sqrt{K}$ are regularly achieved while the $2mm\sqrt{K}$ 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.

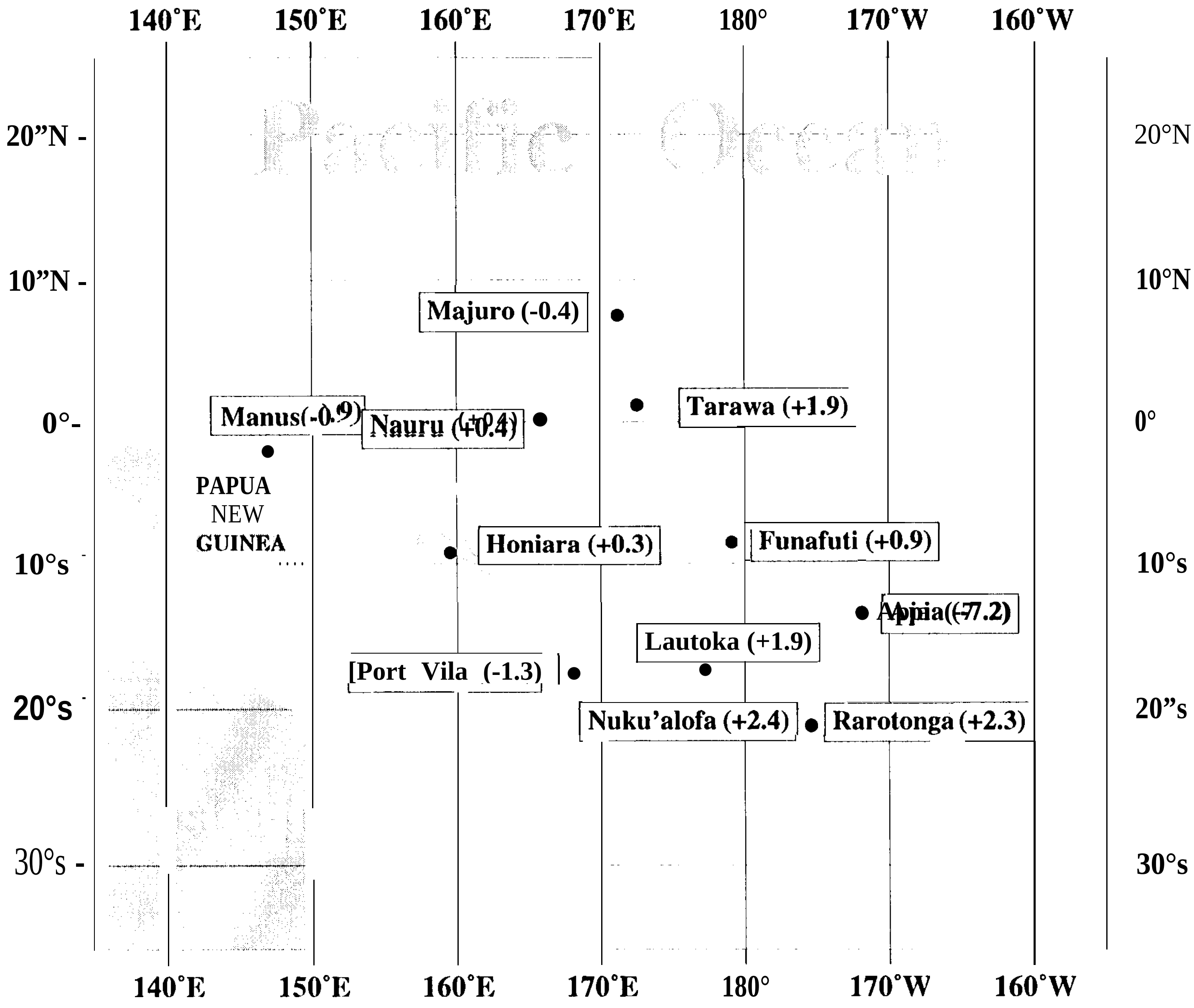
In 1993, the same group of experts again met to discuss advances in geodetic techniques for monitoring tide gauges and recommended that:

- 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

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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 arc 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 arc 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 arc made annually by either spit-it 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.

1NTROD[JC'J'1ON

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 arc shown in figure 1.

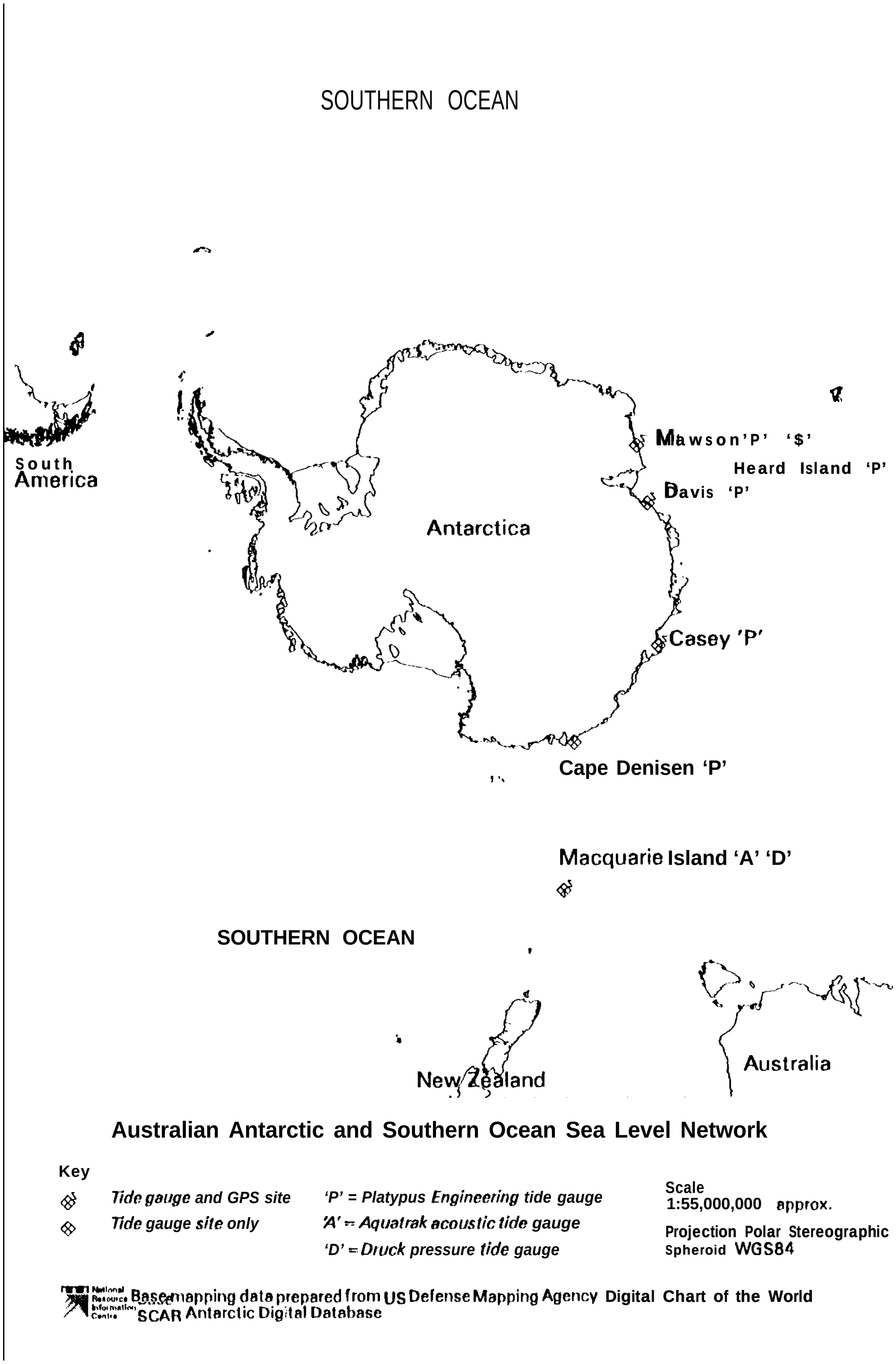

Figure 1. Location map.

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
Macquaric Island	Aquatrak acoustic Druck pressure	Aquatrak 12/93 Druck 12/94	1/97	TmboRogucSNR8100 Dornc Margolin Antcnna
Heard island	Platypus Engineering	8/93	No data to date,	Nonc
Mawson	Platypus Engineering	3/93	1/97	Tutt)oRogllcSNR8100 Dornc Margolin Antcnna
Davis	Platypus Engineering	4/93	1/97	Tutt)oRogacSNJt8100 Dornc Margolin Antcnna
Casey	Platypus Engineering	3/96	No data to dale	TurboRoguc SNR 8100 Dornc Margolin Antcnna
Cape Denison	Platypus Engineering	12/94	No data to dale	Nonc

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:

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

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-3 sin 2Ø +2,361 ~-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 arc 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.

