Intergovernmental Oceanographic Commission

Workshop Report No. 81

Joint IAPSO-IOC Workshop on Sea Level Measurements and Quality Control

Paris, 12-13 October 1992

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1. OPENING

1 The Joint IAPSO-IOC Workshop on Sea Level Measurements and Quality Control was opened by Dr. Albert Tolkachev who welcomed the participants. Dr. David Pugh on behalf of IAPSO and Dr. Klaus Voigt on behalf of IOC both emphasized the importance of collaboration between IAPSO and IOC in delivering new technology and methods required for operation of GLOSS as an important existing element of GOOS. The Workshop was convened following the recommendations of the Group of Experts at the GLOSS 1990 Session in Miami to discuss the latest techniques for measuring the sea surface topography and for quality controlling the data. The List of Participants (Annex III) is attached. Dr. G. Mitchum, Co-Director of the TOGA Sea Level Centre, chaired the sea level measurements session, Dr. G. Maul, Vice-President of IOCARIBE, headed the quality control and processing presentations, and Mr. P. Caldwell of the National Oceanographic Data Centre (NOAA-USA) and TOGA Sea Level Centre served as rapporteur. Papers presented at the Workshop are given in Annex I.

2 New technology for measuring the sea surface topography was reviewed with emphasis on comparisons to conventional gauges and on methods of calibration. The session opened with a look at a variety of acoustical gauges, stilling well dynamics, and automated datum control techniques. Secondly, discussions focused on subsurface pressure devices, inverted echo sounders, GPS measurements from moored buoys, satellite altimetry, and satellite orbit positioning. Finally, quality control and data processing methods used by well-known data centres and agencies were outlined for preparation of a manual that can be distributed as a guide to sea level processing agencies around the globe. Below, highlights are provided of each talk in this Workshop with inclusion of comments from the group of experts on the various topics.

2. SEA LEVEL MEASUREMENTS

3 Operational components of acoustical gauges were described for the French Ultrasonic Tide Gauges and the NOAA Next Generation Water Level Measuring Systems, and results were presented from analysis of the Aquatrak system by research groups in Australia and United Kingdom. The systems have sensors which measure the travel time of sound pulses inside a stilling well. The speed of sound is corrected for vertical differential temperature variations in the well and the sea level height is calibrated with a separate calibration tube located in the upper region of the well. The benefits of the system are the automated nature of the measurements which eliminates human intervention and reduces errors, the high sampling rates which avoid aliaising from very high frequency sea level movements, and the higher degree of precision of the high frequency signals.

4 Mr. P.Y. Dupuy of the French Naval Hydrographic Service described calibration of the speed of sound in the tube as a function of differential temperature, pressure, and moisture. For wells less than 10 m in height and for properly designed systems, the speed of sound is well approximated as a function only of temperature.

5 Dr. B. Parker of the National Ocean Service (NOAA-USA) discussed the self-calibrating nature of the Next Generation Water Level Measuring Systems (NGWLMS) acoustic gauge. Pre- and post-deployment calibrations of the transducer and calibration tube, done annually, have shown no significant error source due to sensor drift or calibration uncertainties. At each site the transducer is directly leveled into the local benchmark network eliminating the need for simultaneous staff observations by a tide observer. NGWLMS field units have been installed at 110 U.S. sites next to the analog-to-digital (ADR) float systems. The ADR systems will remain in operation for at least one year at all sites for the purpose of establishing data continuity and datum ties between old and new systems, and of analyzing both systems for sources of potential long-term biases. At least ten ADR systems will remain in operation next to NGWLMS gauges for ten years or more. Dr. Parker showed results of simultaneous data comparisons between the ADR and NGWLMS.

6 Dr. G. Lennon of the National Tidal Facility of Australia reviewed the uncertainty in the use of the Aquatrak calibration tube. The exact point along the calibration tube relative to the calibration hole is not precisely known. The thermal expansion of the calibration tube also introduces uncertainty. Even with these limitations, in comparisons with other gauges, the datum control of the Aquatrak appears stable for tests made over about a year. Additional examinations of the automated calibration tube are warranted for longer time spans.

7 Dr. I. Vassie of Proudman Oceanographic Laboratory in the UK performed comparative studies of the Aquatrak to conventional and pressure gauges. Although he encountered difficulties in obtaining a single consistent datum between the instruments, at least the datum of the Aquatrak remained stable during periods of no human intervention. The question of sound speed as a function of temperature in the well remains a topic for more studies.

8 The use of stilling wells as an instrumental component of sea level measurements was critically reviewed by Dr. G. Lennon. The relative height of the sea level inside the well versus the desired mean level outside the well was shown through empirical studies to be a function of well design. The change of water density as a function of the tide, current flow around the well, and wave interaction were the principle physical phenomena which can contaminate the measured sea level heights.

9 Finally, Dr. P. Woodworth, Director of the PSMSL in the UK, described an automated calibration device for linking pressure gauge data to a datum. The system consists of a subsurface pressure point, a transducer for measuring atmospheric pressure, a transducer at a fixed point linked to bench marks at the mid-tide level, and a temperature sensor. Favorable results from two sites in the UK provide encouragement.

10 The focus of attention turned to the accuracy of sea level measurements as a function of time and length scales of the sea level variations. For low frequency signals with periods from years to decades, monthly values from the conventional float and well gauges have been sufficiently accurate and an increase in precision from the new methods will not be known until longer records are studied. Yet the stability of datum control by the acoustic gauges over the one- to two-year periods that have been studied provides encouragement for a small increase in accuracy of lower frequency variations with periods of months to seasons. For high frequency variations with periods of hours to days, the new technology has made substantial improvements in precision. It is within these high frequency signals that problems involving the dynamical contamination of stilling wells must be considered. However, other views focus upon the potential for bias to be given to mean sea level values by the inherent characteristics of stilling well perturbations in response to currents, waves and density perturbations.

11 The Workshop continued the topic of measurement techniques by looking at subsurface pressure gauges and inverted echo sounders. These instruments provide measurements in harsh environments and open oceans where stilling wells are not practical. The sea level height is hydrostatically determined based on the height of the water column above the pressure sensor. The sensors also measure the water temperature at the level of the sensor. Through approximations, a sea level height is inferred. The limitations of these instruments are the lack of ability to link the data to a fixed datum for studies of the very low frequency signals, the well-known drift of the pressure transducers that must be empirically modelled and removed, the inclusion of the inverted-barometer effect, and the short turnaround time for replacement of the sensors which is costly. The data are well suited for studies of signals ranging from hours to seasons.

12 Dr. J.M. Verstraete of Laboratory of Physical Oceanography, Muséum d'Histoire Naturelle in France examined the accuracy of the French network of pressure gauges in the tropical Atlantic. The ability to differentiate between the barotropic, steric, and atmospheric effects was reviewed. Theoretical models were used to determine empirical coefficients for estimating these various components of the water column height as measured by the pressure gauge. The accuracy for each term was also analyzed showing the usefulness of the measurements for sea level signals in the hourly to seasonal range.

13 Dr. I. Vassie introduced a new subsurface pressure device for open ocean use with a five-year life span. The instrument has several independent recording modules that can be electronically retrieved to allow a preview of the data before the life span of the instrument power has terminated. Uncertainty enters due to non-uniform sea floors and the possibility of slow settling.

14 Dr. G. Maul of the Atlantic Oceanographic and Meteorological Laboratories (NOAA-USA) described the use of inverted echo sounders (IES) to infer dynamic height anomalies. The measurement is based on the round-trip travel time of sound impulses from the sea floor-mounted instrument to the sea surface and back. Of special interest are the empirical coefficients which are used to derive the dynamic height. In particular, he showed one of the coefficients, which many scientists have used as a constant for all areas of the world, to have spatial and

temporal variability. As a separate issue, the IES data have been used to compliment the GEOSAT altimeter measurements with RMS differences on the order of 3 cm near Clipperton Island. Dr. Maul's experience with IES and pressure gauges is that the bottom pressure in deep water and in tropical and subtropical sites measures the barotropic tides, but that pressure and travel time are uncorrelated. Dr. Woodworth noted that at Tristan da Cunha the deep bottom pressure was well correlated with shallow water pressure measurements.

15 The Workshop turned to the technology of GPS and altimeters which can provide open ocean measurement of the sea surface topography on large spatial scales.

16 Dr. G. Hein of Universität der Bundeswehr München in Germany presented the new method of using differential GPS positioning between an open ocean moored buoy and a land-based station for measuring sea level heights. The system was designed for complementing the altimeters as crossover points away from islands. For a three-hour period around the crossover time of the satellite, the GPS is utilized to measure one-second samples of the height of the moored buoy which can be filtered to eliminate the waves. The buoy incorporates sophisticated apparatus for determining tilt and maintaining accurate time. The first set of results are encouraging with roughly 2 cm accuracy for stations tied to the absolute GPS global reference frame. The system is a prototype and many more tests are needed before it can be used in an operational mode.

17 Dr. C. Le Provost, Research Director at the Mechanical Institute of Grenoble, introduced the technology of altimeters with emphasis on the TOPEX/POSEIDON and discussed applications of this data set. Aspects of the variety of necessary calibration routines and quality checks were detailed and an error budget was displayed. The TOPEX/POSEIDON system presently continues to work well after the recent launch this past August.

18 Dr. P. Woodworth compared altimeter data from GEOSAT to conventional gauges on tropical islands. An RMS difference 5 cm was established in all tropical oceans near islands. The difference was on the order of twice that amount in comparison with tide gauges along the continents. It was assumed that the wave/wind setup along the continents and the less representativeness of the open ocean by continental gauges accounted for the larger disagreement. It was also pointed out that comparisons with GEOSAT data to tropical island gauges showed a spatial dependence related to the contamination of the altimeter data by tropospheric moisture and that one must be very cautious during the reduction and interpolation of altimetry data.

19 Finally, Dr. J. Powell of Space Radar Group, Rutherford Appleton Laboratory, UK discussed a new method for calibrating the orbit of satellites with the use of transponders. This technology encourages greater precision in the reduction of the altimeter data to an inferred sea surface topography.

3. QUALITY CONTROL AND DATA PROCESSING

20 Data processing experts from several important sea level collecting centres discussed their methods of quality control. The goal is to exchange techniques among the centres and to prepare a report that can be shared with various sea level processing agencies around the globe. Several similar themes were repeated in the various talks. For quality inspection of hourly values, the most common methods are the analysis of residuals which are the observed heights minus the predicted tides and the intercomparisons among redundant sensors, if available. For inspection of daily and monthly values, plots are examined for datum jumps or erroneous features and comparisons are made among adjacent stations. For data sets contributed to the international centres, information about the sea level station and the originator's calibration and reduction methods are critically necessary.

21 Dr. P. Woodworth discussed the activities of the PSMSL in quality controlling monthly values for data contributed by a variety of agencies. The quality of the data as it is received varies considerably from agency to agency. For many of the good data sets, a comparison with a nearby station is an adequate test to ensure its scientific validity. Yet when a plot shows obvious datum shifts or erroneous values, it is sometimes difficult to get assistance from the originators in tracking down the problem. Due to these obstacles, the PSMSL has recently requested hourly values for all GLOSS stations, an effort coordinated with Dr. L. Rickards of the British Oceanographic Data Centre (BODC), in order to have the capability to inspect the higher frequency data sets when needed. However,

most hourly sets only go back 10 to 20 years so this will provide limited help. The PSMSL pays close attention to datum control and ancillary information from geodetic surveys.

22 Mr. P. Caldwell outlined data processing of stations within the Indo-Pacific Network maintained by scientists at the University of Hawaii and stations contributed by international agencies. For stations in the Indo-Pacific Network, details of calibration of the measured values to a fixed datum were emphasized. Of importance is the use of conventional float and stilling well systems complemented by calibration from tide staff readings and an automated reference level switch. The sea level gauges and the calibration methods all contain uncertainties, as well as the geodetic surveys of the historic datum to fixed bench marks, so the most important aspect of quality control is the intercomparison of the various redundant sensors based on the redundant calibration methods until an internal consistency is reached. The objective is to have a single scientifically valid series for each station for the final archive. For hourly sea level contributed by international agencies, one important aspect of quality assurance is the evaluation of the ability of the tidal analysis routine to clearly resolve the harmonic components, which are used for predicting tides and in return, for obtaining residuals. The residuals form the basis for quality control and evaluation.

23 Dr. L. Rickards of the BODC discussed the historical purpose of the BODC and their recent involvement with the acquisition, quality control, and archival of sea level data. Quality control is only one aspect of their efforts. They also routinely produce data summaries, maintain inventories, and distribute the data. Their activities provide the framework for establishing the WOCE Sea Level Centre which will prepare annual quality checks on hourly values that are ultimately submitted to the World Data Centres. They have recently initiated an effort to acquire hourly values and station information for WOCE and GLOSS sites from various data collecting agencies and to develop software for data processing and quality control.

24 Dr. M. Odamaki of the Maritime Safety Academy Japan described the interagency efforts of geographic, meteorological, oceanographic, and hydrographic agencies for operating float and stilling well sea level gauges and for processing and archiving the data. The stations are geodetically surveyed to monitor the land movements. Typically, surveys are performed every five-years except in volcanically active regions which require surveys more frequently. The data are reviewed as hourly, daily, and monthly values. In Japan, data processing and exchange systems for monthly mean values are working well but those for daily mean or hourly values in quasi-real time remain. Intercomparisons among the numerous gauges provides the quality assurance although special consideration is made for islands in proximity of the Kuroshio Current.

25 Dr. G. Lennon discussed the quality control of data from the Aquatrak gauges established in Australia and conventional gauges at sites in Southeast Asia. For data received in near-real time at the National Tidal Facility, daily checks are made to monitor the health of the network. Most quality control routines are performed at monthly intervals. Calibration is intrinsically designed into the water level measuring system and does not use post-acquisition adjustment. Most aspects of the data acquisition, quality control, and management of the data have been automated.

26 Dr. B. Parker of the National Ocean Service (NOS), NOAA-USA described quality control procedures used by NOS in acquiring and processing water level data from both the ADR float system and the NGWLMS. The NGWLMS has many improvements over the ADR system. With the NGWLMS, annual leveling is done directly to the sensor, eliminating the need for simultaneous tide staff observations and the resulting monthly adjustments of the ADR data to datum, which have introduced small uncertainties in monthly mean sea levels at some stations. The transmission of data and quality-control parameters via GOES every three hours allows near-real-time data monitoring with the NGWLMS. The new Data Processing and Analysis System (DPAS) for the NGWLMS is a fully-integrated system involving a high performance relational database used in a client-server architecture and a network of 486-PC workstations. DPAS covers all activities from field activities through analysis products and will automate many operations done manually with the ADR system.

4. CONCLUDING REMARKS

27 The Joint IAPSO-IOC Workshop addressed the methods for measuring sea

surface heights and quality assuring the data. The session was attended by scientists and data processing experts from various international agencies and data centres. This report summarizes the highlights of the technical presentations and ingests the comments and suggestions of the participants.

28 The discussion of sea level measurements centre around the new technology of acoustic gauges and their comparison with conventional float and well gauges. The conventional gauges prove adequate for studies of low frequency sea level signals while the acoustic gauges provide greater precision for examining high frequency sea level fluctuations. Other measuring devices were discussed for regions where stilling wells or tide stations can not be placed. Bottom-mounted pressure gauges, GPS measurements of moored buoys, inverted echo sounders, and satellite altimeters provide information on the sea surface topography for a variety of applications yet their permanency is not certain compared to the conventional and acoustic tide gauge.

29 Methods for quality control and processing of sea level values were discussed for the purpose of technical exchange among international data centres and agencies. Publications of these papers will be incorporated into a technical IOC manual and distributed to sea level data collecting agencies around the globe. The manual will serve as a guide to the common processing techniques presently in operation by well-known data centres and agencies.

ANNEX I

PAPERS SUBMITTED

INTRODUCTION

This volume contains the papers presented at a joint Workshop - held under the auspices of the IOC Global Sea Level Programme (GLOSS), and the Tides and Mean Sea Level Commission of the International Association for the Physical Sciences of the Ocean (IAPSO) - in Paris, 12th - 13th October 1992.

The Workshop was organised in two parts. The first part consisted of a series of presentations on traditional and new technologies for measuring sea level. Developments in the hydrodynamic design of the traditional stilling well remain relevant for obtaining true sea level measurements from acoustic gauges. Special attention is now being given to datum control and, for the future, the measurement of mean sea level in geocentric coordinates in the open ocean by deploying GPS receivers on moored buoys.

The second part was a series of short presentations on the data-checking and quality control applied by the major sea level centres. The tidal part of a sea level record has an amplitude and phase which is coherent with the astronomical forcing, so that careful analysis of the non-tidal residuals allows checks on the calibration and timing accuracy of gauges. Each individual national data processing centre will apply its own checks; no attempt has been made to define a set of standard procedures. Nevertheless, data centres and individual scientists will find the procedures outlined here useful indicators of ways in which they can confirm the validity of their own data.

For this publication the technical papers have been collected and edited by Mrs Elaine Spencer of the Permanent Service for Mean Sea Level. The report of the Workshop and summaries of the discussion were prepared by Mr. Patrick Caldwell of the Toga Sea Level Centre. Both GLOSS and the IAPSO Commission are grateful for their cooperation. We hope that this publication will be useful to all those who work in sea level analysis and interpretation.

THE SHOM ULTRASONIC TIDE-GAUGE

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ABSTRACT

The French Hydrographic Service SHOM (Service Hydrographique et Océanographique de la Marine) acquired in 1988 a prototype of a coastal tide-gauge designed by the MORS-ENVIRONNEMENT Department of MORS firm.

