Translated Article

GPS Offshore Buoys and Continuous GPS Control of Tide Gauges

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The sea level has traditionally been observed in coastal regions in order to provide valuable information for ship navigation and harbour safety. Recently, sea level change has been identified being one of the most sensitive indicators of climate change and has significant impact on the socio-economic developments of several countries. It is estimated that around 2.5 billion people live less than 60 km from the coast and that this area shows the greatest biological diversity. A rise or fall of the sea level has, even in a country with a highly developed coastal management, such as Germany, dramatic effects on the habitability and the coastal environment and economy. Dike construction, silting up, saltwater intrusion into ground water or loss of land or ecosystems are only a few of the problems to be considered.

For many decades water levels were only observed at single points through tide gauge measurements. These observations, unfortunately, give only a limit-

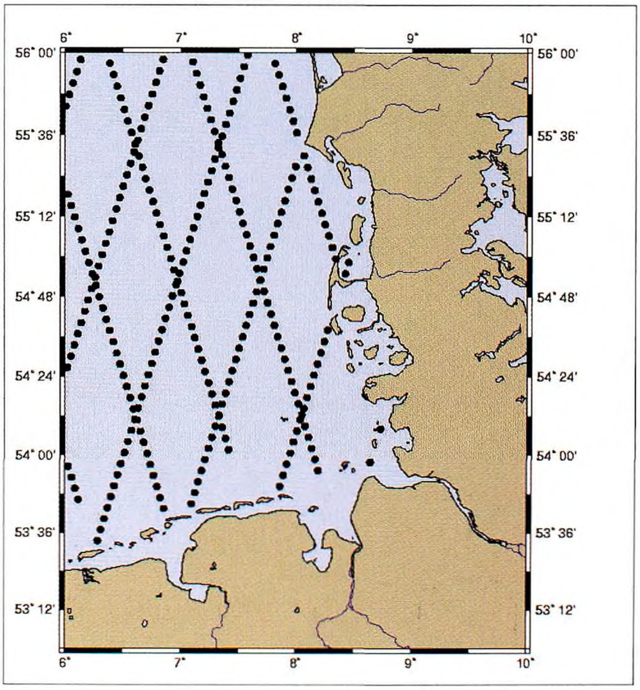

Figure 1: This figure shows the coverage of ERS-2 RA measurements in the North Sea for a 35 days time period. Each point represents one measurement averaged over 6.7 km. The satellites ERS-1 and ERS-2 are in operation since 1991 and 1995, respectively. Therefore, rather long time series of sea level change can be constructed

ed view of the actual global and regional sea level change. Moreover, conventional tide gauge observations are referenced to a local benchmark or a zero level only and not to a global terrestrial reference frame. While this is sufficient for the observation of the relative water level change, e.g. in harbour basins, the detection of climate change related phenomena requires the analysis of the absolute sea level change. Only the separation of vertical movements of the land (e.g. subsidence or post-glacial rebound) from changes of the sea level itself enable conclusions to be made towards recent climatic fluctuations.

Additionally, for solving today's emerging scientific questions the global spatial patterns of sea level change are also of interest. Therefore, remote sensing techniques must be incorporated to obtain global estimates. For the last 15 years, satellite Radar Altimetry (RA) is available in addition to tide gauge observations for monitoring the sea level. Thus, RA has become a major tool for sea level research. However, only the combination of both methods gives reliable estimates about the spatial and temporal changes of the sea level.

At the GeoForschungsZentrum Potsdam (GFZ), studies of the sea level changes have been conducted for many years. In particular, radar altimetry was used, but the interpretation of tide gauge measure-