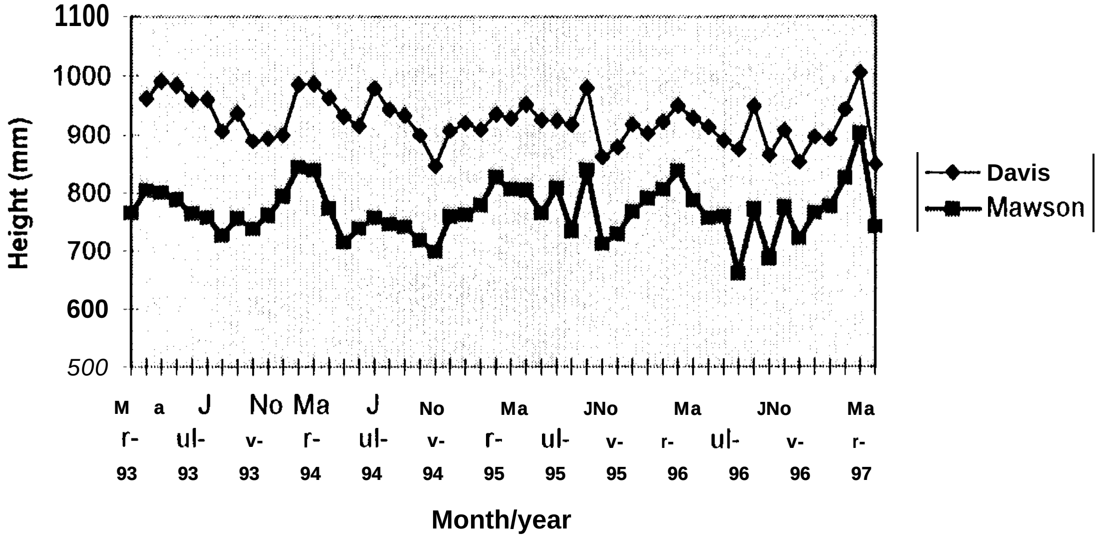

Figure 2. Monthly means for Mawson and Davis. Height values are in millimetres above lowest astronomical tide.

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).

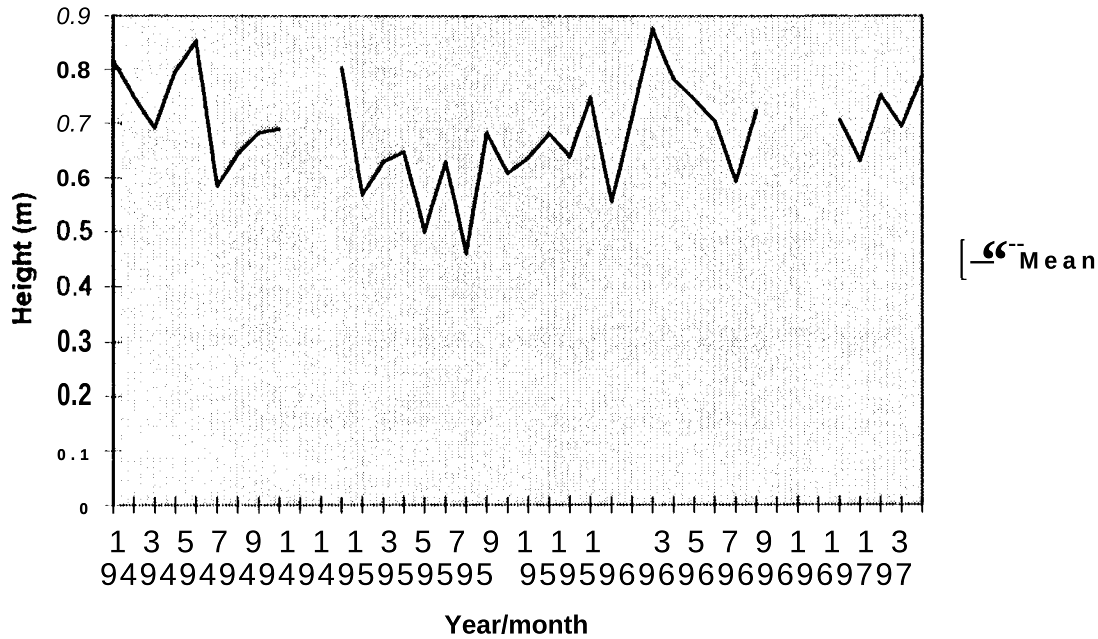

Figure 3. Monthly means for Macquarie Island. Height values are in metres above an arbitrary datum (3.3 m below the Aquatrak reference point). The data is principal y from the primary (Aquatrak) acoustic sensor with some of the gaps filled with data from the secondary (Druck) pressure sensor.

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. Scc 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 SAA STAMOINEN 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 O - 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 arc 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,

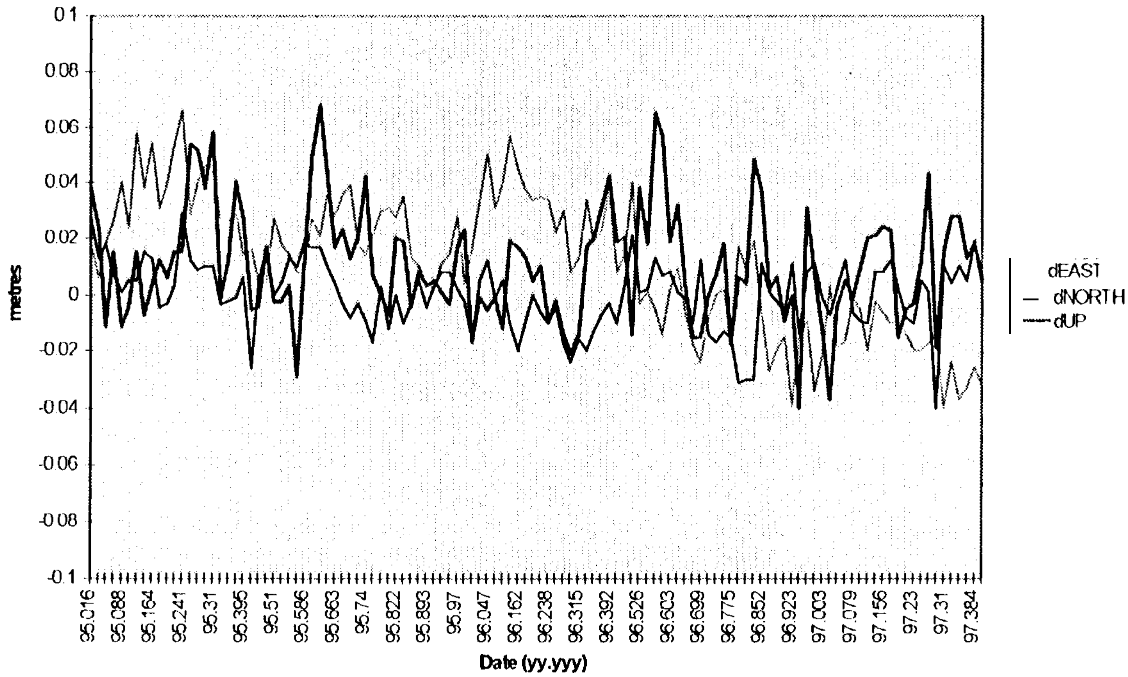

Figure 4. ENU plot of GPS data from Mawson.

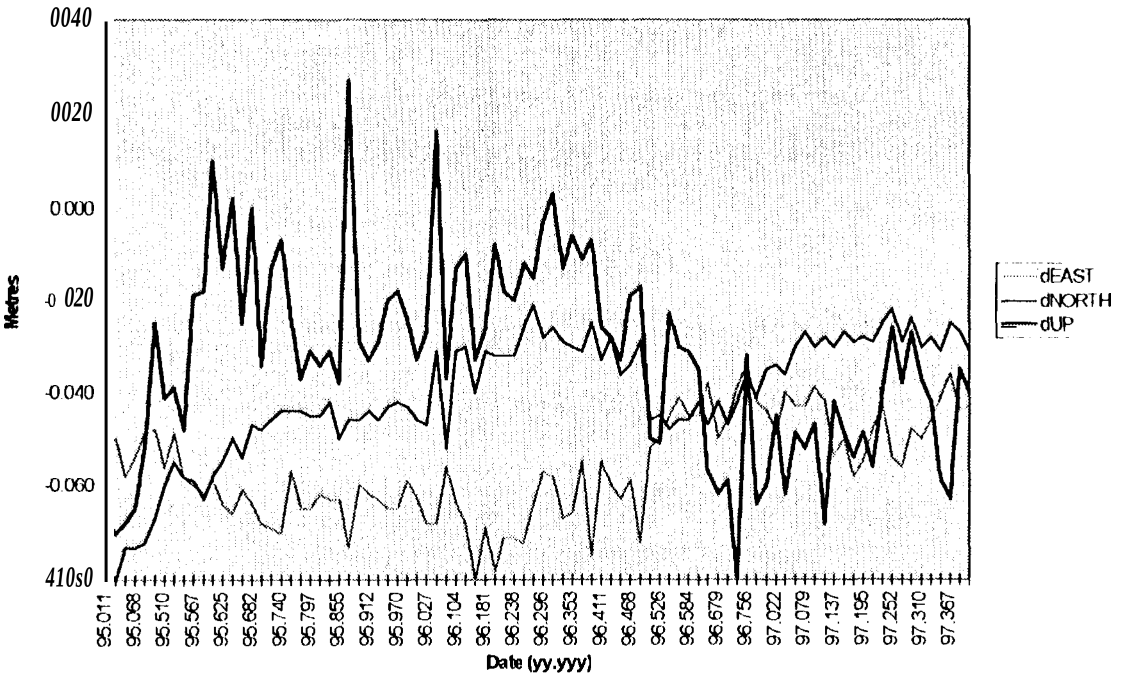

Figure 5. ENU plot of GPS data from Macquarie island.