The prototype is based on a BEN NIVUS 01 ultrasonic water level measurement system.

The evaluation of the tide-gauge installed either inside or outside a stilling-well provided good results : the standard deviation of the level measurements was less than 1.5 cm.

SHOM has acquired in 1992 the first two serial ultrasonic tide-gauges. One of them is installed in Le Conquet and the other one in Brest.

1. GENERAL

1.1 The SHOM need in tide measurements

SHOM publishes tide tables and commercializes a software which predicts tide levels in 166 french harbours.

Tide measurements are necessary to calculate harmonic constituents which are required for predictions. The accuracy of the harmonic constituents and consequently of the predictions depends on both the length and the quality of the measurements. Local authorities and SHOM continuously measure tide levels in some ports.

1.2 The SHOM floating tide-gauges

SHOM uses to fit out its tide observatories with OTT 20030 floating tide-gauges.

Those tide-gauges have many drawbacks :

- they must be checked at least twice a week because of drifts in time and tide level measurements,
- they suffer breakdowns because of mechanical pieces failures.

Moreover, imperfections and wear of the gears can bring out systematic errors, and digitizing of the tide curves is a tedious work involving further errors hazards.

1.3 The MCN (marégraphe côtier numérique) prototype

SHOM has decided to replace its old floating tide-gauges by numerical and accurate ones with the following characteristics :

- height measurement range : 15 m,

- height measurement resolution : 1 cm,
- height measurement accuracy : 5 cm for 3 standard deviations,
- time measurement resolution : 1 s,
- time measurement drift lower than 3 s per month,
- sampling period adjustable from 1 s to 1 h,
- integrating period adjustable from 1 s to 4 min.

Among divers tenders, MORS-ENVIRONNEMENT, the BREST plant of MORS firm, was chosen to design one MCN prototype.

The prototype consists of a BEN NIVUS 01 ultrasonic water level measurement system connected to the MORS-ENVIRONNEMENT stations : the SLS 28 acquisition one and the SLS 20 MAG archiving one.

The BEN water level measurement system is made up of :

- an ultrasonic transducer which emits at 41.5 Khz in the air with an emitting angle of 5° at - 3 db and a range from 0.6 to 15 m,
- a KTY-10 temperature probe,
- a temperature correction system.

The SLS 20 MAG box allows recording of the data on magnetic tapes for later processing.

2. MEASUREMENT PRINCIPLES

2.1 Basic principles in acoustic measurement

The ultrasonic transducer set up above the sea level, emits ultrasonic pulses and detects the reflected signal:

$$H_t = H - \frac{s\Delta t}{2}$$

H_t	:	tide height in m
H	:	altitude of the transducer above the hydrographic datum in m
s	:	sound celerity in the air in m/s
Δt	:	pulse travel time in s

2.2 *Air temperature effects*

The sound celerity in the air depends on atmospheric pressure, temperature and moisture.

$$C = 331.2 \left[1 + 0.97 \frac{U}{P} + 1{,}9.10^{-3}\, t \right] \text{ m.s}$$

C	:	sound celerity in the air in m/s
P	:	atmospheric pressure in hPa
t	:	temperature in °C
U	:	relative moisture

The variations of atmospheric pressure and moisture hardly affect it : if neglected, the error on sea height measurements keeps less than 1 cm with a transducer 10 m above sea level :

$$0{,}97 \frac{U}{P} \text{ is less than } 10^{-3}$$

Meanwhile, temperature is of importance. If we assume vapour saturated air above water and 1013 Hpa atmospheric pressure, we get :

$$C = 331.5 \left[1 + 1.9\ 10^{-3}\ t \right] \text{ m/s}$$

2.3 *Sampling and filtering of sea height measurement*

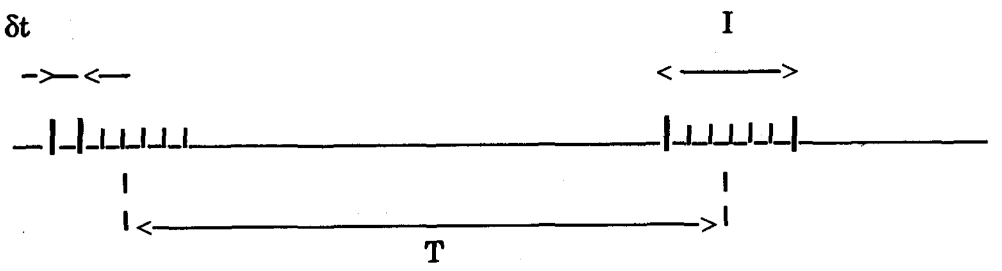
The MCN performs :

- a measurements sampling at a short acquisition period δt (lower than 1 s),
- a measurements integration with an integrating periode I, adjustable from 1 s to 4 min,
- the integrated measurements recording with a recording periode T, adjustable from 1 s to 1 h.

The sea height is :

$$H_t = H - \frac{\overline{C \Delta t}}{2}$$

$\overline{C \Delta t}$: **the measurements average during the integrating period.**



The measurements integration filters sea level variations.

Sea Level variations	Period τ	Ratio k (output signal / input signal) with I equal to		
		1 minute	2 minutes	4 minutes
Tide and Meteorological Phenomena	1 day to 1 year 2 hours 15 minutes	1 0,99988 0,9927	1 0,99954 0,9710	1 0,9981 0,8870
Swell	18 seconds	0,083	0,041	0,021
Waves	5 seconds	0,025	0,015	0,0008

Input signal : sea level variations
Output signal : measurements

$$k = \frac{\tau \sin(\pi I/\tau)}{\pi I}$$

3. TESTS

3.1 Tests outside the Brest-Penfeld stilling-well

The acoustic transducer and the temperature probe were placed outside the BREST-PENFELD stilling-well in the PENFELD river. The temperature probe was placed so that solar radiation could never reach it. The acquisition boxes were kept inside.

A SLS 23 pressure gauge had been working for the same period.

A parabolic formula calibration, applicable to ranges lower than 8 m, was determined.

The standard deviation of the differences between the tide level measurements issued from each of the instruments, was 1.4 cm.

The daily standard deviation ranges from 0.9 to 2 cm. The poorer results seem to be due to bad weather that resulted in a choppy sea.

For fine weather periods the measurements of the WHESSOE float gauge installed in the BREST-PENFELD stilling-well diverge from the MCN ones by less than 1.5 cm.

3.2 Tests inside the Brest-Penfeld stilling-well

The acoustic transducer and the temperature probe were placed in the mouth of the BREST-PENFELD stilling-well. The temperature measured there may differ noticeably from the average temperature of the air in the well. For example, in november, we measured 6° C in the mouth of the well and 12° C for the sea temperature. We decided to close the BREST-PENFELD stilling-well.

The same calibration model as for the outside test was chosen.

Comparing with tide level measurements issued from a SLS 23 pressure gauge, during a spring tide, the standard deviation of the differences amounted to 1.4 cm.

Moreover, one year WHESSOE float gauge measurements were compared to the MCN ones. The standard deviation of the differences amounted to 1 cm.

3.3 Other tests

The acoustic transducer and the temperature probe were placed in the opening of a 30 cm diameter tube installed in the Brest-Penfeld stilling-well.

Tests realized to ranges lower than 8 m gave good results too.

4. THE SERIAL MCN

Each of the tide observatories in Brest and Le Conquet are fitted out with a serial MCN provided by MORS-ENVIRONNEMENT.

The MCN consist of :

- a BEN NIVUS 01 water level measurement system including an acoustic transducer, a temperature probe and the temperature correction system,

- a MORS-ENVIRONNEMENT HT 200 acquisition station intended for the measurements recording in RAM memory and supplying the BEN water level measurement system with commands.

The acquisition stations are equipped with modems to allow a remote control over the MCN and a recollection of the data in a PC compatible software through the telephone network.

NOAA OPERATIONAL EXPERIENCE WITH ACOUSTIC SEA LEVEL MEASUREMENT

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1. INTRODUCTION

In July 1988, following a 4-year design and development period (Scherer, 1986; Beaumariage and Scherer, 1987), the National Ocean Service began installing Next Generation Water Level Measurement System (NGWLMS) field units at sites in the U.S. National Water Level Observation Network (NWLON) along side the analog-to-digital recorder (ADR) float gauges that have been operating at those sites for the last 20 years. At the present time 110 of the 189 NWLON stations have these new systems, as do the 22 NOAA Global Sea Level Network sites around the world.

When converting from one measurement system to another, especially in a national network with data records extending back almost 150 years, it is critical to have an overlap period when both systems are operating, for the purpose of establishing data continuity and datum ties between old and new systems.

The acoustic gauge used as the primary sensor at most NGWLMS sites appears to be more accurate and reliable than the ADR float system with respect to individual water level measurements. However, when one is studying long-term sea level changes (on the order of mm/year) one must also investigate possible very small long-term biases or long-term instrument drift in both the old and the new systems.

2. COMPARISON OF ADR AND NGWLMS FIELD UNITS

The system that NOS has been using for past two decades at tide stations is an analog-to-digital recorder (ADR) float-in-well gauge that records data on punched paper tape at 6-minute intervals. Each data point is an instantaneous value measured when the float is mechanically locked in place while the tape is punched. Individual measurements are recorded with 0.01-foot (3-mm) resolution. The timing is controlled by solid-state timers accurate to one minute per month; however, typical operational timing accuracies are to the nearest tenth of an hour because tide observers do not reset the timers unless they are more than 6 minutes off watch time. The stilling well is typically a 12-inch (30-cm) diameter pipe with a 1-inch (2.5-cm) diameter cone orifice and an 8-inch (20-cm) diameter float; its purpose is to damp out the wave noise so that a reliable instantaneous float measurement can be made. The backup gauge is a nitrogen gas pressure-driven bubbler gauge recording on a pen and ink chart.

A local tide observer makes timer checks and resets, and mails in the paper tapes on a monthly basis. The observer also records from 3 to 6 tide staff readings per week, or he uses an electric tape gauge (ETG) in situations where there is no easy access to the staff, such as on high piers. The tide staff/ETG readings serve as independent checks of water level and are used to calculate monthly settings which are applied to the gauge readings in order to refer them to station datum. Second-order Class I levels (nominal accuracy in elevation difference between points = 3mm * $\sqrt{d}$, where d = distance between the points in km) are run on a yearly basis from the tide staff/ETG to a network of permanent bench marks to monitor the vertical stability of the tide station and its support structure (e.g. a pier) relative to land. Field groups complete yearly performance tests on the gauges along with required corrective and preventive maintenance procedures.

The Next Generation Water Level Measurement System (NGWLMS) has a number of improvements over the ADR. The primary sensor is a downward-looking acoustic sensor. (At locations without stable structures a Paroscientific pressor sensor [run in a bubbler mode] is used as the primary sensor.) The acoustic sensor sends an acoustic pulse down a half-inch (1.3-cm) diameter PVC sound tube and measures the travel time for reflected signals from both the water surface and a discontinuity a known distance down the sound tube (the calibration reference point). The sensor is installed in a six-inch (15-cm) protective well with a two-inch orifice (5-cm); this is more open to the ocean dynamics than the ADR stilling well. Rapid sampling (once per second) and digital processing in the field unit (average and standard deviation of 181 samples; rejection of outlying values) allow high frequency wave energy to be effectively filtered from the data.

Measurements have 1-mm resolution. The clock in the system is controlled by an oscillator located in the GOES satellite transmitter and is accurate to 2 seconds per month. Data are stored in memory and transmitted over GOES every three hours. Telephone connections can also be used to retrieve data and to interact with the system; laptop computers can be used by field personnel to check and maintain the system and retrieve data. Near-real-time data transmission via satellite greatly improves quality control and also makes the data available to users in a more timely manner. Each NGWLMS also includes a backup pressure sensor (with a separate data collection platform), the capability to accept up to 11 meteorological and oceanographic ancillary sensors, and internal storage for presently up to 30 days of data (in case of communications failure).

A significant improvement with the NGWLMS acoustic gauge is that the yearly Second-order Class-I levels are run from the permanent benchmarks **directly to the sensor itself** (instead of to a tide staff), eliminating the need for simultaneous staff readings by an observer in order to connect the sensor to the benchmark system. In addition, the sensor is replaced on an annual basis and recalibrated; instrument stability over the deployment period can therefore be quantified with respect to laboratory standards rather than field comparisons made by the observer.

3. KEY ASPECTS WITH RESPECT TO SEA LEVEL STUDIES

There can be a variety of errors in a water level measurement, no matter what instrument is used, but most such errors are either random or periodic, so that averaging over a month, a year, or longer results in a much smaller error. However, when trying to determine sea level trends on the order of 1 or 2 mm/yr from these data, one must look carefully at each measurement system for possible sources of systematic errors that may not sufficiently average out and could affect a long-term trend calculation.

For example, there is evidence of a nonlinear response in the ADR stilling well to waves (Shih and Baer, 1991) that could affect a single instantaneous water level measurement when winds are strong or from a direction conducive to a higher sea state. During years with more storms and more waves this effect might produce a small bias in the calculated mean sea level. However, the more open protective well and rapid sampling by the NGWLMS acoustic sensor with digital filtering should reduce such effects.

The ADR stilling well is also susceptible to draw-down effects due to currents, so that slowly changing current patterns might have a small long-term effect. With the NGWLMS, in areas of high velocity currents, parallel plates are mounted below the orifice to reduce draw-down effects.

Since the ADR is a mechanical system, gears and bearings can wear and wires can stretch, which could have a small long-term effect on the data. Although annual maintenance is carried out, these effects could be difficult to detect. The acoustic system used by the NGWLMS to measure water level is nonmechanical and avoids such problems. In searching for possible sources of long-term bias in the acoustic measurement technique, attention has focused primarily on situations that might produce a strong temperature gradient in the sound tube. This will be discussed in a later section.

Systems, of course, can break down, or worse, may malfunction in some subtle way that an observer cannot notice. The transmission of the NGWLMS data (including quality control parameters) every 3 hours via GOES allows real-time quality control enabling one to detect problems and correct them before much data is lost.

The most important requirement for long-term sea level studies is datum continuity, i.e. the maintenance over the years of a direct relationship of the measurements to the benchmarks on the land. When trying to determine sea level trends on the order of 1 or 2 mm/yr, it is vital that accurate datum continuity be maintained. With the ADR system much has depended on the tide observer, who visually makes the daily simultaneous observation at the tide staff. These observations, when compared with the measurements made by the float gauge, allow the float gauge record to be related to the benchmarks (which are levelled to the staff not to the gauge). These comparison observations also could detect a slow drift that might indicate a mechanical problem.

But the tide observer, as a human intervention, has been found to be a source of error, especially when using an ETG during times of considerable wave action. As will be seen below, the monthly adjustments to datum, based on the simultaneous staff/ETG readings made by the observer, can often account for much of the difference between ADR and NGWLMS data taken at the same location. In the U.S., the density of tide stations with respect to the large spatial scales involved in interannual-to-decadal sea level variations has proven to be quite beneficial from a quality control point of view, because observer caused shifts in datum can be detected in monthly and yearly means by comparison with nearby stations.

The NGWLMS avoids the problems caused by the requirement for an observer to make simultaneous observations at a tide staff or with an ETG. With the NGWLMS one can level **directly from the permanent benchmarks to the sensor**, thus directly relating the gauge water level measurement to the land. The transducer can also be removed and recalibrated in the laboratory in order to check for stability.

4. THE EFFECT OF TEMPERATURE GRADIENTS ON THE ACOUSTIC WATER LEVEL MEASUREMENT

The NGWLMS acoustic sensor transmits a short acoustic pulse down a half-inch (1.3-cm) diameter PVC sound tube towards the water surface. The elapsed time from transmission until the reflection of the pulse from the water surface returns to the transducer is used as a measure of the distance to the water surface. The sound tube has a discontinuity (the calibration reference point), which causes a decrease in acoustic impedance as the acoustic pulse passes it, resulting in a another reflection, which propagates back towards the transducer. The elapsed time for this reflection is also measured. Since the distance to the calibration reference point is known (1.2m), this distance and the travel time can be used as a measure of the sound propagation velocity in the calibration tube (i.e. the section of the tube between the transducer and the calibration reference point). This information is then used to convert the travel time of the reflection from the water surface into a distance. Air temperature affects the speed of sound, but as long as the temperature in the calibration portion of the tube is same as the that in the rest of the tube, the resulting measurement will be very accurate. However, if the temperature in the tube below the calibration point is different from that above it, an error in the water level measurement can occur. For example, suppose the water surface is 2m below the calibration reference point, and that the temperature in the calibration tube is 1 degree C higher than the mean temperature over the full distance inside the sound tube. The speed of sound in air increases approximately 0.18% per degree C of increase in temperature. Therefore, the pulse will travel a little slower over the length of the sound tube than it did in the calibration tube, so the pulse will take a little longer to travel down and back up the tube and the water level will appear to be a little farther below the transducer than it actually is, in this case 3.6 mm further below.

Field installations of the NGWLMS acoustic sensor are designed to minimize the occurrence of significant temperature gradients over the length of the sound tube. The protective wells are a light colour to minimize radiation-induced temperature gradients. The wells are also ventilated, with holes drilled just above high water and just below the transducer to promote air circulation. Installations are avoided which would effectively place the sound tube within two different environments, for example, the upper part protruding into a heated tide hut with the remainder of the tube exposed to outdoor temperatures, or the upper part of the protective well exposed to the sun with the lower part in the shade.