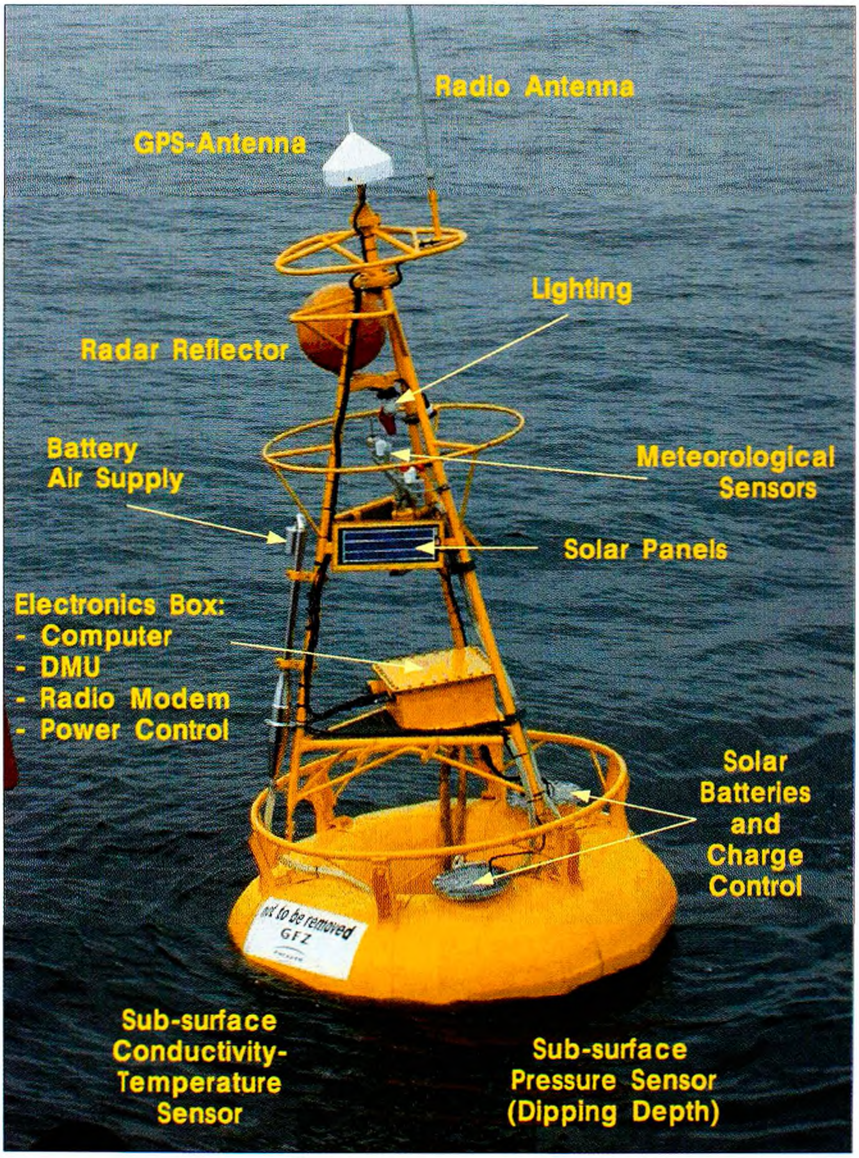

Figure 2: This picture shows the fully mounted buoy (Toroid-buoy) after the deployment in 2002. On top is the GPS antenna, covered by a radome. The box in the middle of the buoy hosts the computer, the accelerometer and the GPS receiver. Below the waterline a conductivity/depth sensor and a high-resolution dipping sensor complement the buoy

ments has recently gained more interest in relation with the growing number of GPS applications and increasing accuracy. Based on the hitherto existing experiences, the SEAL project (Sea level change: An integrated approach to its quantification) was initiated within the scope of the Hermann von Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF) together with the Alfred Wegener Institute for Polar and Marine Research (AWI) in Bremerhaven, the GKSS-Forschungszentrum Geesthacht GmbH and the Geo-ForschungsZentrum Potsdam (GFZ). The central focus of SEAL is an integrated approach of different disciplines to quantify historic and recent sea level changes by using satellite and in-situ measurements, ice and ocean models as well as models of glacial isostatic adjustment. In the context of this paper, two major subprojects should be mentioned: (1) the long-term control of the measurement precision and the intercalibration of different satellite radar altimeters with GPS equipped offshore buoys, and (2) the long-term control of vertical movements of the level benchmarks at tide gauges.