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 l 995-96 the height of the tide gauge was determined by using a staf'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) - AUS 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
All 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	-30,551 (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	?	-3 1 .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 AUS 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 arc 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.

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The Baltic Sea Level Project - History, Present and Future

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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).

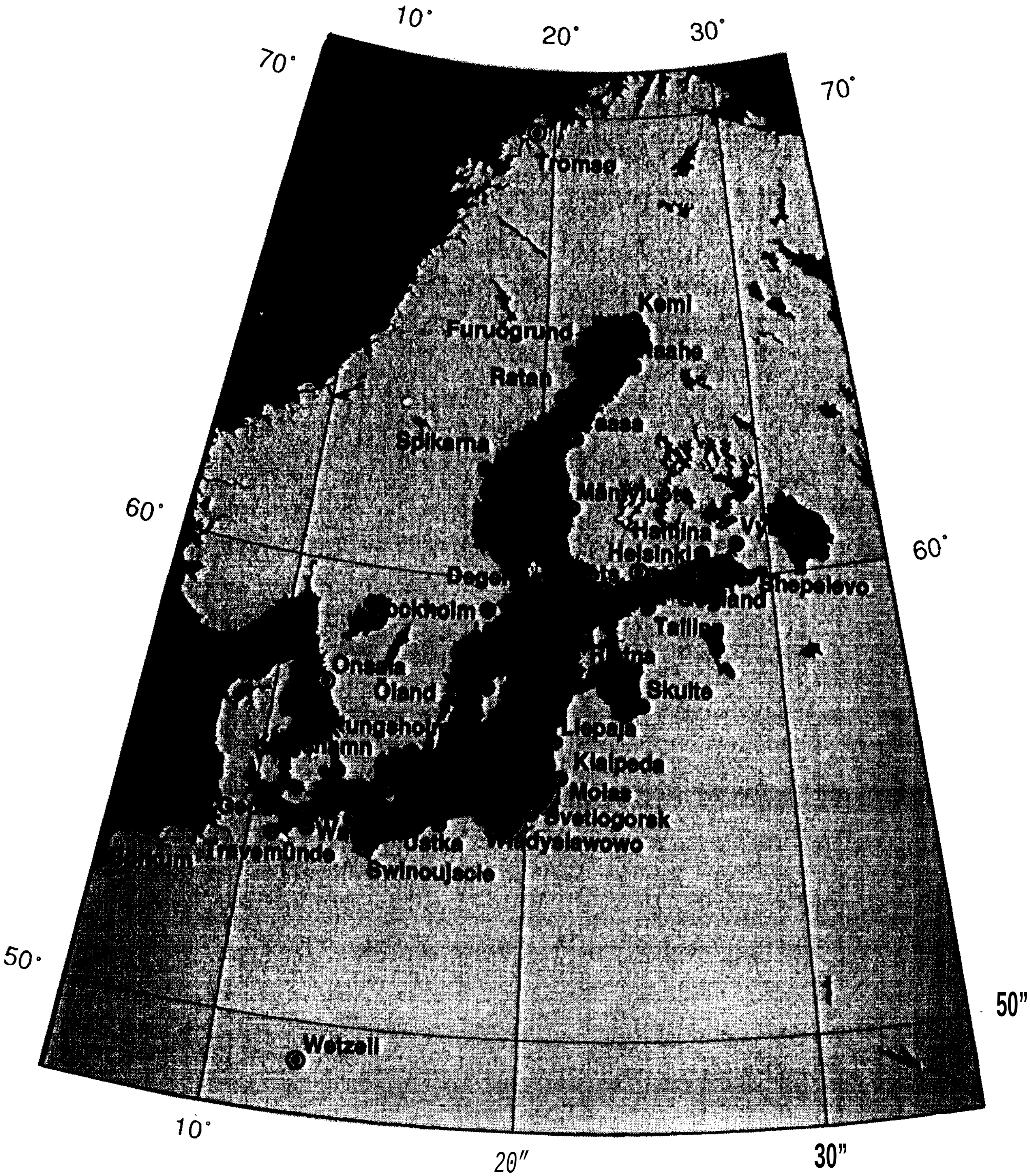

Figure 1. *The Baltic Sea Level network.*