Even with these precautions there still may be situations where significant differences in the air and water temperatures could cause a temperature gradient within the sound tube, especially in a long protective well. Therefore, as a further precaution, two thermistors are placed on the sound tube, one at the middle of the calibration tube (2.0 ft [0.6 m] above the calibration reference point) and one in the lower sound tube (the exact position determined by the tide range at each location). With each water level measurement the temperature at these two points is measured, recorded, and transmitted via satellite to headquarters. This provides the capability to continuously monitor the magnitude of the temperature gradients. It will also allow for the application of corrections to the measured water level based on these temperature differences, if the cause of the temperature gradient at a particular site can not be fixed. In cases looked at so far, comparison with backup pressor sensor data has shown that 60 to 70% of a temperature-caused error could be corrected.

5. ACOUSTIC SENSOR CALIBRATIONS

Previous tests conducted by NOS and the Johns Hopkins University Applied Physics Laboratory (Vogt *et al*, 1986) did not detect long-term drift in the acoustic sensors. However, a program of annual recalibrations has been implemented to quantify any such drift, if it should occur. The present calibration procedure uses a 5-foot (1.524 m) length of stainless steel tube that has been measured and certified by the National Institute of Standards and Technology (NIST). Sensor head and calibration tube remain as a single unit through deployment, calibration, and recalibration.

The results from the calibration check for 53 post-deployment calibrations, which were conducted during 1991, are shown in Figure 1a. The calibration change is determined, i.e., the difference between the length of tube indicated by the sensor and the NIST certified stainless steel reference tube (which the sensor was adjusted to match during the pre-deployment calibration). In Figure 1a one can see that 50 of the sensors showed changes in calibration less than 3mm; the average error was -1.0 mm with a standard deviation of 1.5mm. The skewness seen in Figure 1a is a result of the initial calibrations being somewhat cruder than those done with recently developed procedures. Using the average measurement range, these post-deployment calibration differences can give estimates of the resulting water level measurement uncertainty. Locations with large measurement ranges will have larger measurement uncertainties for the same change in calibration. Figure 1b shows the change in the sensor zero offset based on the post-deployment calibrations. The sensor zero offset is the distance from the top of the sensor calibration tube (where the level fixture is placed) to the actual sensor zero. The sensor zero offset is used to directly relate the sensor measurements to the local benchmarks. In Figure 1b we see a change in the sensor zero of less than 2mm for 44 of the 53 sensors; the average sensor zero offset was -0.2mm with a standard deviation of 1.8mm. To date in 1992, 60 acoustic sensors have been recalibrated, with 20 requiring no adjustment and 40 showing similar results to the 1991 results presented in Figure 1.

Thus, recalibration of the acoustic sensors has shown no significant error source due to drift or calibration uncertainties. If such performance continues, in conjunction with the annual replacement of sensors, then one would not expect a long-term drift from this source that could cause problems with sea level rise studies.

6. COMPARISONS BETWEEN NGWLMS AND ADR GAUGES

For the purposes of establishing data continuity and datum ties between new and old systems, and for investigating errors due to each system, traditional output products that are used in datum computation and tide prediction are derived for both the NGWLMS and ADR systems and compared for simultaneous time periods at each location. The data sets collected from each sensor at each location are independently referenced to the same station datum through levelling connections. The two sets of 6-minute data are processed through the same quality control and editing algorithms and the output products are created using identical algorithms.

When comparing the data records from NGWLMS and ADR gauges installed at the same location many possible effects must be considered when trying to explain any differences seen. These include the possible effects of: waves on the ADR stilling well; errors in monthly datum adjustments to ADR data based on staff/ETG comparisons (especially when there is significant wave action); observer error; ADR timer error; fouling; temperature gradients in NGWLMS acoustic sound tube; etc. Note that some of these errors, including that due to a temperature gradient, may average out over some time period.

The traditional output products routinely compared are: hourly heights time series, times and heights of high and low waters, monthly mean values of tidal parameters, and amplitude and phases of harmonic constants. For the tidal parameters the differences between the two systems have been quite small, especially in relation to the amplitude of the tidal signal being measured. Gill and Mero (1990) reported that the magnitude of the differences found in the comparisons are approximately of the same magnitude as the estimated uncertainties in the measurement systems.

We will concentrate here primarily on the differences in monthly mean sea levels. Monthly means average out the much larger tidal signals, and it is important to see to what extent the differences (and implied errors in one or the other system) also reduce with this averaging. Monthly means and yearly means still have much larger signals than the mm/year sea level rise signal, and it may be difficult to predict how much such differences/errors over many decades will affect a long-term trend calculation. One would expect it to have considerably less effect on a trend than the much larger interannual sea level signal, which can greatly affect the value of a calculated trend depending on where the data records begin and end (Parker, 1991).

The Scripps pier at La Jolla, California is a location with difficult conditions for water level measurement, but as such is a good location for studying the possible errors of both the NGWLMS and ADR systems. This location has considerable wave noise, plus a high pier, which necessitated a long protective well for the NGWLMS (making it a candidate for temperature gradient problems) and the use of the less accurate ETG (instead of the tide staff) for the ADR.

Figures 2a and 2b show the hourly water level differences between the NGWLMS and the ADR for two different two-day periods at the Scripps pier in LaJolla, California. The NGWLMS values are <u>not</u> corrected for possible temperature effects. Also shown in the two plots is the correction that would be made to the NGWLMS water level if the measured temperature difference between the two thermistors in the sound tube were used. During the two days in June shown in Figure 2a, one sees considerable water level differences as measured by the two systems, but small temperature differences. Most of the variation in differences between the NGWLMS and ADR water levels are probably due to wave effects on the ADR stilling well.

The large shift in NGWLMS-ADR hourly heights at hour 20 on June 1st is due to the tide roll being changed and a different monthly datum adjustment (based on simultaneous ETG observations) being applied after June 1st. Gill and Mero (1990) indicate that at the Scripps pier, where there is a high noise environment, the standard deviations in the monthly staff/ETG-to-gauge comparisons used to calculate the ADR settings are typically over 0.10 foot (30 mm). The major variations in the Scripps monthly sea level differences track the major variations in the monthly staff/ETG to gauge settings in the ADR system. The differences are largest in the winter months when the ocean swells and waves are highest and the ETG is hardest to read reliably.

During the two days in March seen in Figure 2b one also sees apparent wave effects. The temperature correction curve is the mirror image of what an error in the NGWLMS hourly height measurement would look like due to the this temperature difference. It is difficult to tell whether such a temperature could be reflected in the NGLWMS-ADR water level differences. The amplitude of the temperature correction curve could possibly be larger if the second thermistor were put lower in the very long sounding tube at the pier.

This influence on ADR data of monthly adjustments to datum based on simultaneous staff or ETG observations made by an observer is clearly illustrated in Figure 3. Here the difference between NGWLMS and ADR monthly means at Monterey, California are plotted on the same graph with monthly staff/gauge differences. The mirror image of the two plots indicates that, at Monterey, the variation in monthly mean staff readings may account for much of the difference seen between NGWLMS and ADR monthly mean sea levels.

An example of a comparison between NGWLMS and ADR, including consideration of related parameters in trying to explain NGWLMS-ADR differences, is given here for the Chesapeake Bay Bridge Tunnel, Virginia, at the entrance to Chesapeake Bay on the east coast of the United States, at about 37° N latitude.

Based on three consecutive one-year least-squares harmonic analyses one sees insignificant differences in the tidal constituents calculated from the NGWLMS and the ADR data. For example, the M_2 amplitude difference between NGWLMS and ADR varies from 0.3mm to 0.9mm (from 0.08 % to 0.24% of the M_2 amplitude, which is approx. 0.379m); this is less than the variation in M_2 from year to year, which itself is quite small. The K_1 amplitude difference between NGWLMS and ADR also varies from 0.3 mm to 0.9mm (from 0.55% to 1.54% of the K_1 amplitude, which is approximately 0.058m); K_1 varies even more from year to year. The M_4 amplitude difference between NGWLMS and ADR varies from 0.00 mm to 0.3mm (from 0.00% to 5.00% of the M_4 amplitude, which is a much smaller constituent, approximately 0.005m); M_4 also varies more from year to year. The results for other tidal constituents are very similar. The NGWLMS-ADR phase differences for these constituents are also very small, less than 0.1 degree for M_2 and generally less than 1.0 degree for K_1 and M_4.

The lower-frequency constituents such as Mm, Msf, Mf, and Sa, although defined astronomically, in fact, include significant nontidal effects (such as periodic meteorological and water temperature effects) because of the frequency bands at which they are found. They can therefore vary considerably from year to year (e.g. Sa can increase or decrease by 50% or more). If NGWLMS or ADR measurements are affected by phenomena that can vary weekly, monthly, or seasonally (such as wave effects on the ADR or possibly temperature gradient effects on the NGWLMS), then one would expect to see larger differences between NGWLMS and ADR results in these lower-frequency constituents. This is generally the case, although the differences are still small. The largest amplitude differences between NGWLMS and ADR are for Sa, with differences ranging from 3.7mm to 9.1mm (from 5.5% to 9.5% of the Sa value). The Mm, Msf, and Mf differences are not this large, but are larger than the strictly astronomical constituents.

The most important differences to be investigated are those in monthly and yearly sea levels calculated from NGWLMS and ADR data, because seasonal and interannual sea level signals are much smaller than the tidal signal, and thus differences between NGWLMS and ADR might be more important. Such differences would be even more important when calculating long-term sea level trends, but one will not have data from a long enough period of overlap between NGWLMS and ADR systems to study this with actual data. One will therefore have to extrapolate from what is learned from shorter-term studies about the causes of NGWLMS-ADR differences.

Figure 4 shows monthly mean sea level (MSL) differences between NGWLMS and ADR for approximately three years at the Chesapeake Bay Bridge Tunnel (CBBT). The figure also shows: (1) the monthly averaged standard deviations of the 181 one-second samples taken by the NGWLMS, which are measures of wave action; (2) estimated monthly water level corrections based on measured temperature differences between upper and lower thermistors on the NGWLMS sound tube; and (3) monthly average differences between the ADR water level measurements and the ETG readings made by the observer. Over most of the record shown in the figure the monthly adjustments to datum based on the simultaneous ETG readings made by the observer do not appear to have significantly affected the ADR values. This was surprising considering an ETG was being used in an area known to have wave action, and the observer was suspected of having made the comparisons look better than they were. Near the end of the record, with a new observer, one sees two peaks in the standard deviation (indicating changes in wave action), two peaks in the ADR-ETG differences, and finally two peaks in the NGWLMS-ADR differences. The observer could also have caused a bias, which might account for the fact that over most of the three-year period at CBBT the NGWLMS mean sea levels are greater than the ADR sea levels.

There appears to be a seasonal cycle, with minimums in NGWLMS-ADR mean sea level differences occurring in winter; in the winter of 1989-90 and the winter/spring of 1992 the ADR mean sea levels were greater than the NGWLMS values. NGWLMS gives a MSL up to 24 mm higher than ADR in the summer of 1989 and up to 15 mm lower than ADR in the winter of 1989-90. The monthly standard deviations are not available for the entire time period, but one will notice maximums in the winters of 1990-91 and 1991-92, at the same time that NGWLMS-ADR is decreasing, which could be caused by an increase in ADR values due to increased wave action. The temperature gradient in the NGWLMS sound tube also appears to reach a positive maximum in the winter, which would mean that the NGWLMS values would have been made lower during that period. However, the temperature effects do not appear to be of the required magnitude to have a significant effect on the NGWLMS water levels, the equivalent water level correction reaching 3 mm only twice during this time period. The timing also does not match the MSL curve as well as the standard deviation curve. However, it is always possible that the lower thermistor might not have been placed low enough in the tube represent the full temperature gradient.

These and other results are not yet extensive enough to be more than suggestive, but as the data continues to accumulate and be analyzed, definitive answers will result from these comparisons about errors caused by wave action on the ADR, tide staff and ETG readings, observer error, the effect of temperature gradients in the NGWLMS, and other aspects of both systems.

7. CRITERIA FOR MAKING NGWLMS THE PRIMARY GAUGE

Although NGWLMS systems have been installed at 110 NWLON locations along side ADR's, they are still not considered the primary gauge at most stations. At least one year of comparison observations must be obtained and analyzed in order to decide that the ADR can be removed and the NGWLMS gauge can be used as the primary gauge. Some of the procedures established to help in the decision-making process include: (1) a stability check; levels bracketing the compared periods do not differ by more than 0.02 ft (6 mm); (2) an instrument calibration check; (3) a temperature check; (4) a datum tabulation check; (5) data analysis comparisons; the mean difference range for hourly observations should be ±0.03 foot (9 mm) for benign stations and 0.06 foot (18 mm) for noisy stations; (6) monthly mean comparisons should ±0.03 foot (9 mm); and (7) datum recovery;

differences in the long-term means between the different systems must not exceed a 0.03 ft (9 mm) difference in Mean Sea Level.

At ten key stations the ADR will be kept operating for at least 10 years in order to make longer-term comparisons.

8. SUMMARY

Recalibrations of the sensor head-calibration tube in the laboratory have shown no drift or virtually no drift in most cases.

Comparison studies between the NGWLMS and ADR gauges have shown small differences, on the order of millimetres, for the various tidal and datum parameters, and are generally within the uncertainty of the instrumentation. Such differences are very small when compared to typical tidal ranges and even seasonal and interannual sea level variations. The differences in mean sea level from the two systems are being looked at more carefully because we wish to assure that there is no long-term bias in either system that could contaminate long-term sea level trend estimates (which are only of the order of mm/year).

The results of these investigations, though suggestive of causes of the differences, should still be considered as anecdotal, since each gauge has a different situation (with respect to wave action, heating of the sounding tube, etc.) and not enough data have yet been acquired at all NGWLMS stations. A minimum of one year of simultaneous data is required, and some stations will be operated for a decade or more with both NGWLMS and ADR gauges.

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Cary Wong provided the statistics on the NGWLMS thermistor temperature differences. This paper was reviewed by Don Beaumariage, Wolfgang Scherer, Ledolph Baer, Michael O'Hargan, Mike Basileo, Phil Libraro, and Jack Fancher.

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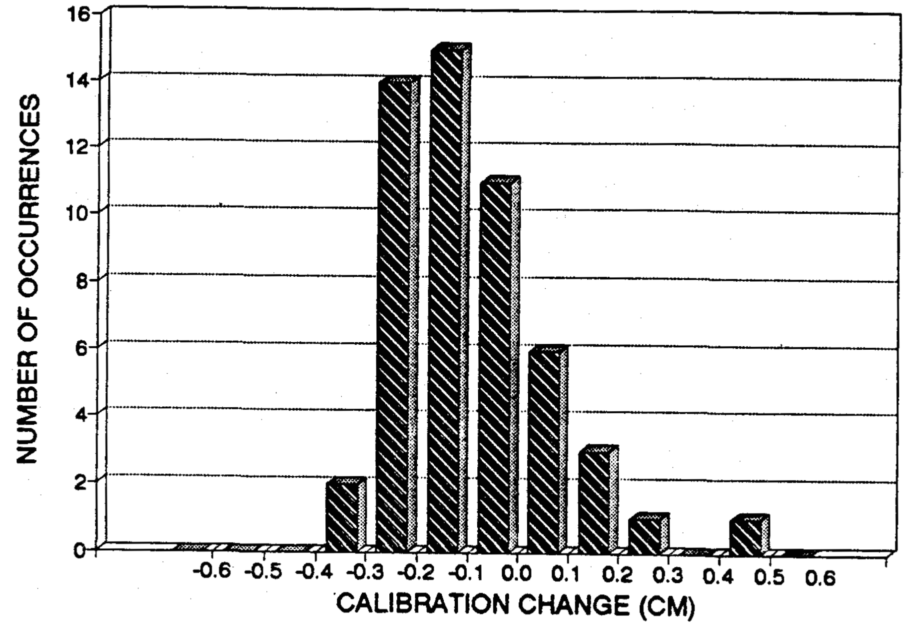
FIGURE CAPTIONS

Figure 1. (a) Results from the post-deployment calibration check for 53 NGWLMS acoustic sensors;
(b) the change in the sensor zero offset based on the post-calibration checks (the sensor zero offset is used to directly relate the sensor measurements to the local benchmarks). In both plots x-axis values are the boundary values for the interval represented by each bar.

Figure 2. The hourly height differences between the NGWLMS and the ADR for two different two-day periods from the Scripps pier. (The NGWLMS values are not corrected for a temperature effect.) Also shown in the two plots is the first-order correction that would be made to the NGWLMS water level based on the difference in temperature at the two thermistors on the sounding tube.

Figure 3. The difference between NGWLMS and ADR monthly means at Monterey, California plotted on the same graph with monthly staff/gauge differences.

Figure 4. Monthly mean sea level differences between NGWLMS and ADR at the Chesapeake Bay Bridge Tunnel, Virginia, over a three-year period. Also shown are: the monthly averaged standard deviations of the 181 one-second samples taken by the NGWLMS, which are measures of wave action; estimated monthly water level corrections based on measured temperature differences between upper and lower thermistors on the NGWLMS sound tube; and monthly average differences between the ADR water level measurements and the ETG readings made by the observer.