Altimetry Calibration with GPS-buoys

Radar Altimetry

Satellite radar altimetry (RA) is a tool to monitor the sea level continuously and with almost global coverage. A radar altimeter onboard a satellite or aircraft transmits a radar pulse in its nadir, perpendicular to the Earth's surface. This radar pulse propagates through the atmosphere, is reflected by the ocean surface and finally recorded by the altimeter's receiver. From the recorded signals, three estimates can be derived: (1) the distance between the platform and the Earth's surface resulting from the travel time, (2) the significant wave height ($H_{1/3}$), (3) the wind speed above the water level. If the height of the platform is known, e.g. from its orbital sensors, the sea surface height can be calculated from (1).

In particular RA was developed to resolve oceanographic questions. The first satellite radar altimeter was tested in the Skylab-mission (1973), later, the satellites GEOS-3, SEASAT and GEOSAT carried

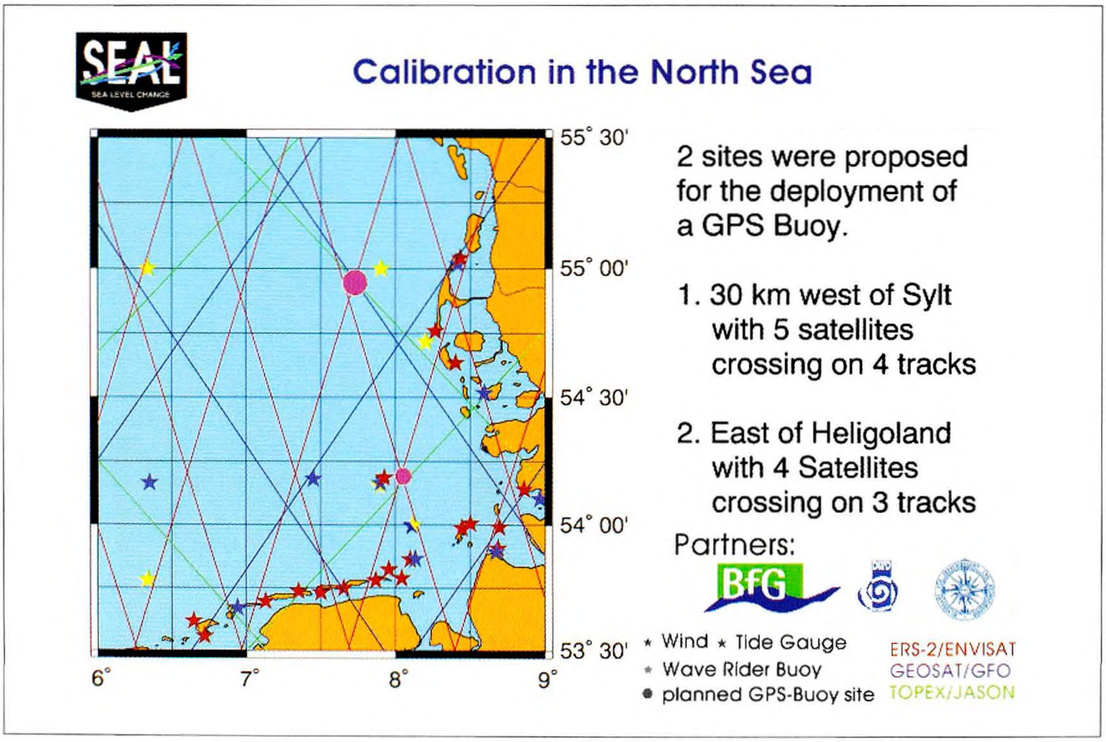

Figure 3: The figure shows the tracks of the satellites' overflights in the area of the North Sea together with other sensors useful for altimetry calibration. There exist two potential positions, which would be suitable for the mooring of the buoy. The satellites ERS-2/ENVISAT, GFO-1 and TOPEX/JASON-1 cross in the west of the Island of Sylt, ERS-2/ENVISAT and TOPEX/JASON-1 in the east of Heligoland. Which position will be chosen in the end depends on the final tests of the data transmission