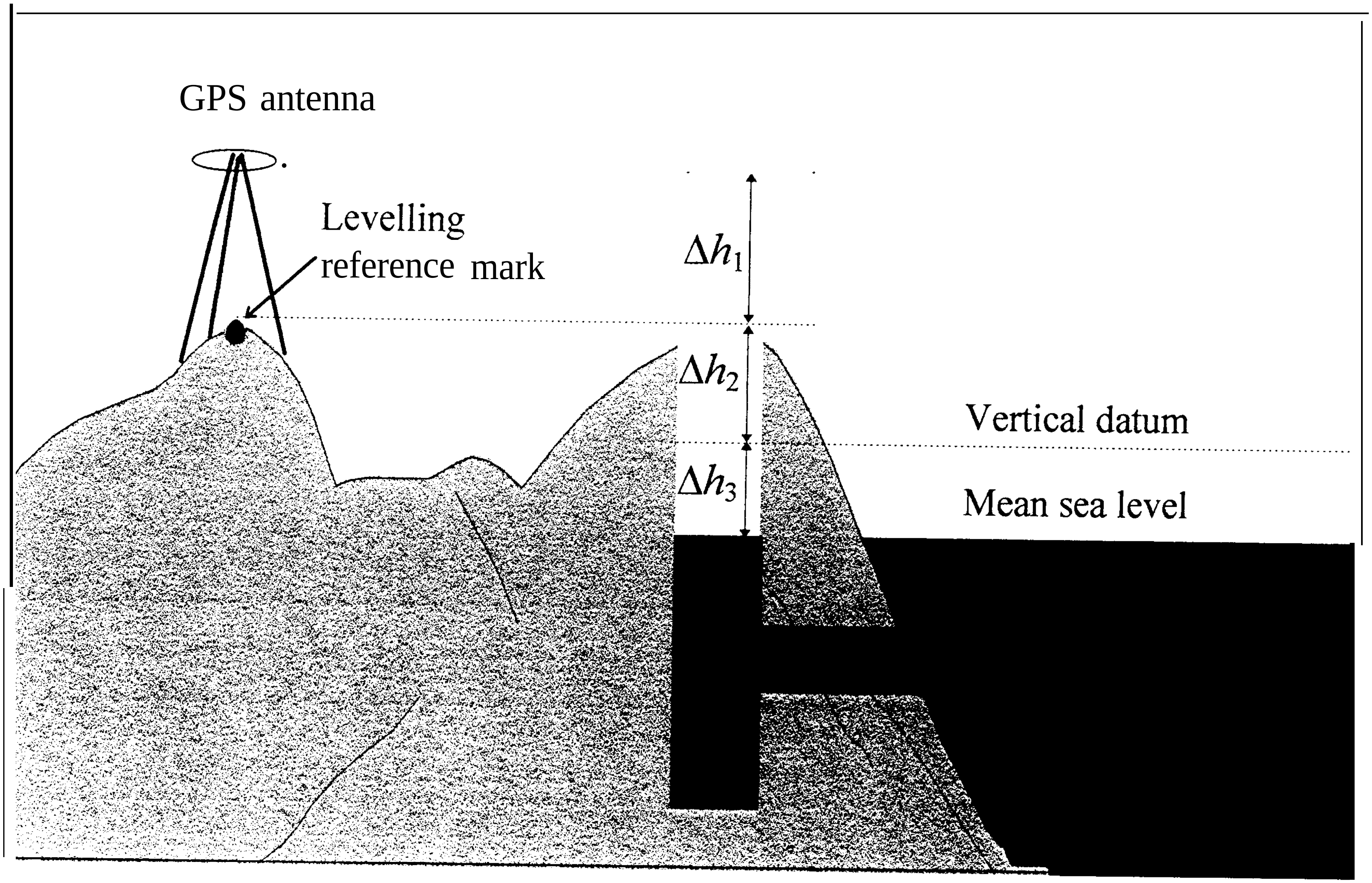

Figure 2. *Arrangements of the GPS observations at tide gauges.*

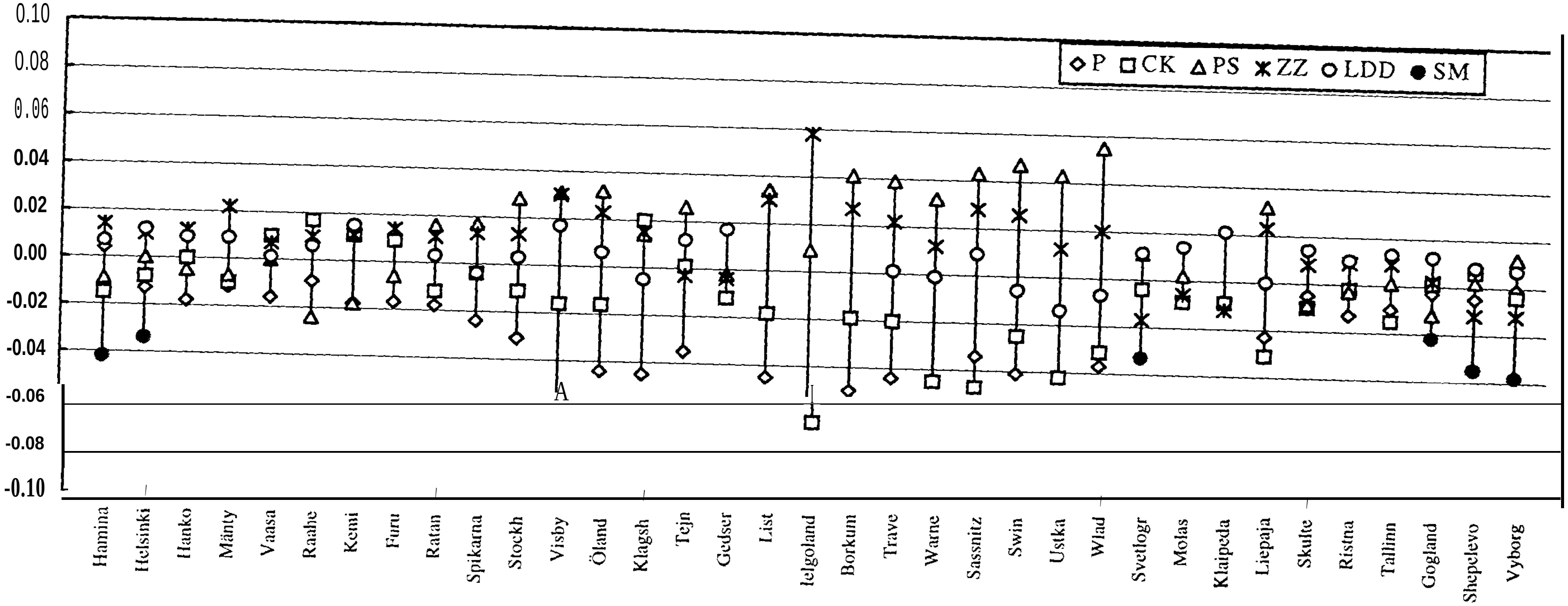

Figure 3. *Repeatability (in m) of the height component of the second Baltic Sea Level GPS Campaign obtained from the results of six separate computing groups.*

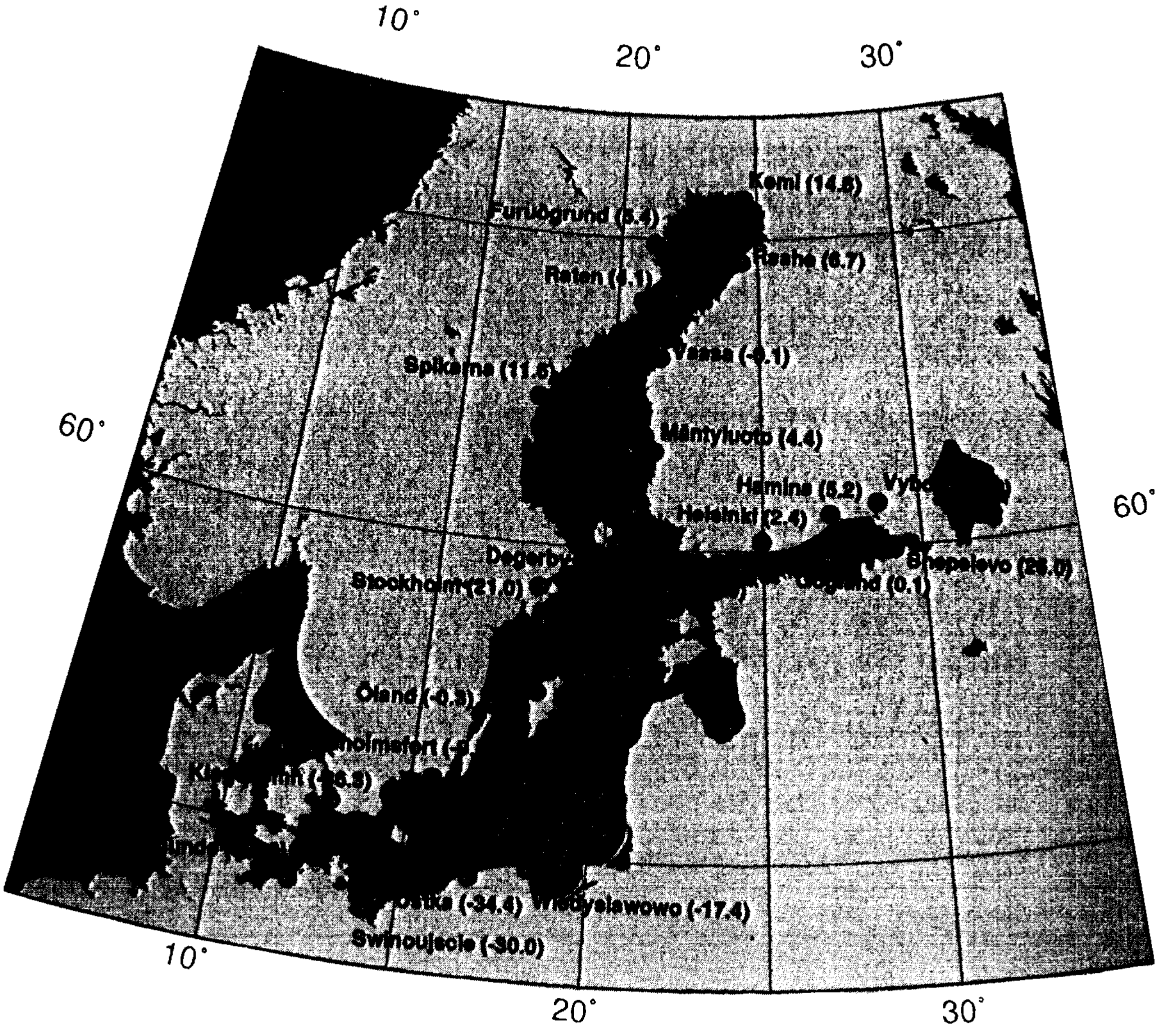

Figure 4. *Sea Surface Topography of the Baltic Sea.*

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 bench-marks 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.

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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.

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European Vertical GPS Reference Network - EUVN

Concept, Status and Plans

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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.