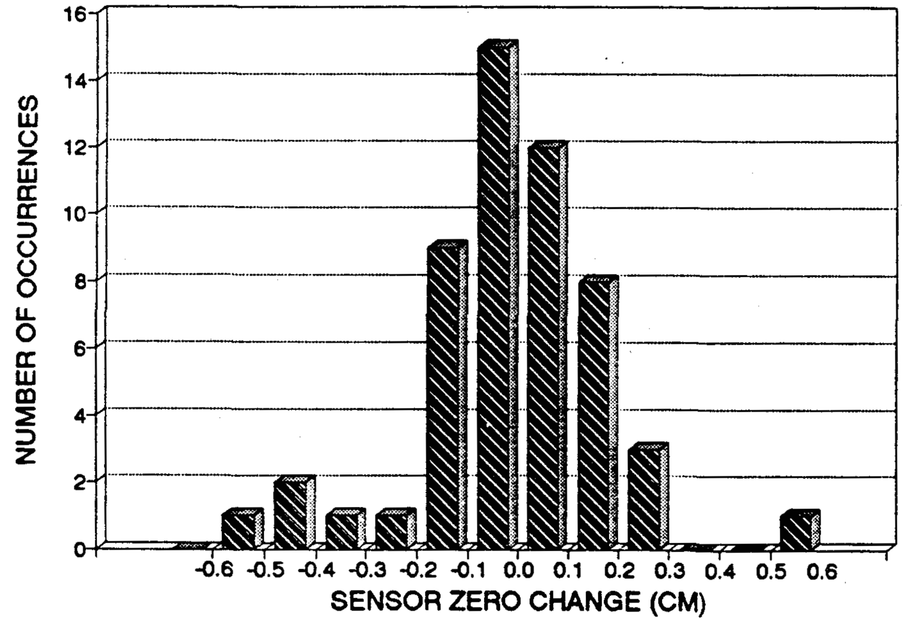
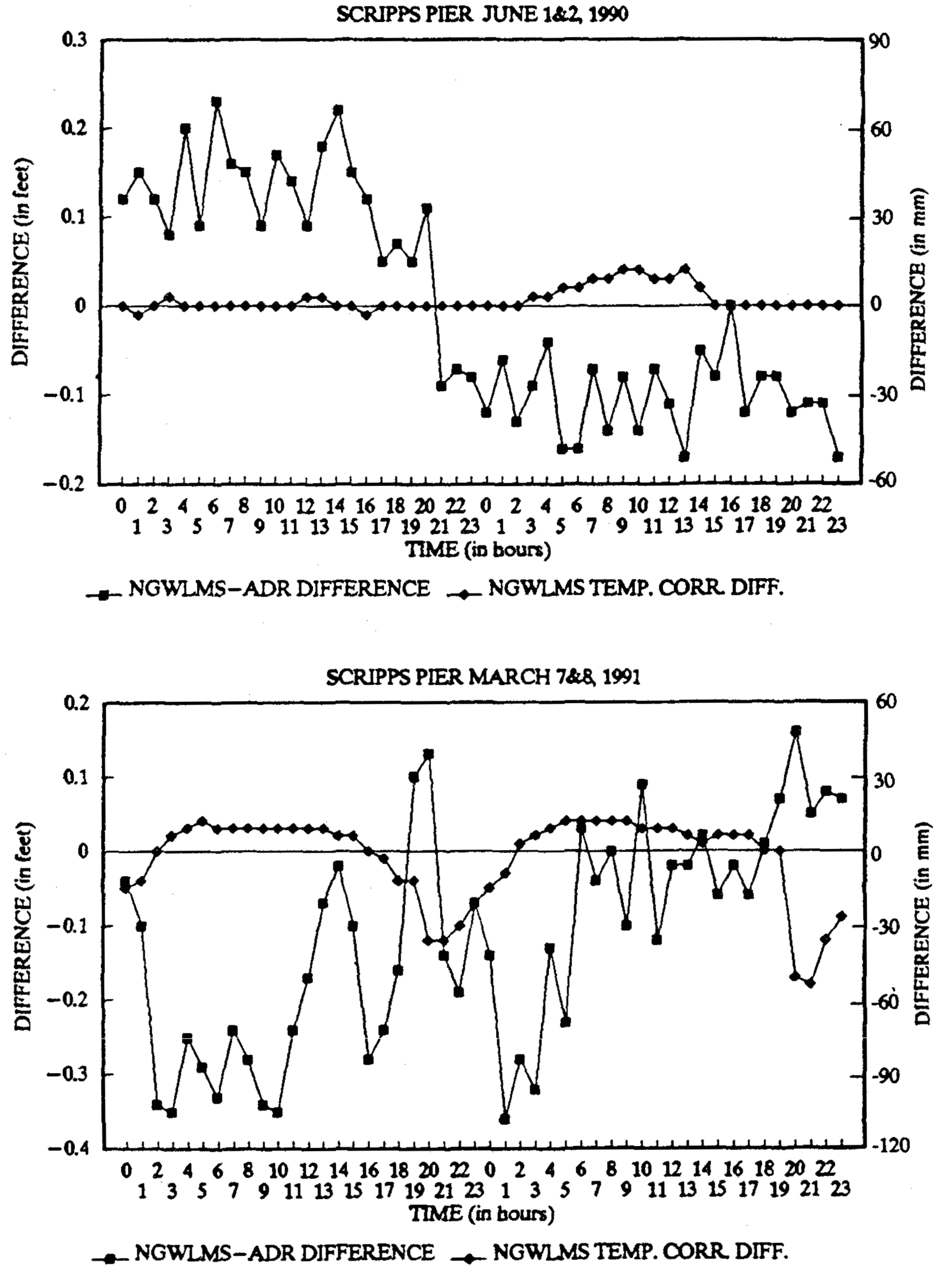


Figure 1. **(a)** Results from the post-deployment calibration check for 53 NGWLMS acoustic sensors; **(b)** the change in the sensor zero offset based on the post-calibration checks (the sensor zero offset is used to directly relate the sensor measurements to the local benchmarks). In both plots x-axis values are the boundary values for the interval represented by each bar.

HOURLY HEIGHT CORRECTION COMPARISON



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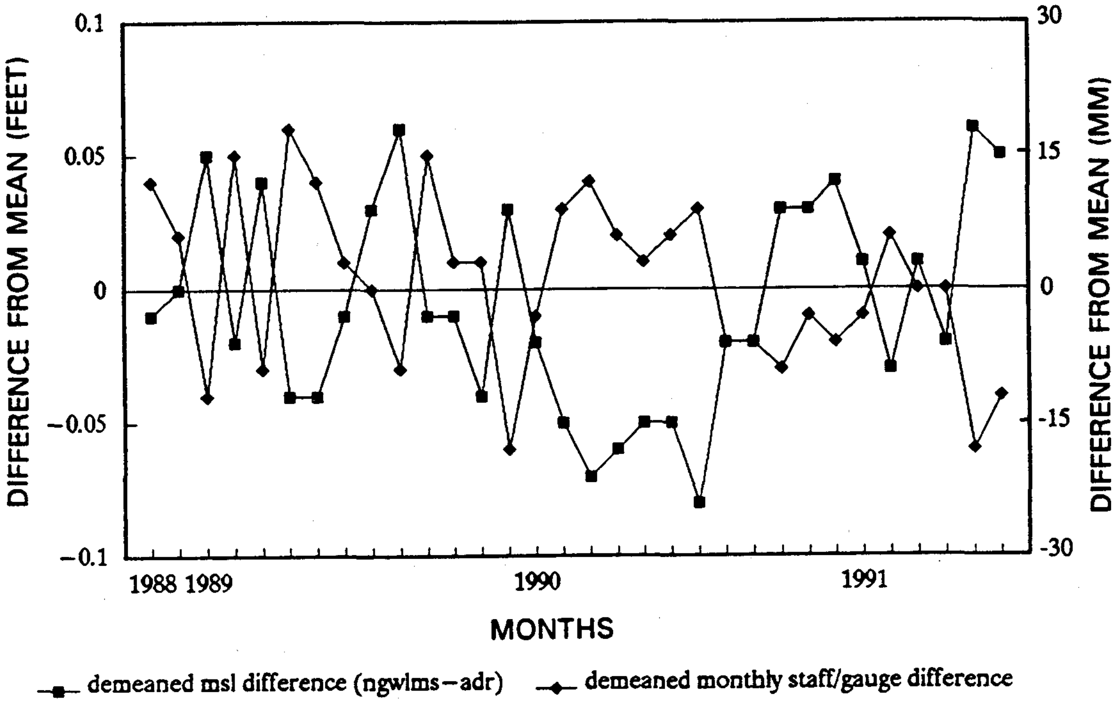
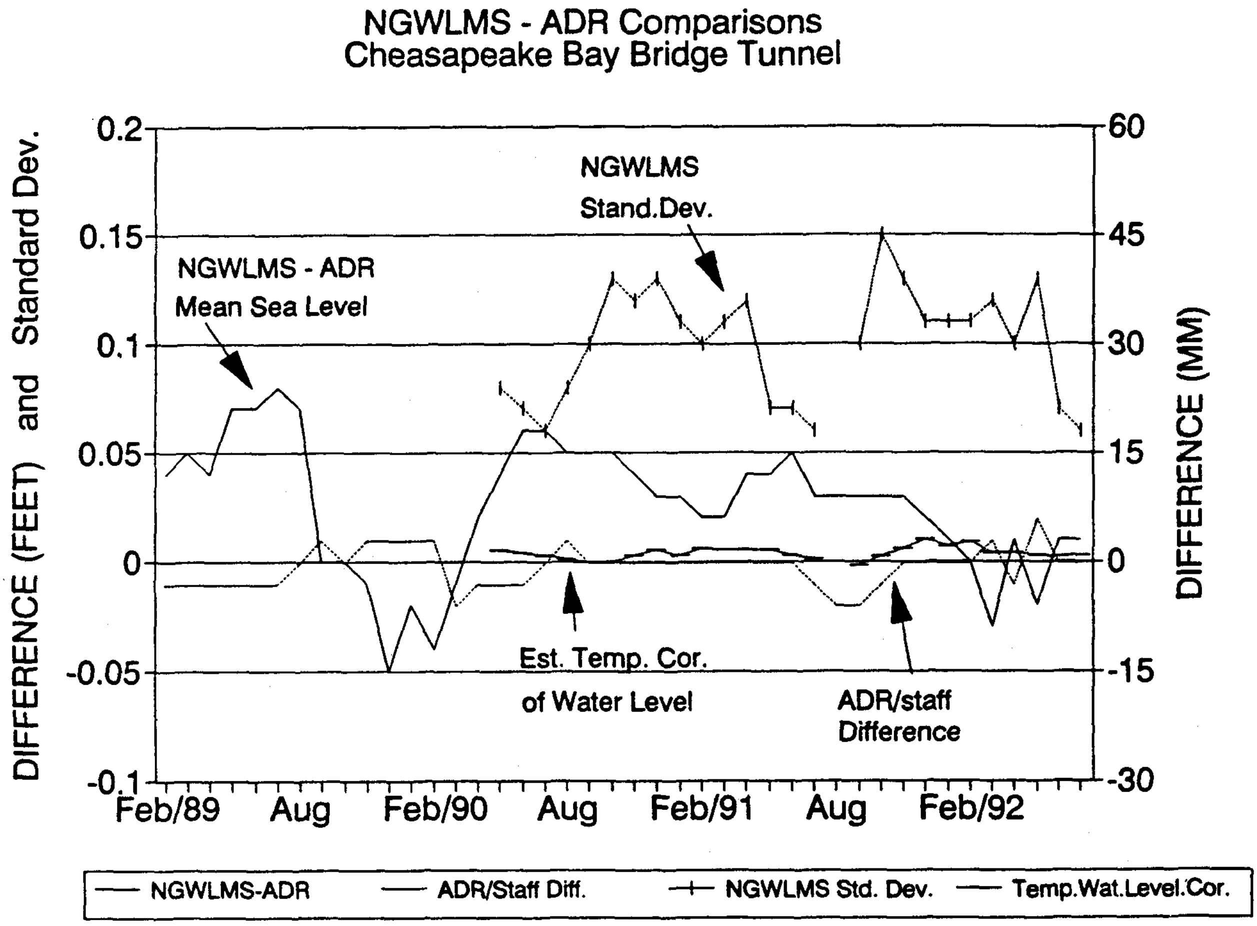


Figure 3. The difference between NGWLMS and ADR monthly means at Monterey, California plotted on the same graph with monthly staff/gauge differences.



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ACOUSTIC SEA LEVEL MEASUREMENTS IN AUSTRALIA

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1. INTRODUCTION

The monitoring of sea level in Australasia has seen a major change in recent years, from a historic position where an aged unco-ordinated series of float-operated tide gauges was operated by local authorities for the purposes of navigation, to the present situation where major national initiatives are serviced by high resolution computer-driven telemetering instruments operated by a central national facility.

The change was spurred by a political concern over the threat of greenhouse rising sea levels and this established demanding specifications matched to a signal of order 1 $mm.y^{-1}$, which incidentally encompasses the requirements of most current aims of scientific research in matters of sea level. Previously, attempts to establish historic trends of Australian sea level showed a wide range of estimates from different stations, some positive, some negative. It was only the knowledge that the Continent had a reputation as a geologically rigid crustal element, which in turn allowed one to take the mean of stations in the region, that values approaching the world consensus had been achieved. In order to satisfy the ultimate aim of the new arrays, then significantly better performance is required with main specifications as follows:

a high resolution, ideally sub-millimetre, if the target signal has the magnitude stated earlier.

a matching ability to maintain a stable datum which itself implies three riders:

* the datum of observation should be accessible for zero-order levelling connections.

* the ability to change sensors while maintaining datum at the sub-millimetre level of accuracy is important.

* an approach to a concept of absolute sea level so that the datum needs to be supported by a comprehensive geodetic program incorporating the techniques of survey, satellite altimetry and the new geodetic technologies derived from geophysics and astrophysics in attempts to understand the local reference levels on the earth's surface, noting that tide gauge measurements are otherwise essentially relative.

a supporting program of time series analysis capable of the decomposition of the low frequency band of the sea level spectrum so as to enable the differentiation of noise and real signals, noting also that the procedure requires the physical and regional verification of the latter.

near real-time telemetry is desirable as an early warning of malfunction, although trouble-free performance is expected.

This paper will concentrate upon the instrumental issues only.

Given this basis, superimposed upon the restrictions of financial allocations within fiscal time slots, a rapid selection of instrumentation from available equipment was required, and this led, with little hesitation, to the Aquatrak/Sutron system developed for and by NOAA/NOS and associated with the acronym, NGWLMS. It was the opinion that this instrument had the virtually unique potential at least to approach the requisite specifications.

Over the last two years a Baseline Array of fourteen stations has been planned and commissioned, as identified in Figure 1. Of this number, three stations: Darwin, Spring Bay and Cocos Island (in the Indian Ocean and not shown in Figure 1) are co-operative initiatives of NOAA/NOS and the National Tidal Facility (NTF), the equipment being provided by NOAA, the installation jointly commissioned and the station operated by NTF. One station, Burnie in Northern Tasmania is also operated by NTF, its establishment shared by NTF and CSIRO, and its main purpose is to function as a groundtruth station for the Topex-Poseidon Program. The Groote Eylandt station still remains to be installed with a significant contribution by the local mining company, GEMCO Pty Ltd.

Again following a commitment by the Prime Minister of Australia in 1988, another major initiative has been undertaken to monitor greenhouse rising sea levels on behalf of the Forum Island Countries of the South Pacific and, in addition to a major information and training component, some eleven stations are committed as shown in Figure 2. The first at Lautoka in Fiji has been commissioned from 23rd October, 1992.

The Australian Sea Level Fine Resolution Acoustic Monitoring Equipment (SEAFRAME) stations are, at this stage, very similar to the NOAA NGWLMS, see Figure 3, and are supplemented by relevant meteorological sensors for barometric pressure, wind speed and direction plus sea water and air temperatures.

2. A COASTAL TEST BED

Given the nature of the problem and the conviction that work of a quality to satisfy the specifications will be at the threshold of what is physically and technically possible, the need for a coastal field station capable of intercomparison of sensors and associated gear, was deemed to be essential. In this connection advantage has been taken of facilities at Port Stanvac just 14 Kms distant from the NTF where a substantial jetty projects outwards from the coastline at a secure site operated by Mobil (Australia) Pty Ltd. The site also may be classed as a high energy site since it has a window through Investigator Strait to the "infinite" fetch of the Southern Ocean. At this stage the work program is in its early stages, however with the assistance of the Refinery a work area has been prepared on the jetty where a 2.1 m x 2.1 m plan Tide Gauge Hut has been established with two steel tube stilling wells and one protective well together with other facilities. Presently a SEAFRAME station is in operation and once again this is a collaborative venture with NOAA/NOS. The plan is to calibrate, test and compare a number of sensors and tide gauge systems while maintaining the SEAFRAME station nearby.

3. A CALIBRATION LABORATORY

Within the NTF itself there has been established an electronics and instrument calibration laboratory. This comprises a long room, some 10 m in length, arranged along an inside wall so that sunlight will not fall on the confines of the laboratory which is air conditioned throughout the year. A special feature is a long bench which supports an insulated box. In this structure it is possible to install two or more acoustic sensors and their sounding tubes for individual or comparative calibration up to 9 m. The box is also arranged to be fan-ventilated so as to limit or control temperature profiles along its length and is fitted with high quality thermistors to check upon the latter. The central spine of the box supports overlapping "readers", the high quality 3 m sections of a survey tape, graduated in centimetres and millimetres and calibrated for a certain temperature and tension. The aim is to have the possibility of accurate measurement down the box and this is achieved using a macroscope which is mounted on a trolley which runs on rails attached to each side of the box. The trolley can be clamped, so that accurate readings can be made of the length of the sounding tube, or a section thereof, by spanning the view of the reader and tube with the macroscope graticule. Note that the windows visible in the photography do not have vantage to the open air but to an atrium enclosed within the building.