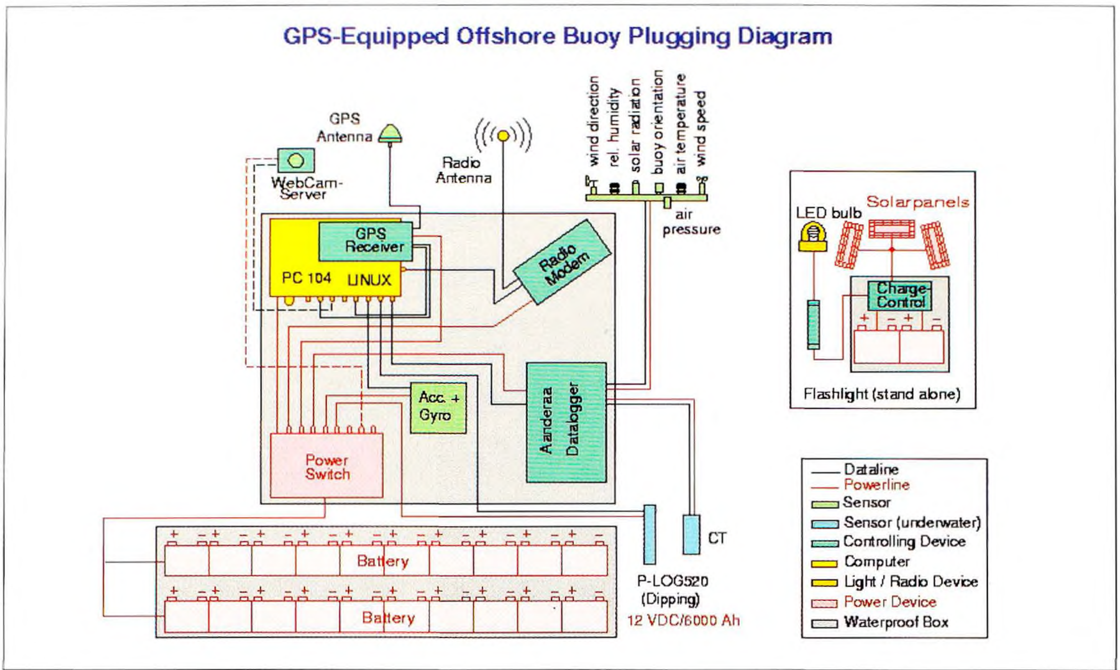

Figure 4: Structure diagram of the technical components used in the development of the GPS-buoy

altimeters. Since 1991, precise RA measurements have continuously been available with the ERS-1 (followed by the ERS-2) and since 1992 with the TOPEX/Poseidon satellite. Both satellites are steered in their trajectory in such a way that they cover the Earth's surface every 35 days and 10 days, respectively (Figure 1). The global homogenous coverage is opposed to a temporally low resolution compared to tide gauge intervals. Since 2002, two new RA missions are operational, JASON-1 (launched 7 December 2001) is the successor of TOPEX/Poseidon, and ENVISAT (launched 1 March 2002) follows ERS-2. Long time series of sea level measurements are available from these missions and will be continued in an improved quality in the future. The multiple missions provide global time series of about 17 years compared to 100-150 years of localised tide gauge records.

The analysis of RA data of different satellites reveals two problems. There exists a time gap between the mission's end of GEOSAT and the start of ERS-1 and every radar altimeter has individual errors, e.g. sensor biases as well as drifts due to the ageing of the satellite electronics. To construct a homogeneous time series from all missions and to correct the apparent sea level changes of the individual missions conditioned by the drift, appropriate calibrations have to be carried out. So far, mainly tide gauges near satellites' overflights or the analysis of the differences at crossover points of the satellites were used.

The use of tide gauges for the calibration of RA has some disadvantages. The tide gauges are mainly installed at the coast where RA has a decreased performance and accuracy due to disturbing radar reflections from the land surface. There are almost no tide gauges, which are situated directly below a satellite's overflight. The necessary interpolations between the tide gauge measurement and the nadir of the satellite reduce the accuracy of the calibration. In order to get an absolute calibration and a drift determination, the heights of the tide gauge benchmarks must be monitored with GPS. A more direct method is to anchor a GPS-equipped buoy exactly in the nadir of a satellite's overflight. From the GPS-measurement at the moment of overflight the instantaneous sea surface height can be calculated. From the measurements of the satellite, whose height is defined in the same co-ordinate system, the bias is determined.