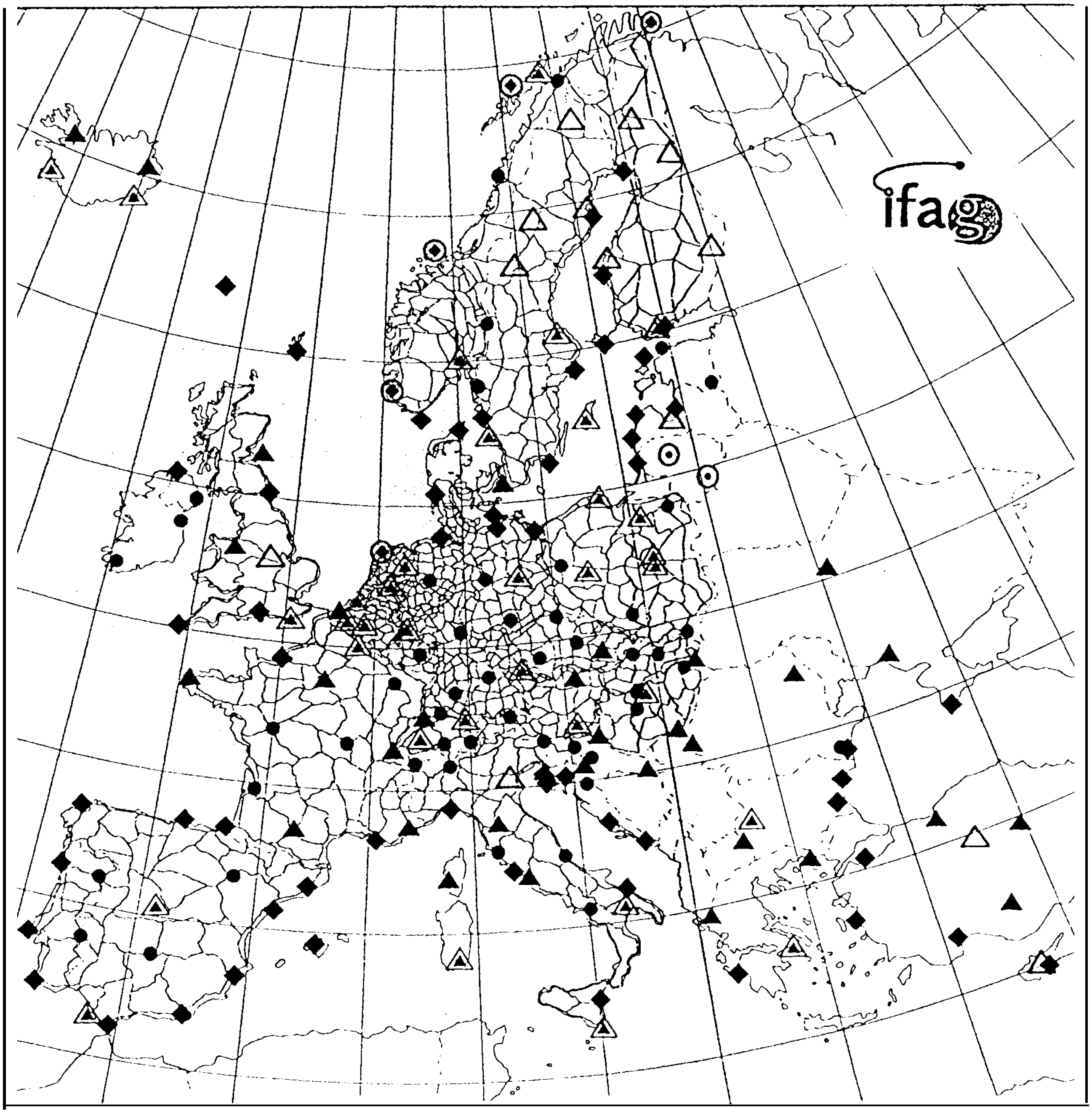
3. Schedule of the EUVN-activity

The GPS-observation campaign called EUVN97 is scheduled from May 21/1 8:00 UT to May 29/06:00UT. 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

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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.

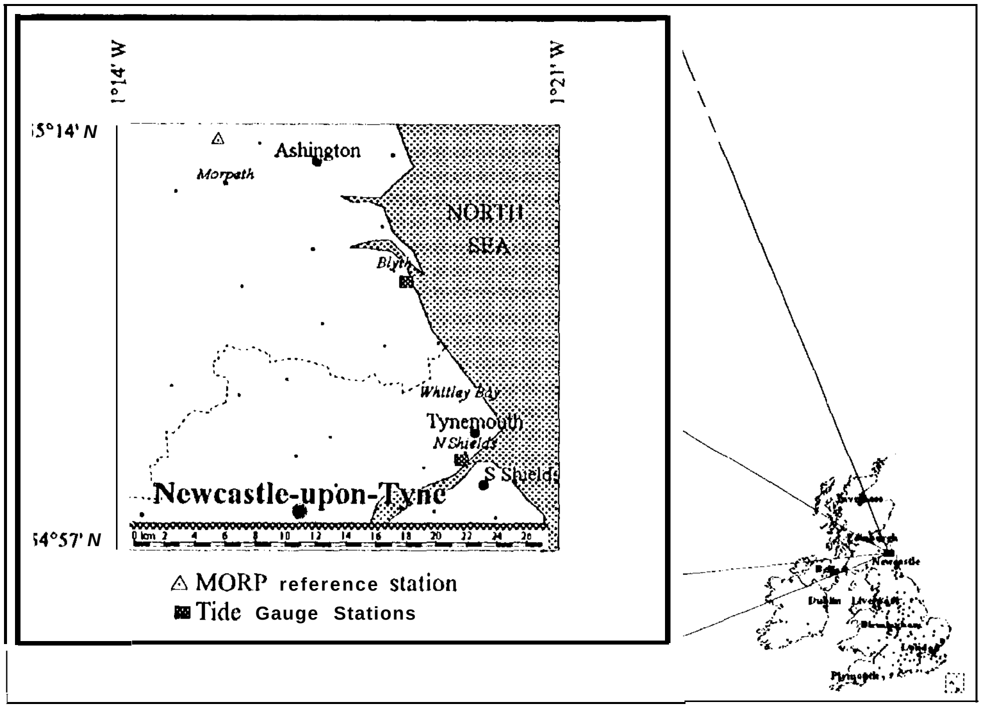

Figure 1. Location of the permanent GPS station MORP and the Tide Gauges

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

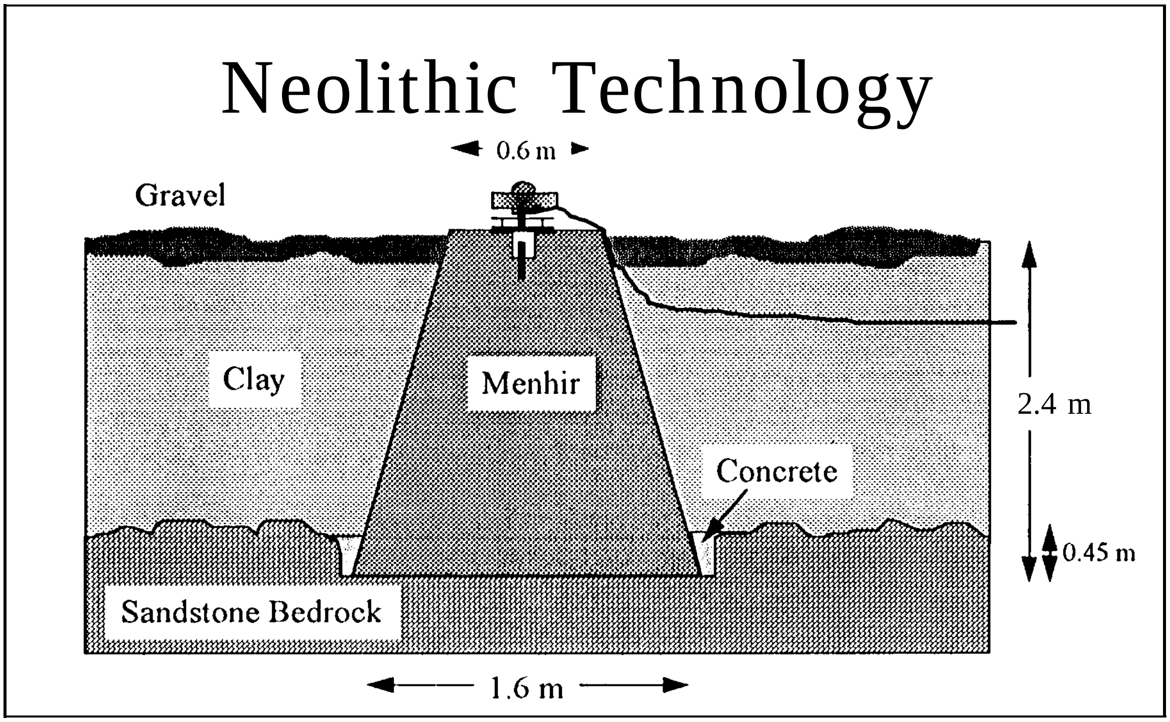

Figure 2. Cross section showing the ground structure of MORP (Blewitt et al.,1996b)

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).