Future plans envisage a vertical calibration laboratory where a real water surface can be used, and ultimately a dynamic test bed where a more realistic model of the restless sea surface can be modelled.

These initiatives demonstrate a commitment to determine the performance characteristics of sea level instrumentation and to push this to its operational limit.

4. THE ACOUSTIC SENSOR AND ANTICIPATED PERFORMANCE

The acoustic sensor is not new in sea level monitoring nor is the Aquatrak sensor the only acoustic sensor available for the purpose. In earlier years, the acoustic principle was taken up, put on trial, but abandoned because of its sensitivity to temperature, humidity and, to a lesser extent pressure. The Aquatrak becomes attractive because of rather special features, notably a device which automatically adjusts its calibration as conditions change in the flight path of the acoustic pulse. Note also that the manufacturing company, BARTEX, does not make unduly optimistic claims for its performance. The common calibration accuracy offered by the company quotes 0.025% accuracy with an optional service on request to 0.01%. The company does however claim a resolution of 0.001 ft (or $^1/_3$ mm) and "no drift".

Given the heavy demands upon resolution and accuracy now current, it is necessary to examine every aspect of the sensor system and its stability. This work is currently in its infancy at the NTF but some comment can be made.

5. THE MEASUREMENT PRINCIPLE AND ITS IMPLICATIONS

It is interesting to examine the technique which is used for self-calibration. The sensor should be regarded as the Aquatrak head **plus** its individual calibration tube. Here one should note that some distance below the head there is a small hole in the tube, see Figure 4. This has the effect of creating an interference signal which is reflected back to the Aquatrak head so that the system can identify the time taken for the pulse to travel the "Cal length", notionally four feet. In a very simple way, shown in Figure 4, the system operates in the following manner:

There are two time intervals counted and stored by the Aquatrak head. The first is the time taken for the pulse to be reflected by the "Cal. hole" and to return to the head. The second time interval is then commenced, but by this time the pulse has continued on its journey towards the water surface and is at twice the "Cal. distance" from the head. The second time interval is terminated when the pulse, reflected from the water surface, reaches the head. This travel time is interpreted as double the distance to the water surface using the knowledge that the first count represents double the "Cal. length" which is known. Consideration of this system identifies the fact that measurement of the water surface is referred to the origin of the interference signal generated by the "Cal. hole". In practice sea level is measured downwards from this reference point. The following comments are then relevant:

* The reference point is not a physical feature accessible to a surveyor, but rather an inferred location, in fact some distance in excess of 1 cm below the "Cal. hole", which needs to be determined by laboratory calibration.

* The question arises as to whether the location of the pulse origin is identical, at sub-millimetre accuracy, with the location of the device which terminates the counts and, perhaps more importantly, does either display a drift in time?

* There are identified two aspects of calibration which require careful attention: a) the delta test, i.e. if the water level were to move through exactly 1 m, would the sensor indicate a change of exactly 1 m at sub-millimetre accuracy. To what extent is the delta calibration stable in time and to what extent is the calibration linear e.g. will the calibration differ, depending upon the length of the flight path. b) the inference of the offset: there is a need to experiment in order to determine the "Cal. length" for the particular arrangement of Aquatrak head and calibration tube so that the reference point can, in turn, be related to a physical mark accessible to survey procedure. Again the question must be asked: Is the inference of the offset fixed in time? Is the inference of the offset affected by the length of the acoustic flight path?

At this stage answers are rare and it must be acknowledged that the NTF calibration and testing program has only recently begun. It has however been adopted as a matter of principle that the field life between calibration exercises should ideally be approximately one year so that it is anticipated that each sensor plus "Cal. tube" will be replaced at this interval and be returned to the laboratory for re-calibration.

6. LABORATORY CALIBRATION

The Delta Test

Here the aim is to examine the performance of the sensor in its ability to measure to two positions, the relative position of which is known. The procedure is to set up the experiment in the insulated box previously described and to measure over several minutes to the base of a tube which has been capped. Then a tube of known length is attached with the cap transferred to its further end. An extended measurement to the new position of the cap then follows and the difference between the two measurements should agree with the known length of the added tube. In the event of disagreement it is possible to rotate a threaded stainless steel collar attached to the Aquatrak by which the latter mates with the "Cal. tube". The change in calibration is therefore achieved by changing the distance from the sensor down to the "Cal. hole". At the NTF we have selected a ceramic material for the Delta Test Tubes and a number of different lengths are used, all carefully measured by the State standards office. The specifications of the ceramic medium claim a coefficient of thermal expansion of 0.0000081 parts per ^{0}C which represents 0.081 mm per ^{0}C in a 10 m length. To date experience is limited but again preliminary comments can be made as follows:-

Calibration checks

In testing Aquatrak heads initially provided and calibrated by BARTEX and calibrated again by NOAA/NOS, a typical early result is indicated in Figure 5. The plotted values can be interpreted as a linear response with a small calibration error shown by the gradient, and with the intercept of the zero error line occurring at a distance of 4 m or so from the head. Small rotations of the collar can be used to change the gradient of the response function although the zero error intercept of this and other sensors seems to be always near the 4 m level. If the sensor is removed from the calibration rig and returned for a repeat check at some later date, the condition, including any residual gradient, is repeated in the test. No explanation has been found for the calibration gradient on receipt of the sensors since we have confidence that NOAA will have faithfully produced an effective earlier calibration. NTF does not have long term data for verification so that at this stage we must bear in mind that the sensors may suffer from transport shocks.

In the case illustrated in Figure 5 a comparison is made with different bases of measurement. Although there is some improvement which derives from multiple samples it is clear that there exist systematic problems in that the plots display a negative bias at a regular interval of 1.5 m. This is currently diagnosed, until verified, as a problem with one of the tubes used in the calibration procedure. At intervals of 1.5 m down from the head some potential interference occurs and this may well cycle along with the permutation of tube selection which occurs during calibration. This feature provides further evidence that we operate in an evolving system.

Thermal properties of acoustic propagation

Although the self-calibrating system has many attractions, even this feature needs careful scrutiny. The most obvious comment would be to question whether it can be assumed that, in an operational mode, the air conditions which exist in the "Cal. tube" are truly representative of the total flight path of the pulse. This is partly a matter for attention at the time of installation and commissioning when care can be taken over exposure to ventilation and also to shade and sunlight. For this purpose also the sounding tube is monitored for a temperature profile which can be used as the basis of corrective calculations. Although temperature corrections are not made routinely in the array operation, they may well prove to be necessary in order to meet the specification of the program. It is understood that BARTEX, in association with NOAA/NOS, is considering other solutions to this problem including a multiple calibration system in an attempt to integrate all acoustic conditions down to the water surface. It is however quite clear from the tests conducted at the NTF that the temperature profile in the sounding tube has a dramatic effect upon the propagation speed of the acoustic pulse and is a major factor in the overall accuracy of the instruments performance, e.g. a 15^{0}C gradient in a 4.5 m sounding tube would give an 86 mm error, according to relationships determined by NOAA/NOS (personal communication).

Thermal Properties of Materials

It is also clear that the stability of calibration relies upon the stability of the "Cal. length", which in turn depends upon such matters as the thermal expansion of the materials used. The calibration tube itself is fashioned from a plastic material, CPVC, which does have a significant coefficient of thermal expansion, thought to be 0.005% per degree Celsius. This, in practice, would suggest an error of 0.5 mm in a 10 m flight path for every degree of discrepancy from the temperature existing at the time of the Delta Test Calibration. This applies even though it is the expansion which takes place in the "Cal. length" which creates the problem. In fact the measurement principle automatically multiplies the error down the total path to the water surface. In this context BARTEX has suggested that, by happy coincidence the thermal expansion coefficient of the CPVC calibration tube is matched equally but in an opposite sense to the temperature characteristics of the head itself. Again there may well be a relevant automatic adjustment since the same temperature change which alters the calibration length, also alters the propagation speed of the pulse. Preliminary tests on this aspect of the system have **not** been able to confirm that satisfactory compensation occurs; rather the reverse.

Sensitivity of tidal range

As the length of the sounding tube increases there is a substantial increase in the standard deviation of results. This feature, together with the comments under "Calibration Checks" suggest that there is an optimum range of measurement of the Aquatrak system which seems to lie between 3 and 5 metres from the head. This counsels caution in its use where large tidal ranges occur.

Datum Control

Preliminary results indicate that datum appears to be stable in the order of 0.2 mm when operating at the optimum range.

Offset

There is insufficient experience in determining the offset at the present time although again there is some evidence of variability depending upon the distance from the head used in its assessment. Also there is evidence of cross-correlation with the results of the Delta Test so that the matter is quite complex. Until we learn more, it is our practice to select a value for the offset matched to the mean sea level of the station involved.

7. CONCLUSIONS

The testing of the Aquatrak system is in its early stages but will continue to be subjected to a series of tests until confidence is gained in overall performance or until satisfactory improvements have been achieved. At this stage, and despite the above cautionary comments, there is confidence that, when optimum calibration is achieved, and given restriction to the optimum range of 3 to 5 m, that mm accuracy will be achieved. It may be concluded that cautious optimism remains.

FIGURE CAPTIONS

Figure 1. The Australian Baseline Array of SEAFRAME stations for the high resolution monitoring of sea level.

Figure 2. (No legend necessary)

Figure 3. Diagrammatic view of a SEAFRAME station.

Figure 4. The self-calibration feature of the Aquatrak measurement principle.

Figure 5. A Delta Test calibration, in which a comparison is made of the different bases of measurement.

- ■ Instantaneous single sample
- ♦ Mean of 10 samples at one second
- ▲ Mean of 181 samples at one second as in the operational mode.

PHOTO LEGENDS

Photograph 1 The SEAFRAME station of Hillarys, north of Perth.

Photograph 2 Detail of the protective well and its structural support at Hillarys.

Photograph 3 The calibration and test base at Pt. Stanvac showing protective well for the Aquatrak sensor and two stilling wells projecting from the base of the hut.

Photograph 4 The calibration box for Aquatrak sensors showing an operator using the macroscope trolley.

Photograph 5 Three Aquatrak heads installed in calibration box.