The Federal Maritime and Hydrographic Agency of Germany (BSH) in Hamburg kindly provided a suitable buoy for GFZ's SEAL project. It is a toroid buoy, which can serve as a platform for multiple sensors. To test the dynamic characteristics of the buoy as well as to find a suitable method for the mooring, FS Gauss deployed two identical buoys in the North Sea for two weeks in February 2001.

Scientific and Technical Realisation

The GPS-buoy (Figure 2) will be deployed in the southern North Sea, where sufficient logistic support can be provided in order to maintain a continuos operation. Moreover, the overflights of different satellites cross at the particular sites. Including the measurements of the significant wave height by the BSH, the measurements of the wind speed by the DWD, and the tide gauge data, which are kept at the German Federal Institute of Hydrology, there exist a full set of in-situ measurements for the calibration.

Two positions are suitable for a mooring (Figure 3). The satellites ERS-2/ENVISAT, GFO-1 and TOPEX/JASON-1 cross to the west of the island of Sylt, ERS-2/ENVISAT and TOPEX/JASON-1 in the east of Heligoland. The first position has the advantage that all altimeters of the current and planned missions can be calibrated. Therefore, this position is finally favoured, even if the radio communication between the buoy and the land station is less efficient.

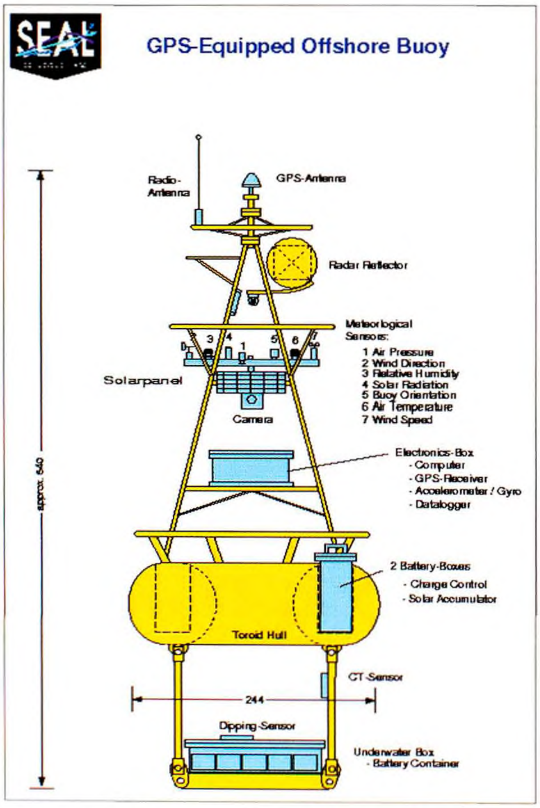

Figure 5: Technical plan of the GPS buoy construction

The central element of the buoy (Figure 4) is a GPS-receiver. During an overflight GPS-measurements has to be carried out at a rate of 10 Hz to register the movement of the buoy correctly. Additionally, installed acceleration sensors and tilt meter can be used both for the correction of the buoy movement and as an additional parameter for the GPS solution. Moreover, the significant wave height can be estimated by combining the vertical movement derived from GPS with the vertical accelerations. Sensors for meteorological parameters (e.g. wind speed and air pressure) complete the equipment (Figure 5). With that there are corresponding in-situ data available for all of the three values derived from the RA.

At present the components for the buoy are being integrated. It is expected that the buoy can be deployed in September 2001.

Tide Gauge Benchmark Control by Continuous GPS

The information of the tide gauges is used by the GFZ for the calibration of the RA and for the study of local sea level changes. Therefore, the tide gauge benchmarks have to be integrated into a geodetic network, e.g. by GPS, to get the absolute height reference. In the near future continuously recording GPS-receivers will be installed to a larger extent near to tide gauges in order to record the changes in height without interruption. Suitable GPS-networks are the networks of the International GPS Service (IGS), EUREF or SAPOS®. In these networks co-ordinates are calculated on a daily basis for all points. The corresponding time series is used later on to analyse and correct for the vertical movement of the tide gauge benchmark.

Up to the present, the solution strategy for large continuous GPS networks, e.g. within the IGS, is mainly focused on the determination of the horizontal co-ordinates and their changes. The height component of the GPS co-ordinate, which clearly has larger uncertainties in the order of one magnitude (Figure 6), is often down-weighted accordingly during the combination of the daily solutions. This ensures a higher reliability of the horizontal component, but affects the height component used for sea level studies.