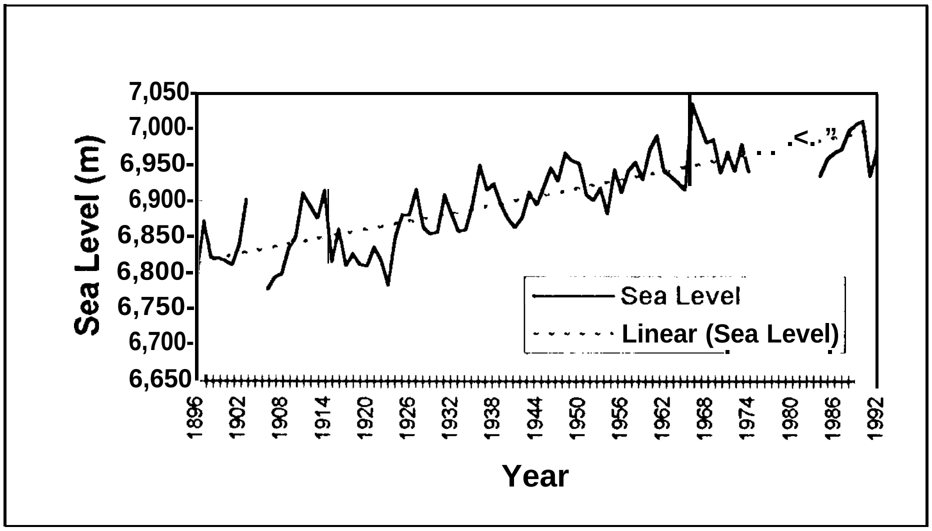

Figure 3. North Shields Sea Level Trend

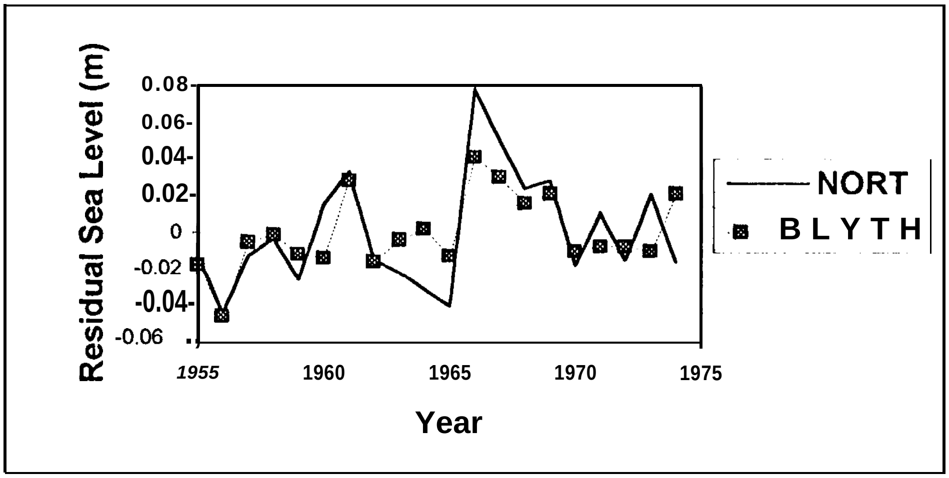

Figure 4. Sea Level Correlation Between Blyth and North Shields

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.

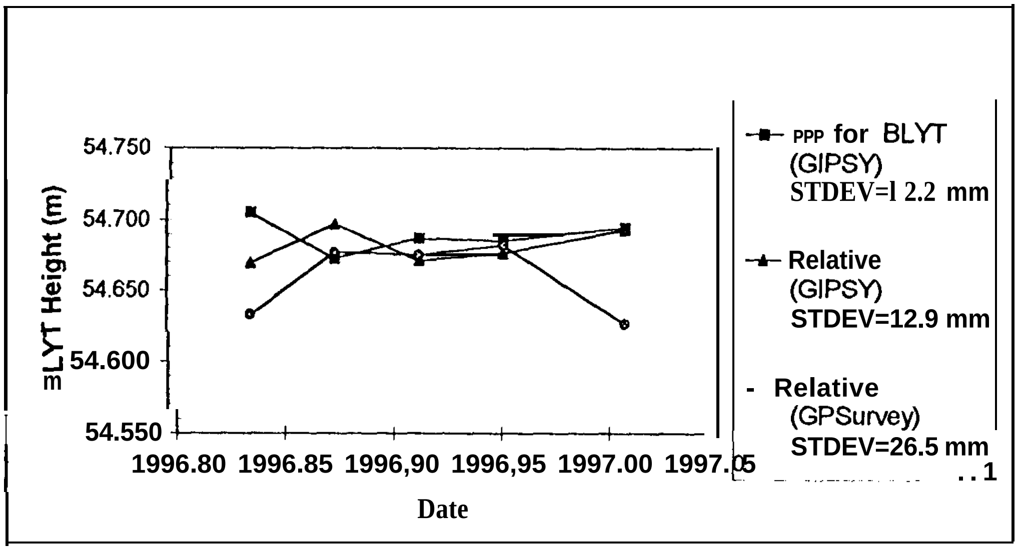

Figure 5. Software/Technique For Point Positioning: BLYT-MORP(16 km)

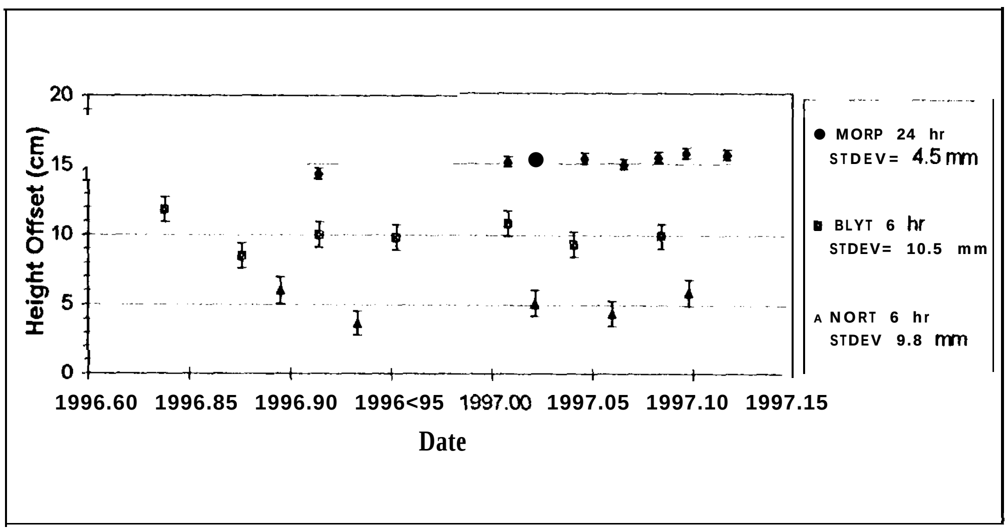

Figure 6. Precise Point Positioning (GIPSY, 30 sec data)

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).

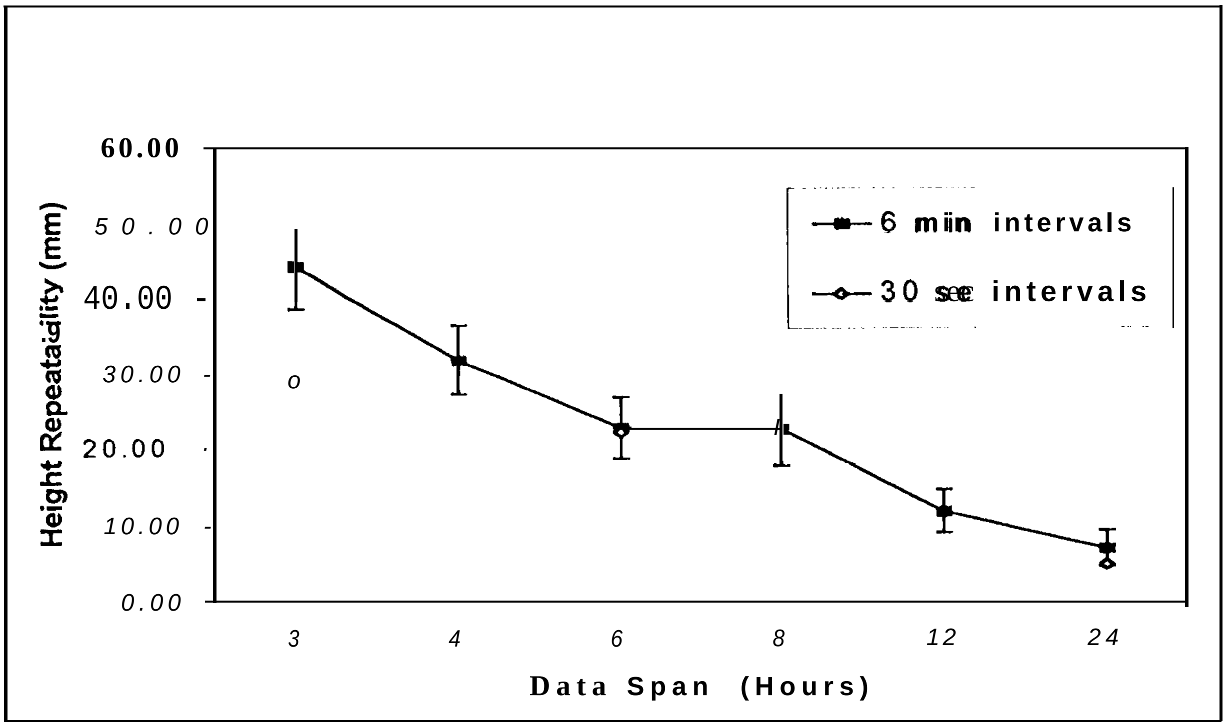

Figure 7. Effect of Data Span on Precision (MORP Precise Point Positioning, GIPSY)

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.