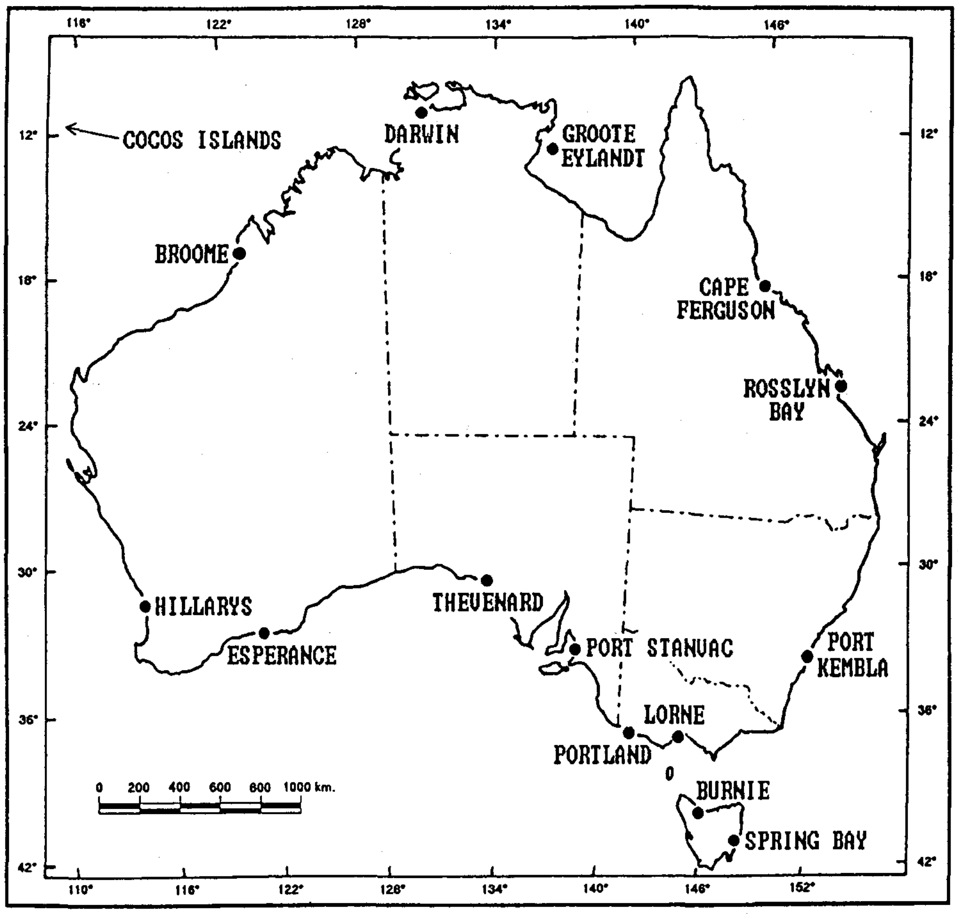


Figure 1

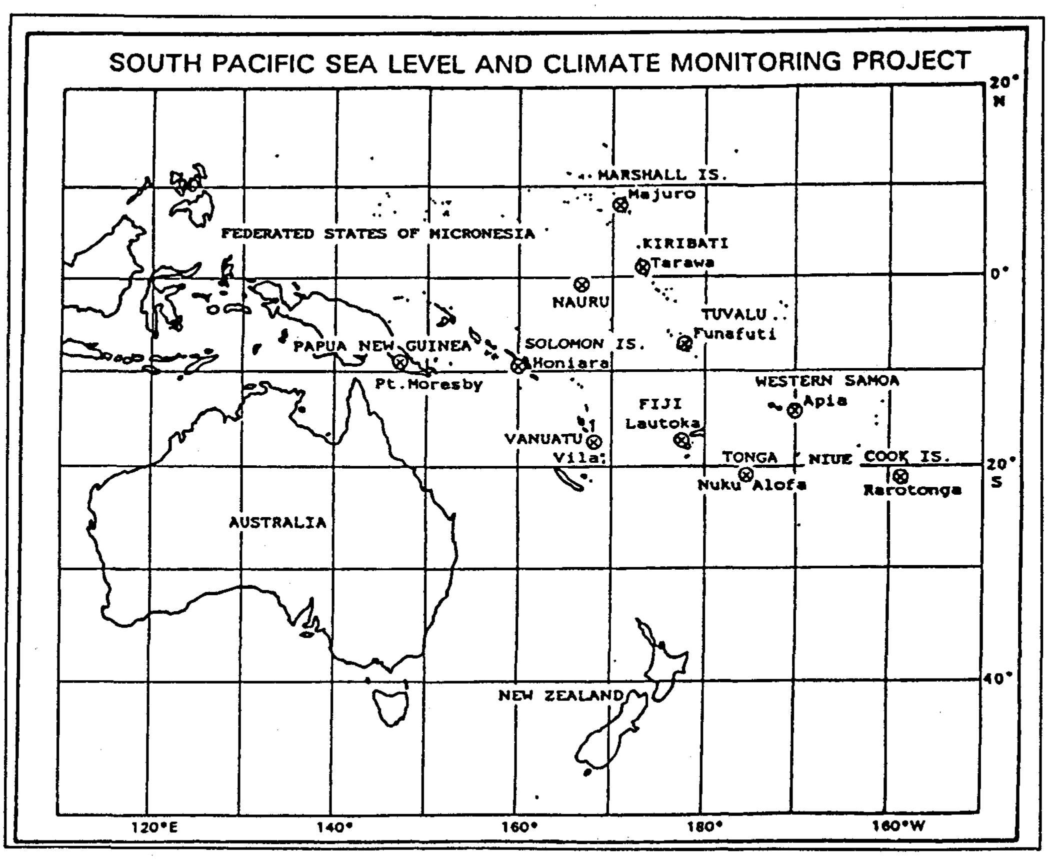


Figure 2

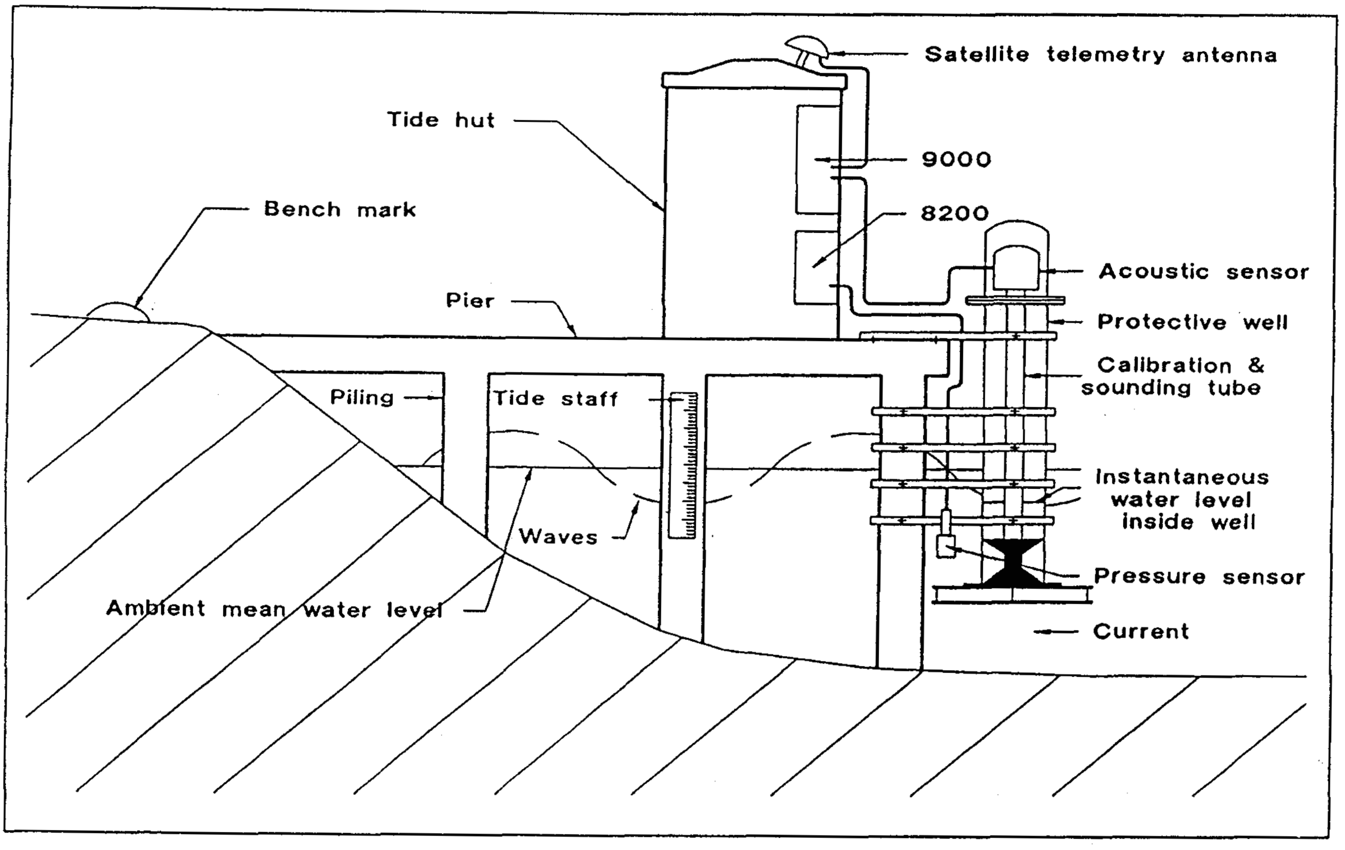


Figure 3

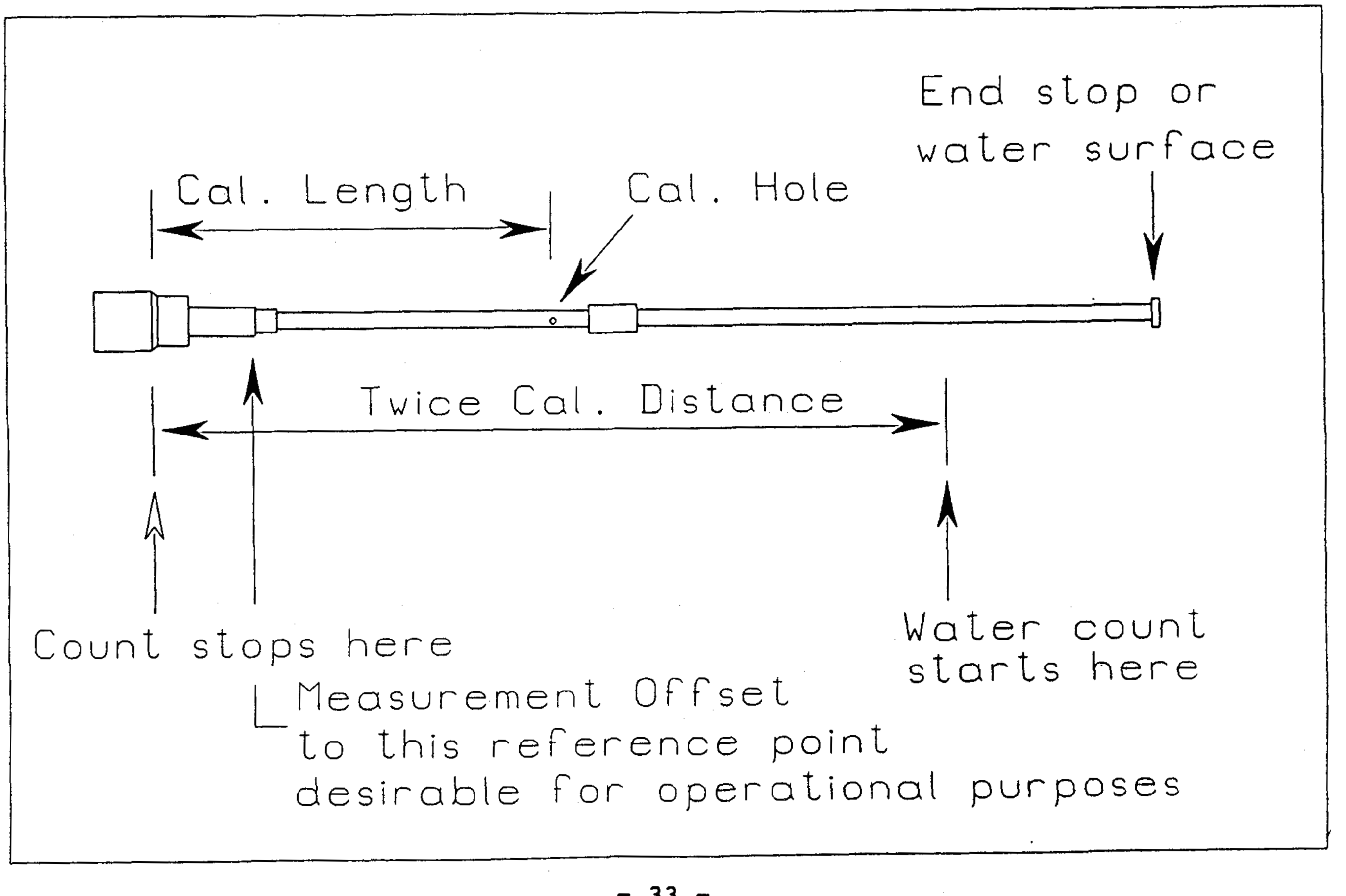


Figure 4

Sensor 1030–3323
Plot of instantaneous and averaged data

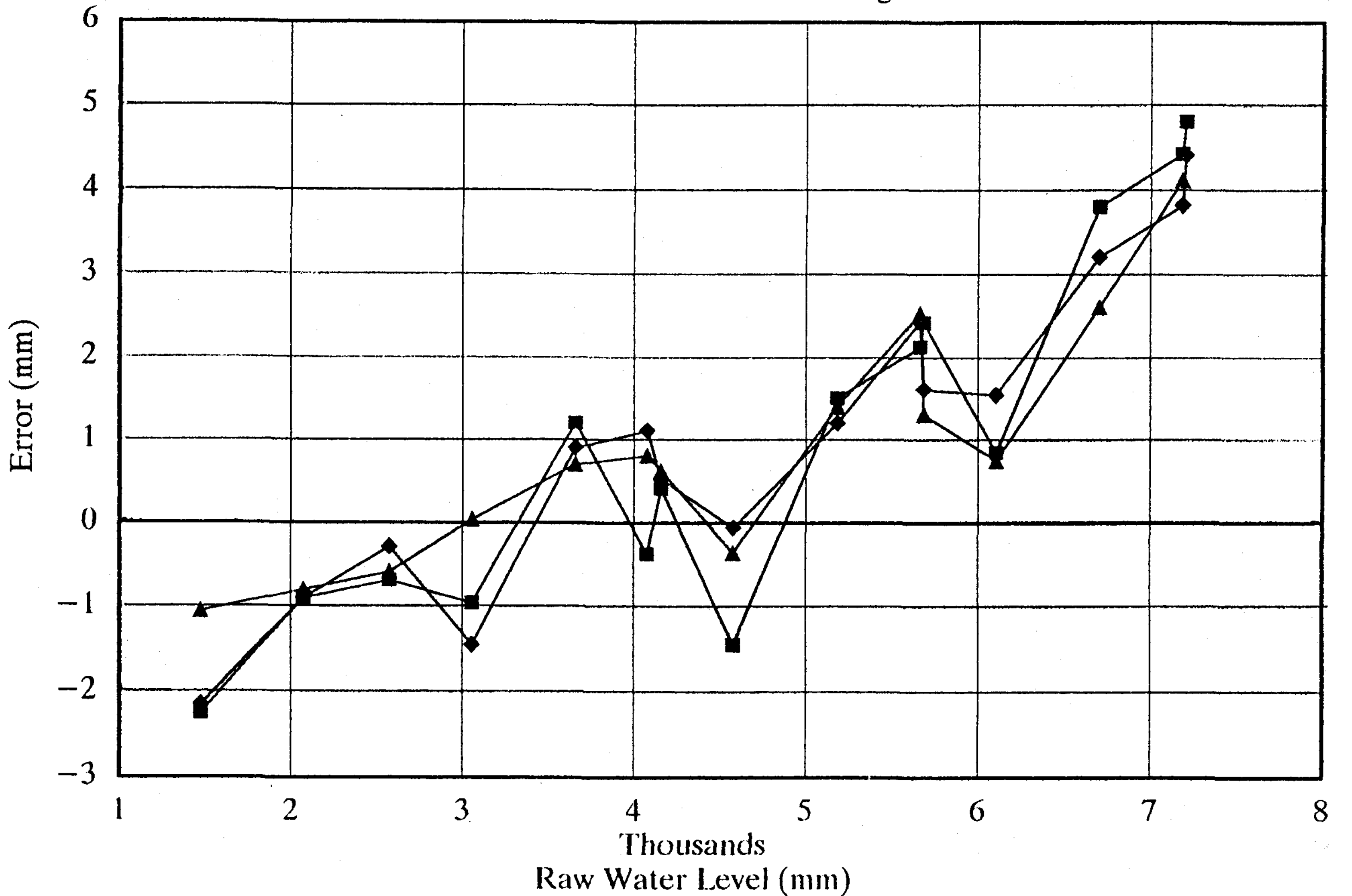
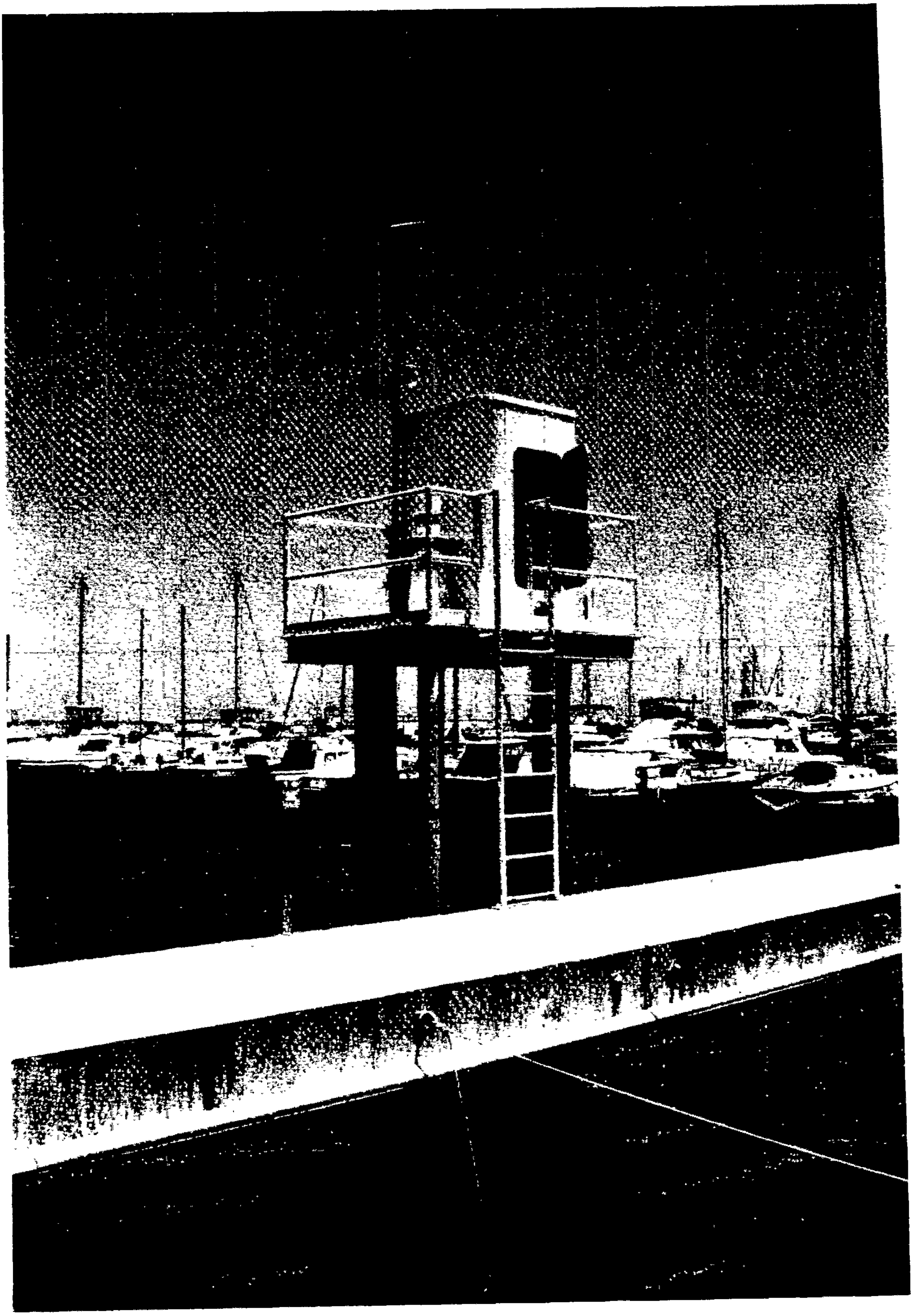
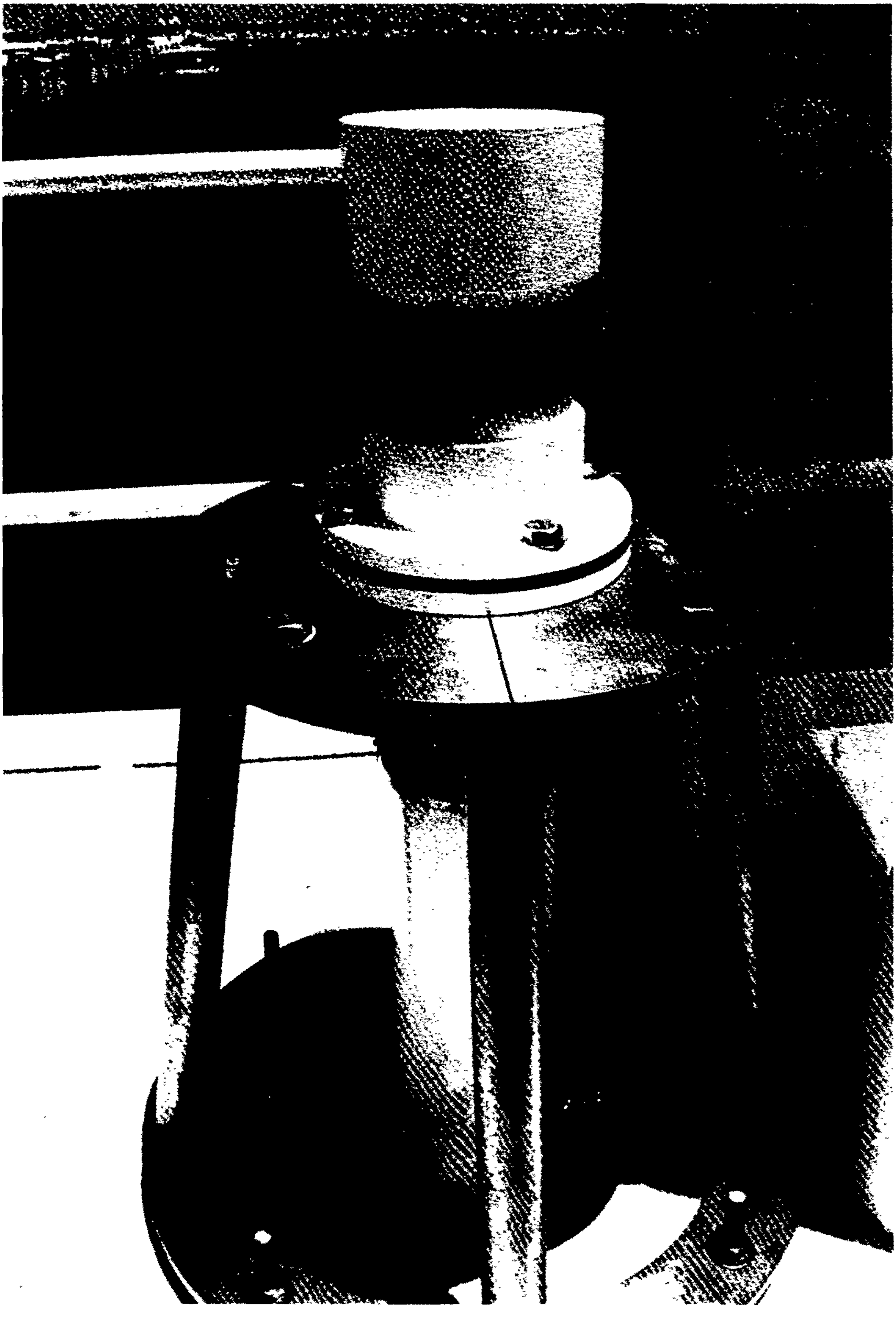