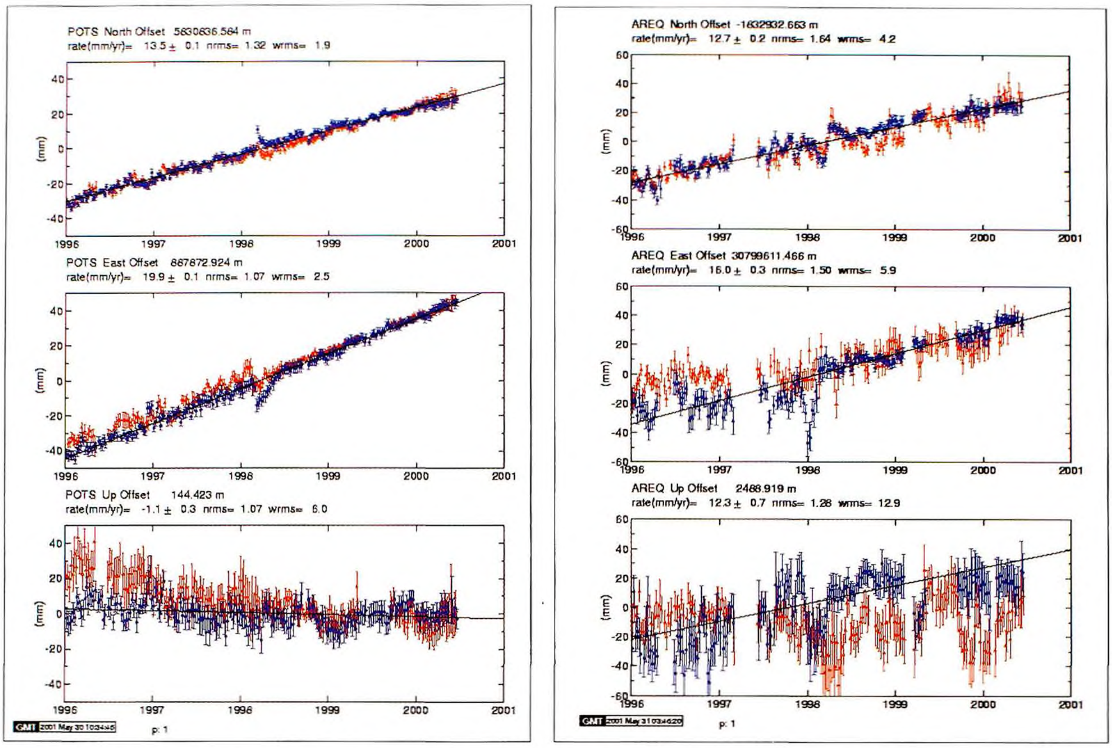

Figure 6: The picture shows the movement (north, east, height) for the IGS-GPS-stations Potsdam (left) and Arequipa (right) calculated by two analysis centres of the IGS (GFZ and SIO). While the horizontal components of both solutions are comparable, the height component shows distinct differences (data from http://bowie.mit.edu/ ~fresh/)

Recently, the GFZ proposed the initiation of a pilot project to the IGS, which is specifically planning the evaluation of continuous GPS-measurements at tide gauge stations (GPS Tide Gauge Benchmark Monitoring Pilot Project/TIGA-PP, http://op.gfz-potsdam.de/tiga/). GFZ's contribution to this international project is an effort of the SEAL project.

Figure 7 gives an overview of tide gauges near permanent GPS-stations. Only for a very limited subset of these stations levelling ties exist between the GPS benchmarks and the tide gauge benchmarks. Therefore, a large international effort is needed to increase the number of permanent GPS at tide gauges.