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

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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, 199 1). 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 bc 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.

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IGS-PSMSL

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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

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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 center; will be discussed.

IGS DATA ANI) 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 arc 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., orrc second) in support of other programs; the data arc 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.

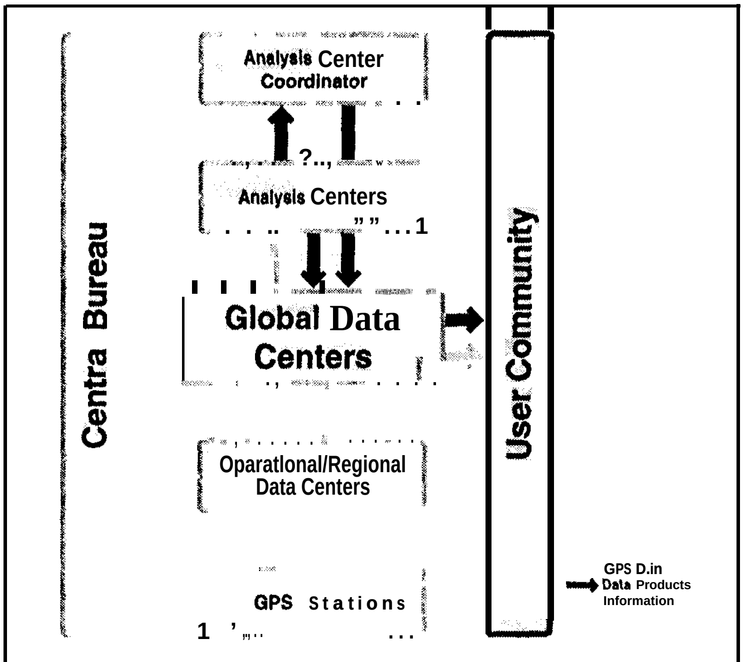

Figure 1. Flow of IGS Data

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 global] y distributed stations, These stations are continuously tracking and are accessible through phone lines, net work, 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 arc utilized by every analysis center (Gurtner and Neilan, 1995). A core set of nearly seventy sites arc analyzed on a daily basis by most centers; these sites arc 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

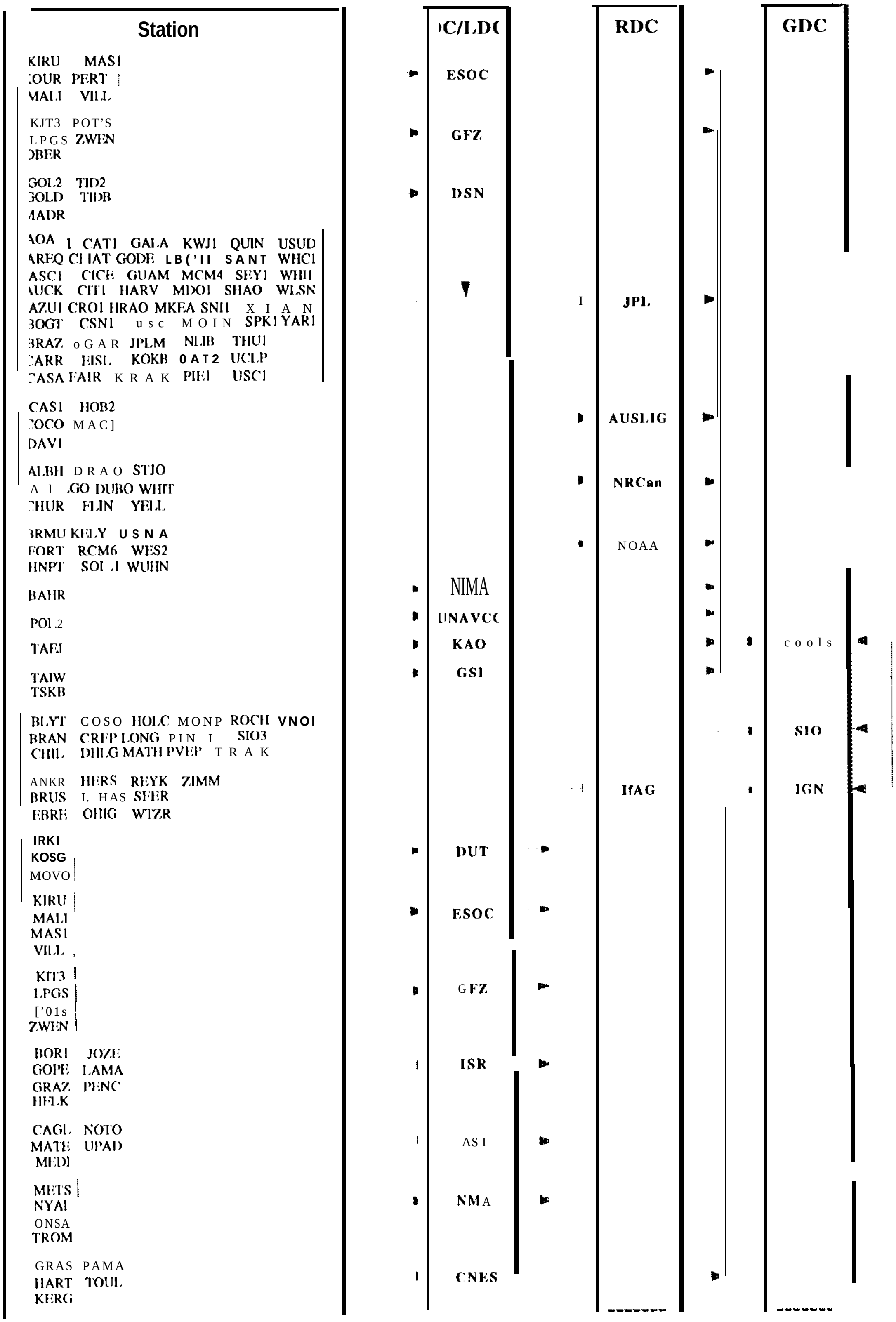

Figure 2. IGS Data Flow (by Data Center)

‘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
ASCl•		JPL	CDDIS
AUCK*		JPL	CDDIS
AZU1		JPL	CDDIS
BAHR*	NIMA		CDDIS
BLYT			SIO
BOGT		JPL	CDDIS
BOR1	ISR	IfAG	rGN
BRAN			SIO
BRAZ*		JPL	CDDIS
BRMU*		NOAA	CDDIS
BRUS		IfAG	IGN
CAGL	AS I	IfAG	IGN
CARR		JPL	CDDIS
CAS1*		AUSLIG	CDDIS
CASA		JPL	CDDIS
CAT1		JPL	CDDIS
CHAT*		JPL	CDDIS
CHIL			SIO
CHUR		NRCan	CDDIS
CICE		JPL	CDDIS
CIT1		JPL	CDDIS
COCO*		AUSLIG	CDDIS
COSO			SIO
CRFP			SIO
CRO1*		JPL	CDDIS
CSN1		JPL	CDDIS
DAV1•		AUSLIG	CDDIS
DGAR*		JPL	CDDIS
DHLG			SIO
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	ISR	IfAG	IGN
GRAS	CNES		IGN
GRAZ	ISR	IfAG	IGN
GUAM*		JPL	CDDIS
HART	CNES		rGN
HARV		JPL	CDDIS
HERS		IfAG	rGN
HFLK	ISR	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) I IfAG	CDDIS I IGN
KIT3*	GFZ	(none) I IfAG	CDDIS I IGN
KOKB*		JPL	CDDIS
KOSG*	DUT	IfAG	rGN
KOUR*	ESOC		CDDIS
KRAK		JPL	CDDIS
KWJ1*		JPL	CDDIS
LAMA	ISR	IfAG	IGN
LBCH		JPL	CDDIS
LHAS*		IfAG	IGN
LONG			SIO
LPGS*	GFZ		COON I IGN
MAC1		AUSLIG	CDDIS
MADR*	DSN	JPL	CDDIS
MALI*	ESOC	(none) I IfAG	CDDIS I IGN
MAS1*	ESOC	(none) I IfAG	CDDIS I 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	IfAG	IGN
OAT2		JPL	CDDIS
OBER	GFZ	(none) I IfAG	CDDIS I 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) I IfAG	CDDIS I IGN
PVEP			SIO
QUIN		JPL	CDDIS
RCM6*		NOAA	CDDIS
REYK*		rfAG	IGN
ROCH			SIO
SANT*		JPL	cools
SEY1		JPJ.	CDDIS
SFER		IfAG	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	IGN
USC1		JPL	CDDIS
USNA		GODC	CDDIS
USUD*		JPL	CDDIS
VILL	ESOC	(none) I IfAG	CDDIS I 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) I IfAG	CDDIS I IGN

67 global stations; 146 total stations

Notes: * indicates global stations

I notation indicates duplicate flow of data

‘I’able 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 I and 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 arc 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 arc also generated at NRCan; rapid orbits are available within 24 hours while the predicted orbits arc 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 IG S 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.