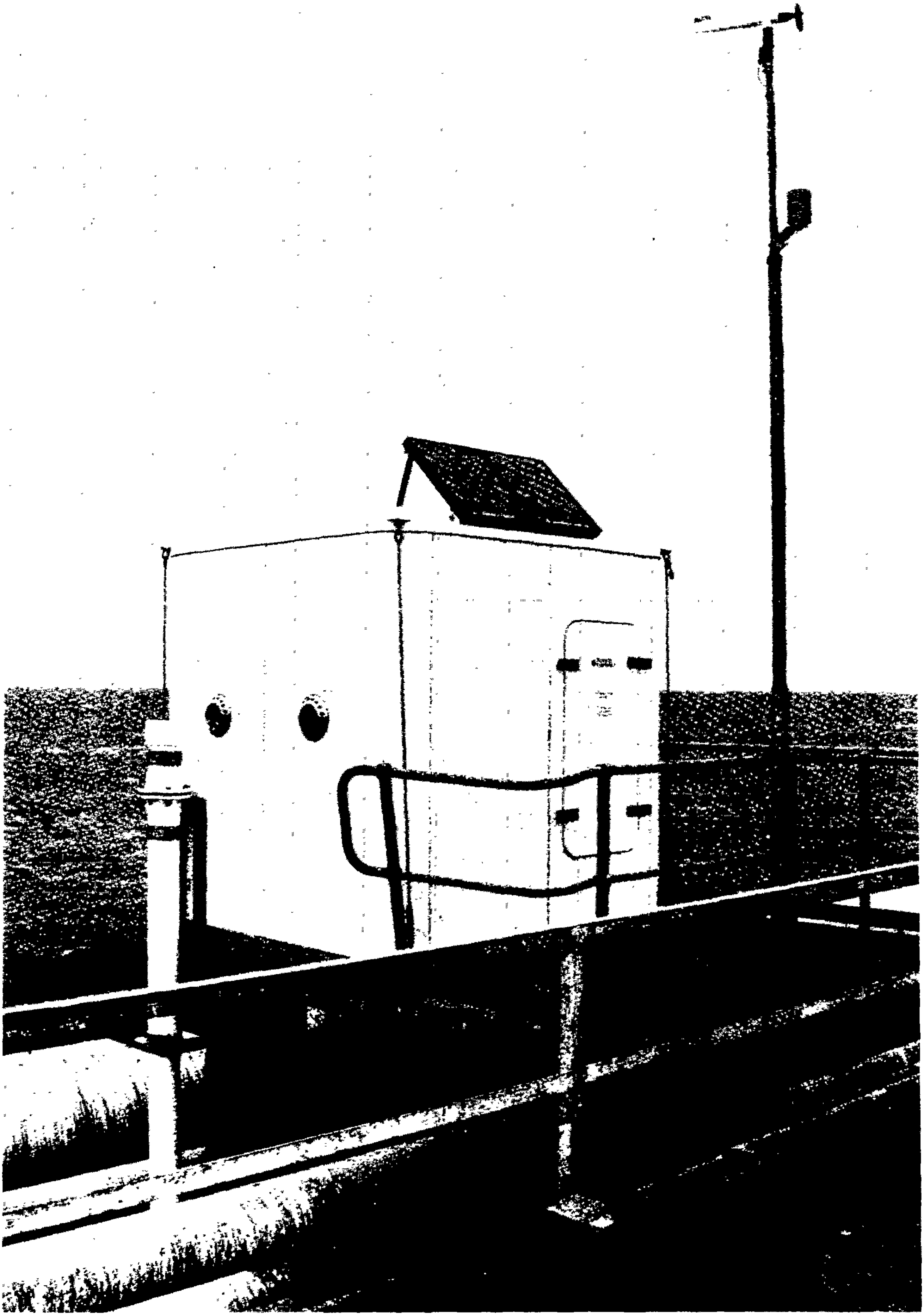
Figure 5



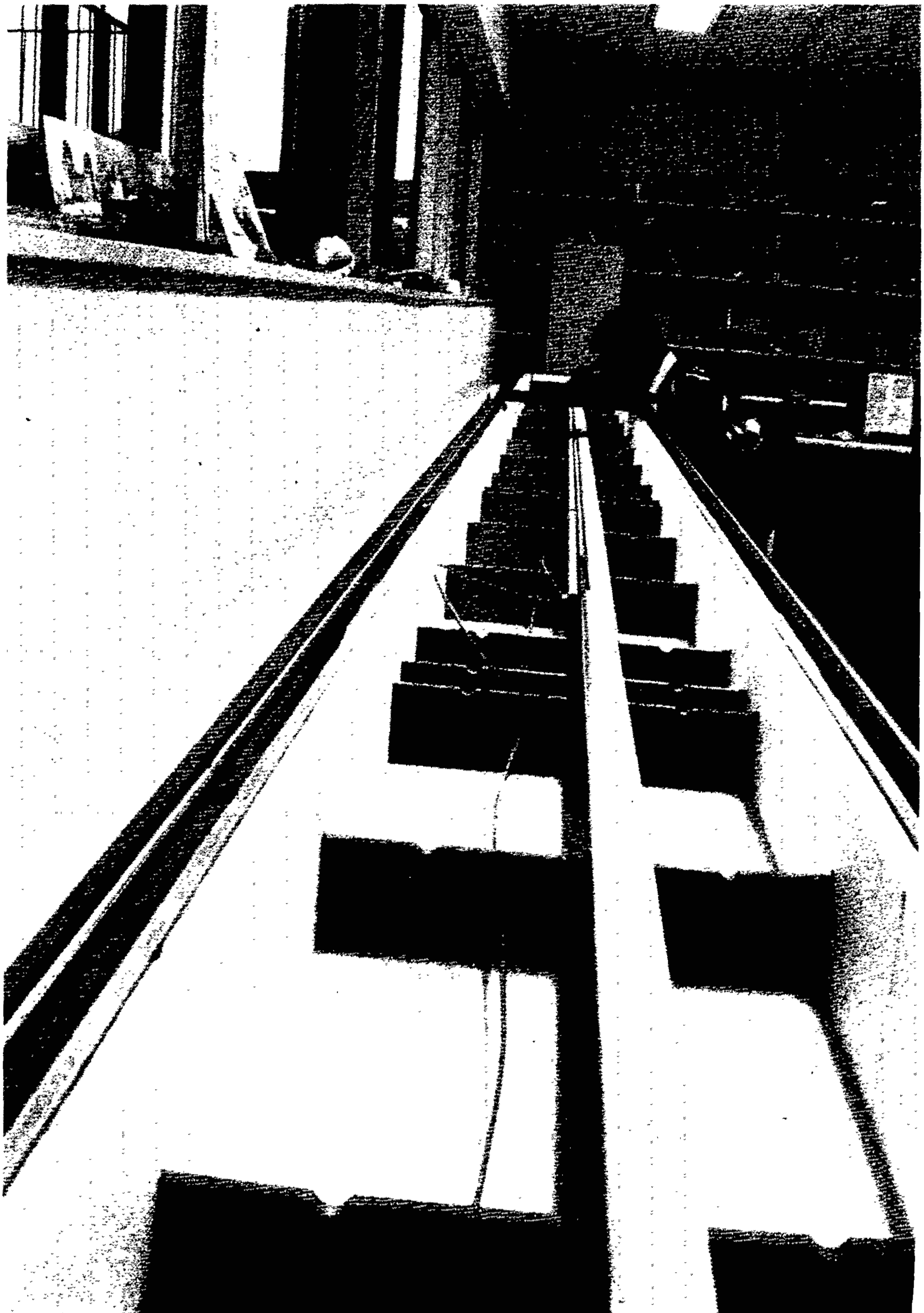
Photograph 1 The SEAFRAME station of Hillarys, north of Perth.



Photograph 2 Detail of the protective well and its structural support at Hillarys.



Photograph 3 The calibration and test base at Pt. Stanvac showing protective well for the Aquatrak sensor and two stilling wells projecting from the base of the hut.



Photograph 4 The calibration box for Aquatrak sensors showing an operator using the macroscope trolley.

Photograph 5 Three Aquatrak heads installed in calibration box.

COMPARISON OF NGWLMS, BUBBLER AND FLOAT GAUGES AT HOLYHEAD

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1. INTRODUCTION

The Proudman Oceanographic Laboratory (POL) like many other oceanographic laboratories has an interest in measuring the level of the sea accurately. The field experiment discussed in this report was set up in collaboration with the U.S. National Ocean Service (NOS) to compare the latest technology in water level measurement with well tried and tested conventional gauges. The New Generation Water Level Measurement System (NGWLMS) had been tried in regions with a relatively small tidal range but not in shelf areas like the U.K. (Gill & Mero 1990). Holyhead on the west coast of the U.K. was used as a test site as it part of the U.K National Tide Gauge Network and is therefore well maintained. It has a fairly large tidal range (5m at Springs) which provided a thorough test for the equipment. In spite of this large range the tidal regime is reasonably linear, there are no strong tidal currents or important harbour affects to complicate the measurements (Figure 1).

During the experiment there were 3 types of tide gauge installed at Holyhead for the period June 1989 to August 1991.

1. An NOS New Generation Water Level Measurement System (NGWLMS).

2. A Munro float gauge in a stilling well.

3. A Bubbler gauge outside the well used as part of the national tide gauge network.

4. During the later stages an absolute pressure gauge as used in the Southern Ocean for the POL ACCLAIM network was installed.

Our main interest in this study had been to determine whether all or any of these instruments could measure sea level in an absolute sense from an established TGBM and whether the stability of the measurements relative to this benchmark could be maintained over a period of at least 1 year but longer if possible. However as the experiment progressed it became obvious that establishing a common datum and datum stability were problems and the experiment concentrated on these rather than the question of an absolute datum. The latter became the subject of a separate study which will be reported on separately (Smith et al 1991). Some attention was paid to the measurement of the tidal part of the signal but this measurement seemed easier to achieve than the maintenance a datum.

2. INSTRUMENTATION

Several papers have already been published on the attributes of and problems with various tide gauge systems therefore only a brief description of each type is given here and only in so far as it affects the experiment.

The stilling well at Holyhead is 1m diameter with a conical inlet. The float is connected to a Munro chart recorder which has a potentiometric output into the DATARING system of the National Network. This allows the data to be interrogated remotely over the public switched telephone network. For a discussion of stilling wells see (Lennon 1968) and (Noye 1974).

In the Bubbler gauge, the equivalent sea level pressure in the bubbler tube is monitored by a quartz crystal sensor and converted to sea level by software in the system which also applies various 'Bubbler' corrections. (Pugh 1972). A differential sensor is used to remove the effect of atmospheric pressure and a mean density is applied which is derived from salinity measurements made routinely at Holyhead.

The NGWLMS instrument is described in Scherer 1986. It has an inner acoustic tube of 1 cm diameter protected by a 150mm outer pipe which has no effective 'stilling' properties. The acoustic head is located accurately at the top of the assembly and has an interchangeable precision made distance piece with can be used as a reference point. The instrument adjusts for variations in sound velocity by making a ratiometric measurement of the acoustic distance to the sea surface relative to a known calibration hole in the side of the sounding tube. This corrects for any first order effects of the change of sound velocity with humidity or temperature. Temperature, which is measured by two thermistors separated by approximately 1m near the top of the tube, is recorded but not used to adjust the measurements of acoustic distance.

The ACCLAIM gauge is fundamentally an absolute, as opposed to a differential, quartz crystal sensor located in the sea and measuring total pressure (sea level + atmosphere) and sea temperature. A digital barometer separately measures the atmosphere and the three variables are logged locally and also transmitted by satellite DCP link to POL. This gauge is most applicable to hazardous environments as the sensitive elements are under water and only connected to the remote monitoring equipment by heavy armoured cable.

The sampling schemes of the various instruments are not all the same. The float and bubbler gauges average and sample the sea level signal every 15 minutes, the NGWLMS averages 1 second acoustic pulses over 3 minutes but only samples the data every 6 minutes, and the ACCLAIM gauge averages the variables over 15 minutes and records them locally but further averages them over 1 hour for transmission over the DCP. These different averaging and sampling schemes are likely to have insignificant effect on the results in this particular case. There might have been some effect if a seiche of 3 - 6 minute period were present but the only unusual signal present at Holyhead is a small harbour resonance which is excited by ferry traffic at a period of just less than 1 hour.

3. DIARY OF EVENTS

22 June 1989

NGWLMS installed at Holyhead. Levelled to TGBM.
The Bubbler and Float Gauges were already operating.

26 June 1989

The tide gauges were re-levelled. Temperature and salinity readings were taken.

The gauges continued to operate for 1 year from this time. Comparison of the data showed that the mean levels of Bubbler and NGWLMS differed by 15 mm initially and 10mm by the end of the year. This caused us to consider changing the equipment.

10th May 1990

A new Aquatrak sensor was fitted to the NGWLMS and all gauges were re-levelled. Readings of absolute sea level were taken using a calibrated tape. This revealed that the Bubbler was reading 6mm low. This was adjusted to be correct.

Unfortunately it was impossible to determine any more information from this data because the new Aquatrak gave substantially different readings from the previous sensor. This was caused by a small amount of adhesive that had penetrated the joint near the calibration hole resulting in a mean level offset and a significant error in tidal range. This data was discarded.

18 June 1990

A new Aquatrak was fitted using a clamp fastener instead of adhesive. At this time the outer pipe was painted white to establish if there was an effect of sunlight on the readings. The Munro gauge was checked and the datum of the Bubbler was verified.

From this time the comparative readings of the NGWLMS and Bubbler reverted to similar values as with Aquatrak number 1. The tidal range as measured by the two instruments was similar but there was a mean level difference (NGWLMS higher than Bubbler) of approximately 10mm.

27 June 1990

Munro and Bubbler were again compared and the datum re-established.

9 August 1990

Datums and tidal levels were established using a precision pneumatic calibrator. About this time the software in the DATARING was changed and its datum re-adjusted. Prior to this we believe that the datum was set too low by approximately 7mm.

September 1990 - August 1991.

In this period no datum adjustments were made to either the Holyhead bubbler or stilling well systems.

4. DISCUSSION

As a means of comparing the different instruments we have differentiated between the tidal component, the long term mean and the mean on a shorter time scale of a day to a week. In both the latter cases the most useful comparisons were made by subtracting data from pairs of gauges (Figures 4,5 & 6). Large scale effects were measured equally by all instruments but we were more concerned with effects at the centimetre and sub-centimetre level. Attempts to relate the individual gauges to external influences by removing a predicted tide was found to be unproductive as the Holyhead non-tidal residuals due to meteorological effects are several times larger than the small scale effects (Figure 2). Only when the data from the instruments were subtracted did these small scale features become apparent. This procedure however had the disadvantage that it was more difficult to attribute any anomalies to any one instrument.

4.1 Tidal Component

Tidal analyses were performed on the data at various stages as it was being collected in order to make comparisons. However the essential features can be illustrated by concentrating on the data between June 1989 and May 1990 and the data between September 1990 and August 1991. All tidal analyses used the Harmonic Method, fitting 60 constituents to the observed data by least squares. Table 1 shows the amalgamated results from the above data.

TABLE 1 - Harmonic Constituents

	Float Gauge		Bubbler Gauge		NGWLMS	
	H	G	H	G	H	G
	(cm)	(deg)	(cm)	(deg)	(cm)	(deg)
O1	10.3	29.8	10.2	29.0	10.3	29.6
K1	11.2	177.8	11.3	178.2	11.3	176.9
M2	180.9	291.8	181.5	291.9	181.8	291.8
S2	59.4	328.9	59.6	328.8	59.8	329.0
M4	3.4	28.6	3.3	25.9	3.6	26.2

The harmonic constituents from the 3 instruments show good agreement, particularly in the phases. There is a net gain of approximately 0.2% in the amplitude of the NGWLMS over the Bubbler which was confirmed by daily response analysis for M2 between the gauges over the entire period. The gain varied between 1.0 and 1.004 with a mean of 1.002. An attempt to correlate the variation in gain with temperature proved unconvincing. However the values given for the harmonic constituents are within their standard errors so that they can be assumed to be the same. The low M2 amplitude quoted for the Float gauge is caused by the lag in the stilling well so that the difference between the two gauges contains a tidal element of approximately 1 cm range.

4.2 Mean Levels

Period June 1989 - May 1990

There was an obvious difference in the mean levels of the NGWLMS and Bubbler systems during this period whereas the Float and Bubbler gauges agreed. Initially the difference in the mean was 20mm but reduced to 15mm towards the end of the period. The drift in datum was attributable to a change in the Bubbler which was found to have altered by 6mm when it was checked in May 1990. This can be seen in Figure 3a which contains a year of the difference signal between the Bubbler and NGWLMS gauges. The large change in level in the diagram is at the time the first Aquatrak sensor was changed. Figure 3b shows the sea level differences between Float and Bubbler gauges for the same period.

Period September 1990 to August 1991

In the period September 1990 to August 1991 no datum adjustments were made to either the Holyhead Bubbler or Float gauges and their relative datum was observed to be stable between the beginning and end of the period. Just prior to this period a error had been discovered in the DATARING software which prevented the correction for air in the Bubbler tube from being applied. This was rectified bringing the mean levels of the NGWLMS and Bubbler instruments more in line with each other to within a few millimetres. We know from experiments at Holyhead with a datum probe which is under development at POL (Smith et al., 1991) that the bubbler datum for July 1991 onwards was precise to a few millimetres, implying that the absolute accuracy of the bubbler system was precise at that level for most of 1991. Prior to this it may have underestimated real sea level by approximately 7mm.

The problems with establishing a common datum were caused by the Bubbler system and the change in Aquatrak sensor would appear to have been unnecessary. However it did serve a useful purpose. Firstly the replacement Aquatrak demonstrated the effect on the NGWLMS of a calibration error. We observed a change in mean of 3cm and a similar change in the tidal signal. These can easily be shown to be in agreement with a theoretical calculation of the effect of miscalculating the position of the calibration hole. When the 3rd Aquatrak was installed it reverted to the same mean level as with Aquatrak number 1 one month earlier. This suggests that the NGWLMS has a stable datum and that the calibration procedures adopted for the instrument are reliable.