The TIGA-PP was set up with the following aims:

1. Set-up, maintenance and extension of a network of tide gauges equipped with GPS
   - Selection of tide gauges with a long and well documented history
   - Combination of this network with other space geodetic methods (e.g. SLR, DORIS, VLBI)
   - Definition of minimal standards for the tide gauge systems and application of IGS standards for the GPS-stations
2. Surveys to improve the determination of the height component from GPS and to define a stable reference system
3. Reprocessing of existing IGS-GPS-data by using improved reference systems (e.g. ITRF2000), improved software and an improved distribution of stations
4. Development of a processing chain for GPS-data at tide gauge stations with a high latency to enable as many GPS-stations as possible to participate (e.g. in the Antarctica or of stations without INTERNET access)
5. Development of a processing chain with a low time delay to support near real time applications

Within the scope of this project several analysis centres are going to evaluate the GPS data with the same standards but with different software systems. Furthermore, special studies for the combination of these data are necessary which aim to derive the accurate height and its temporal changes as good as possible.

The results of the TIGA-PP height information for

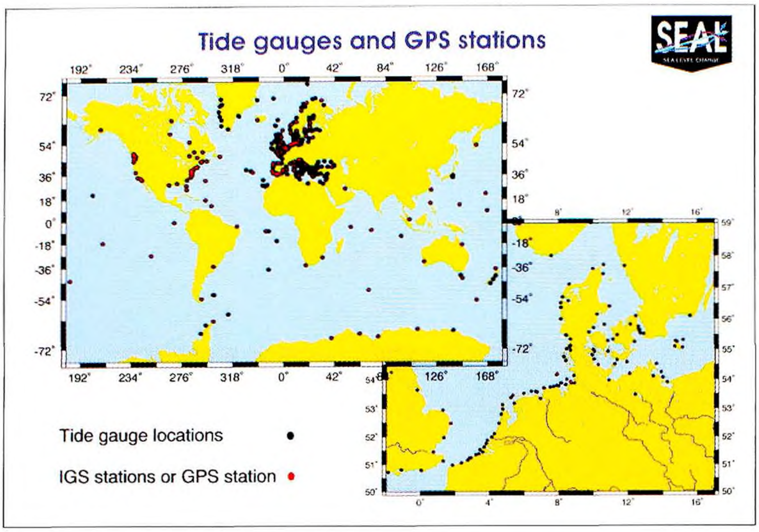

Figure 7: The figure shows the distribution of tide gauges (black dots) and tide gauges near permanent GPS-stations. While the distribution of stations in Europe is satisfying, corresponding stations are missing in large parts of Africa, Asia, South America and Russia (Data from http://igscb.jpl.nasa.gov/, http://sonel.ensg.ign.fr/phpgen/projects/survey.cgps.php3, http://www.ngs.noaa.gov/CORS/, http://www.gdiv.statkart.no/eoss/)

the tide gauge benchmarks will be available for a certain set of stations/data and on a continuous basis. These data can serve as a global reference system for regional groups such as the European Sea Level Service (ESEAS). Moreover, it can be expect that other scientific projects will be triggered by TIGA-PP, revealing further-reaching aspects than described here.

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Post Scriptum

The manuscript is based on a presentation at a meeting of the German Hydrographic Society in early 2001. The GPS buoy was successfully deployed in May 2002 together with four bottom mounted tide gauges. In total 18 overflights were recorded till August 2002. Currently the buoy is upgraded, while the tide gauges measurements are still continuing. The redeployment is scheduled for 2003. Both the GPS buoy project and the TIGA Pilot Project are ongoing.

Biographies

Tilo Schöne is a senior scientist at GFZ Potsdam, Department Geodesy and Remote Sensing, Germany. His main research fields are radar altimetry applications for sea level change studies including the calibration and intercalibration of different radar altimeters and the application of tide gauges for sea level change studies.

Christoph Reigber is the Director of the Department Geodesy and Remote Sensing at GFZ Potsdam, Germany. His main research interests are the determination of global gravity field models using satellite and terrestrial data, the determination of Earth kinematics using satellites, and crustal deformation and Earth system studies.

Alexander Braun holds a PhD in geophysics from the University of Frankfurt in 1998 specialising in geodynamics and satellite altimetry. Between 1998 and 2002 he worked for the GFZ Potsdam on sea level change and satellite altimetry. Since 2002, he is a Byrd Fellow at the Byrd Polar Research Center of the Ohio State University. His research interests cover sea level change and the deformation of the Earth's crust and lithosphere using space geodetic observations.

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