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Sea Level Data Flow

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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).

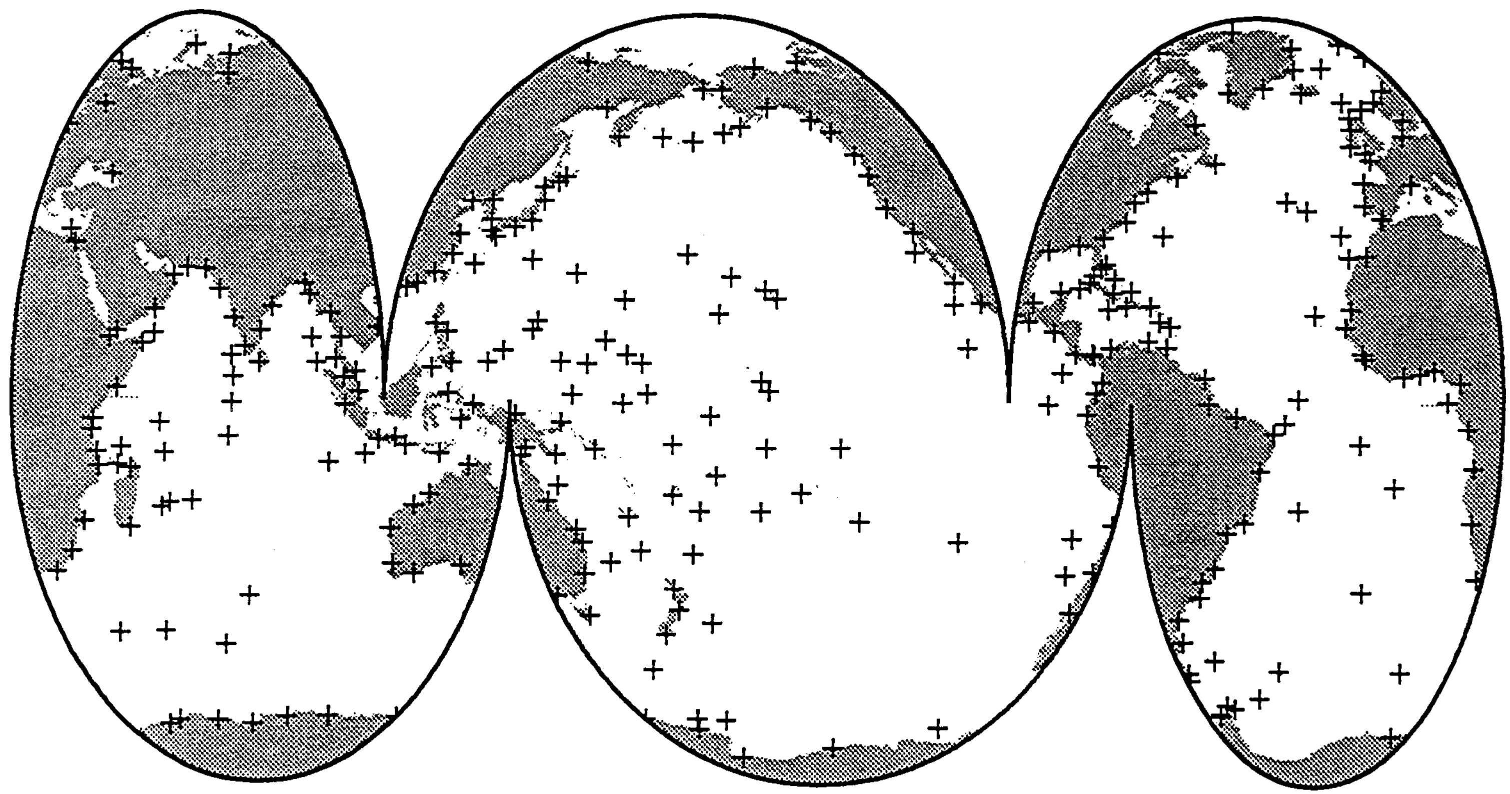

Figure 1. Projected Global Sea Level Observing System, 995.

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.

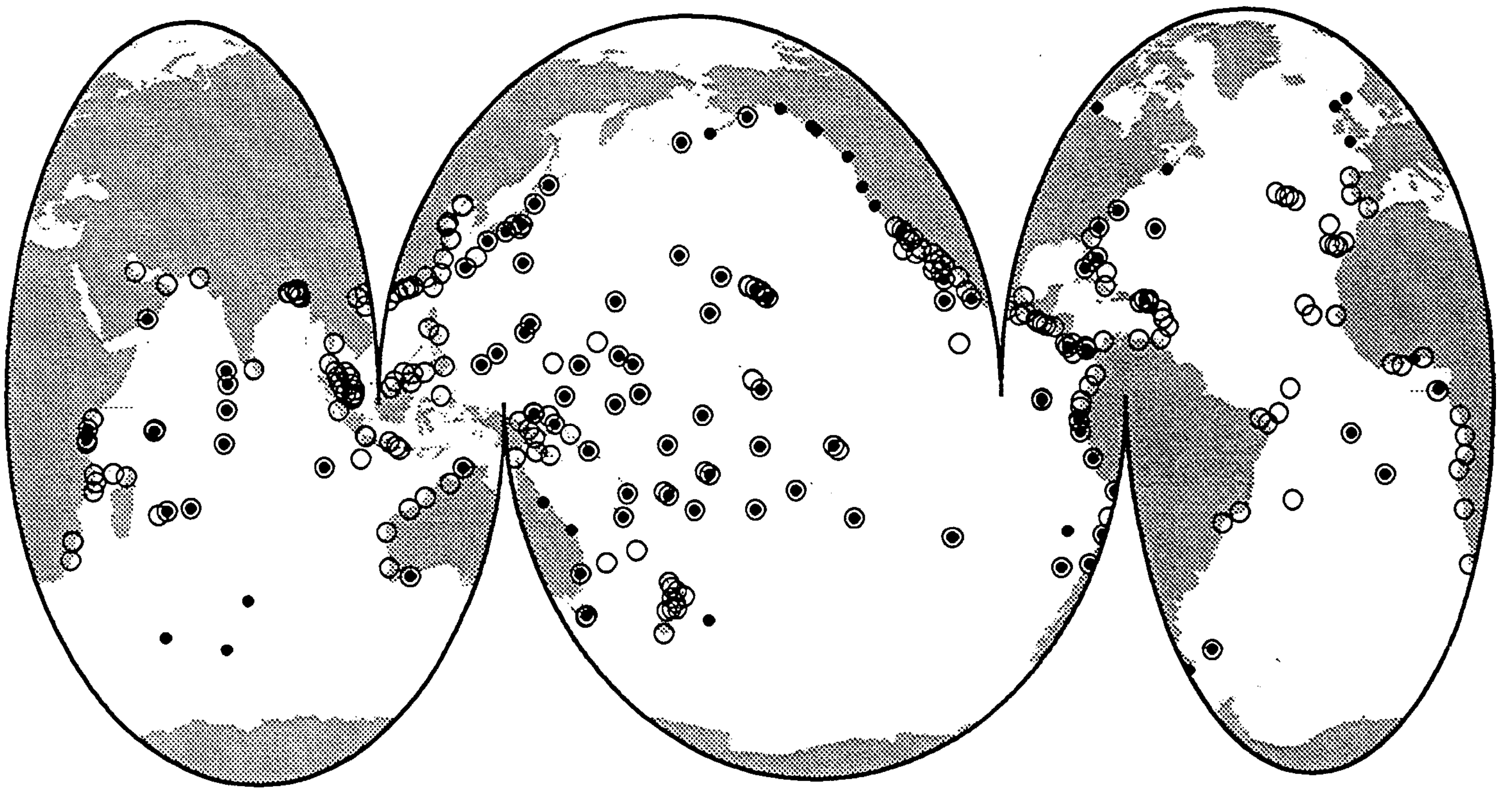

Figure 2. Joint Archive for Sea Level database, June 1997.
Solid circle indicates "Fast Delivery" component.

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