4.3 Short Term Stability of the Mean Level

In this section, we are not commenting on the absolute datum accuracy of the systems but on their temporal stability. The most obvious effect is that the difference between the various instruments is not zero. RMS differences between NGWLMS and Bubbler are approximately 10mm and instantaneous level differences are occasionally 50 mm (Figure 3a). For the Float and Bubbler systems these figures are 5mm and 30mm respectively (Figure 3b).

There is an obvious effect of temperature. Figures 4 & 6 show air temperatures derived from the 2 thermistors which are separated by just over 1 meter in the top of the NGWLMS outer tube. Surprisingly they shown temperature gradients of up to 7°C at times. Also shown on the diagrams is the difference in sea level between the NGWLMS and Bubbler. In Figure 3 there are sea level differences of approximately 50mm simultaneous with temperature gradients of 5°C on 11th, 23rd and 24th July 1989. However between these dates there are temperature gradients of a similar magnitude but no associated effect on sea level.

This puzzling feature occurs throughout the duration of the experiment where, on occasions, sea level differences appear to correlated with temperature anomalies and at other times appear to correlate with temperature gradients measured between the thermistors. At other times there is no temperature dependence whatsoever. Presumably this is because the temperatures that are used for the comparison are not those that cause the sea level anomalies. Neither does this prove which of the instruments is temperature sensitive and since these effects are relatively small they cannot be seen in the non-tidal residuals from any one instrument.

An examination of the Float and Bubbler records (Figure 5 for July 1989) shows no sign of the transient changes in temperature associated with temperature gradients. It is reasonable to assume that the Float and Bubbler cannot be sensitive to temperature gradients in the NGWLMS tube but there are signs of a direct dependence on temperature. This is also true for the NGWLMS and Bubbler records and is apparent in Figures 4, 5 and 6.

Diagrams for the whole period from June 1989 to August 1991 are available but are too numerous to reproduce here. However they tend to suggest that the NGWLMS is sensitive to temperature gradients in the sounding tube. A value for this sensitivity is difficult to determine because the sensors are in the top part of the tube only but is of the order 4mm per °C. Presumably the effects are more pronounced from the Holyhead deployment than previously because of the very long length of sounding tube below the calibration hole.

There is also a dependence on temperature directly but this seems to affect all instruments in some manner. It has not been possible to determine a direct relationship between temperature and any individual instrument but temperature is obviously a primary factor in limiting measurements at sub-centimetre precision. It therefore needs careful study in each of the instruments and is worthy of further work.

One noticeable feature of the temperature gradients is that positive differences (top minus lower thermistor) occur in the morning and negative gradients occur in the evening suggesting that solar heating of the tube is the principal cause.

5. CONCLUSIONS

The experimental work discussed in this report had the objective of comparing the NGWLMS with established tide gauges and looking at the performance over a 2 year period. The first conclusion is that most if not all tide gauges measure sea level at the centimetre level well enough but of course they were designed with this precision in mind. To achieve accuracies of a few millimetres requires much more careful procedures.

There were obvious difficulties in establishing a correct datum for the Bubbler partly due to technical problems with the instrument and with the computer software. Great care is obviously necessary to achieve the correct values and frequent checks are required.

The NGWLMS had good datum stability as evidenced by changing instruments. The calibration procedure adopted appears to be reliable.

Temperature appears to be the main disturbing influence on the instruments in trying to achieve millimetre precision. The NGWLMS is sensitive to temperature gradients in the sounding tube particularly when the tube is long as at Holyhead. On the occasions when a sea level anomaly occurred with a temperature gradient the magnitude of this effect was of the order of 4mm per degree difference between the thermistors.

All the instruments appear to be temperature sensitive to some extent. It was not possible to determine a direct relation but the effects are below the centimetre level and worthy of further study.

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FIGURE CAPTIONS

Figure 1. Spectrum of Holyhead data to illustrate the structure of the tides and the general background level. The small rise in energy around 1.2 cph is due to harbour resonance.

Figure 2. Non-Tidal residuals - Bubbler gauge June 1989-June 1990. This indicates the general level of non-tidal signal at Holyhead.

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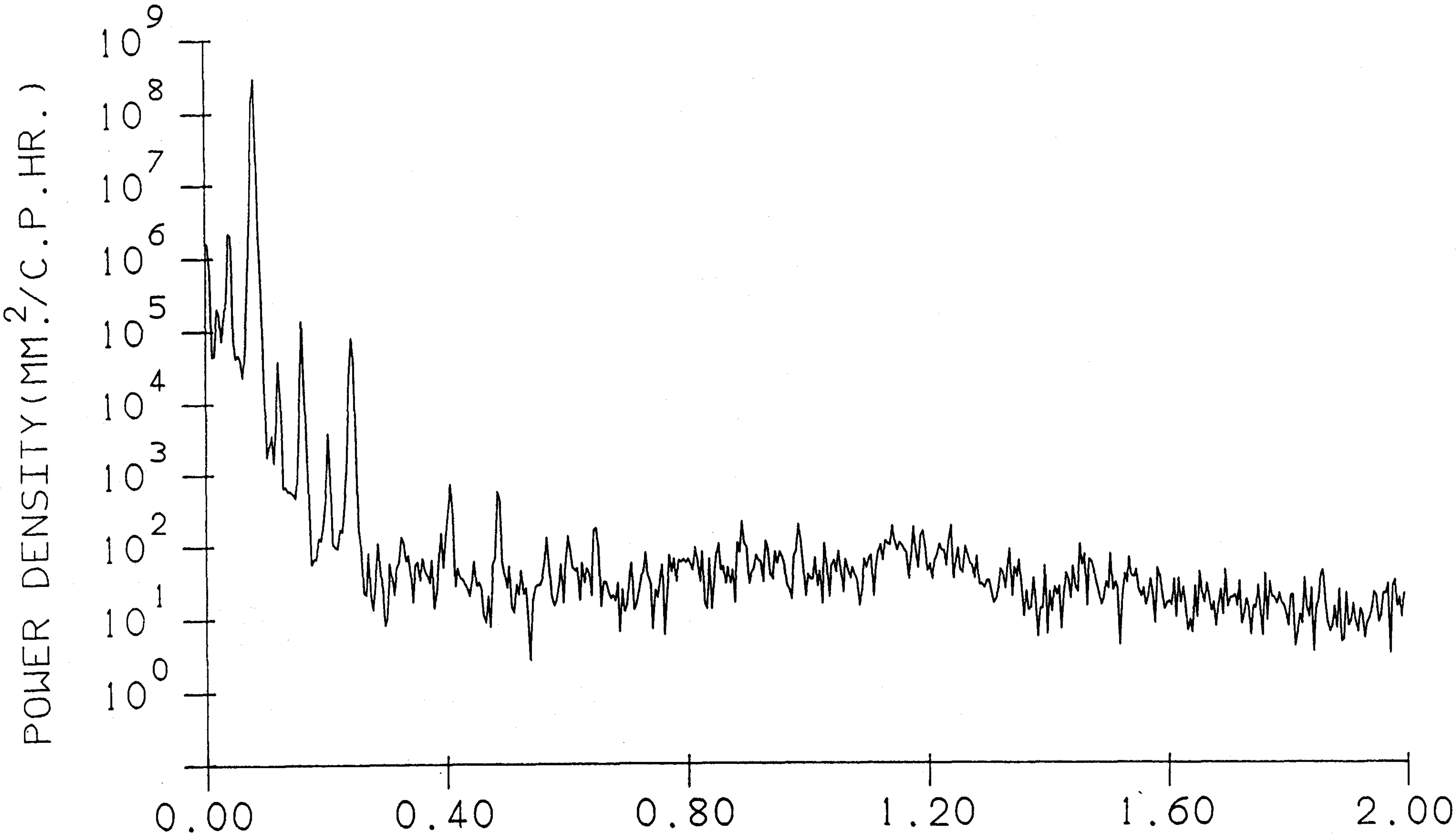
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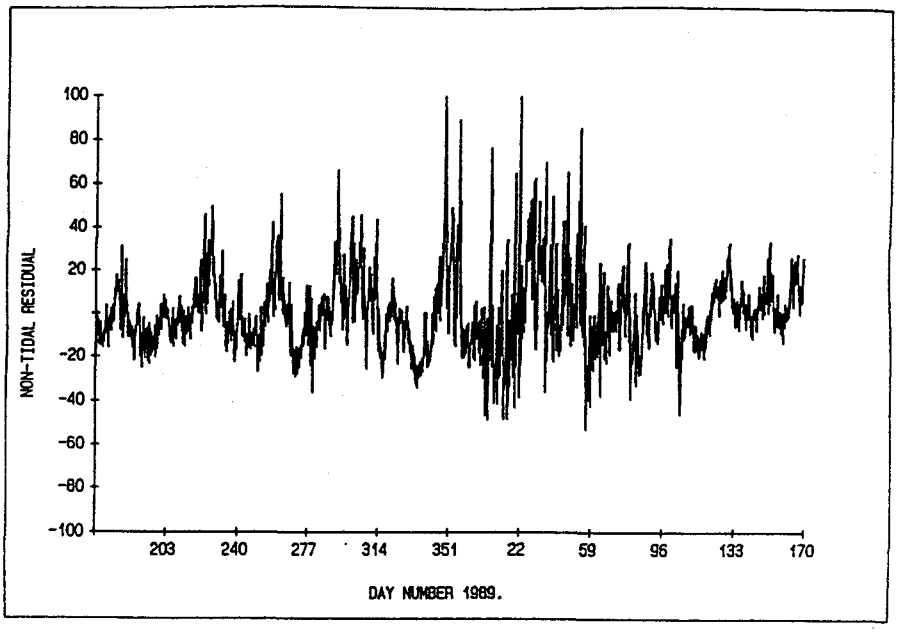
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0.00
0.40
0.80
1.20
1.60
2.00
FREQUENCY(C.P.HR.)

Figure 1.



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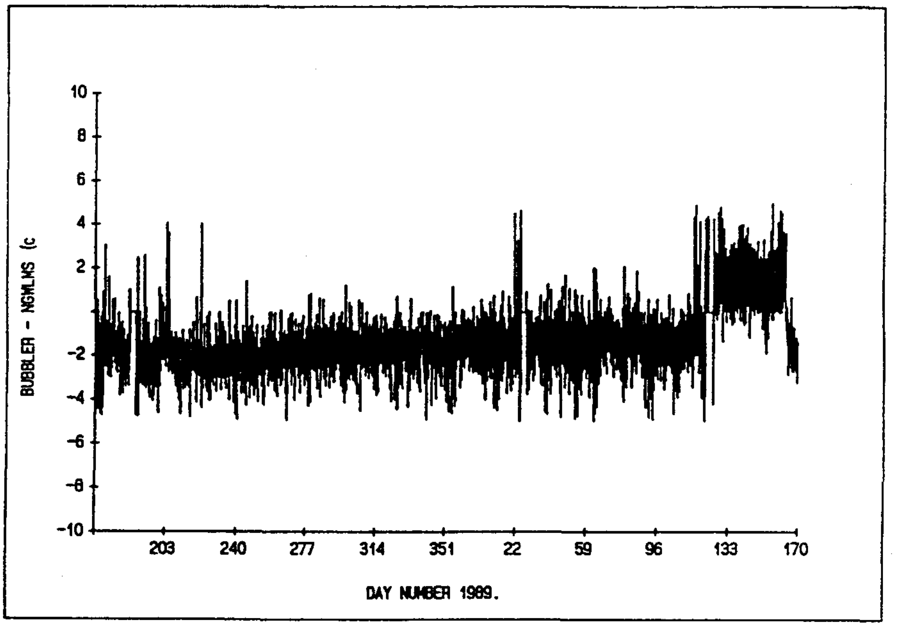


Figure 3a.

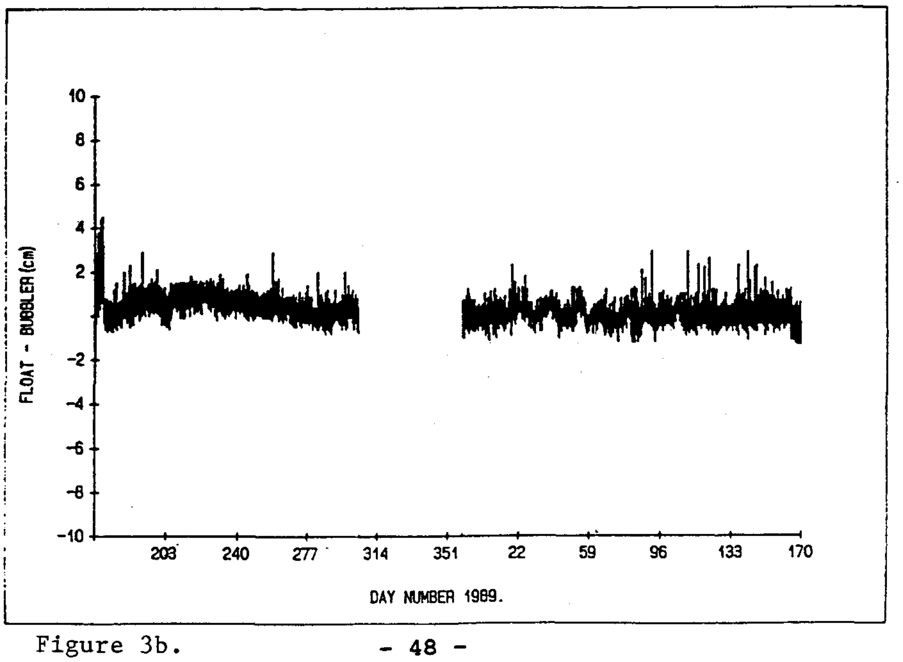


Figure 3b.

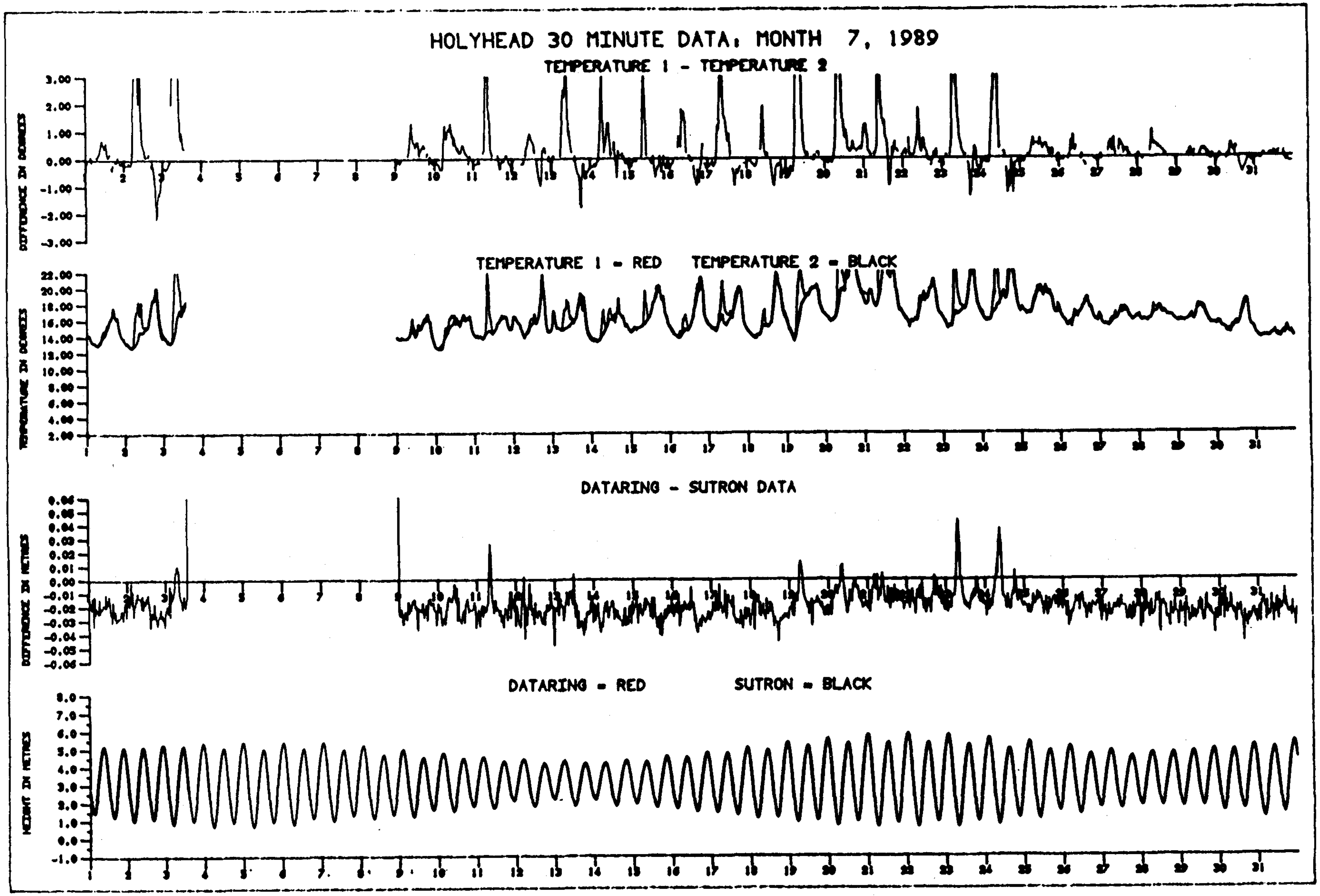
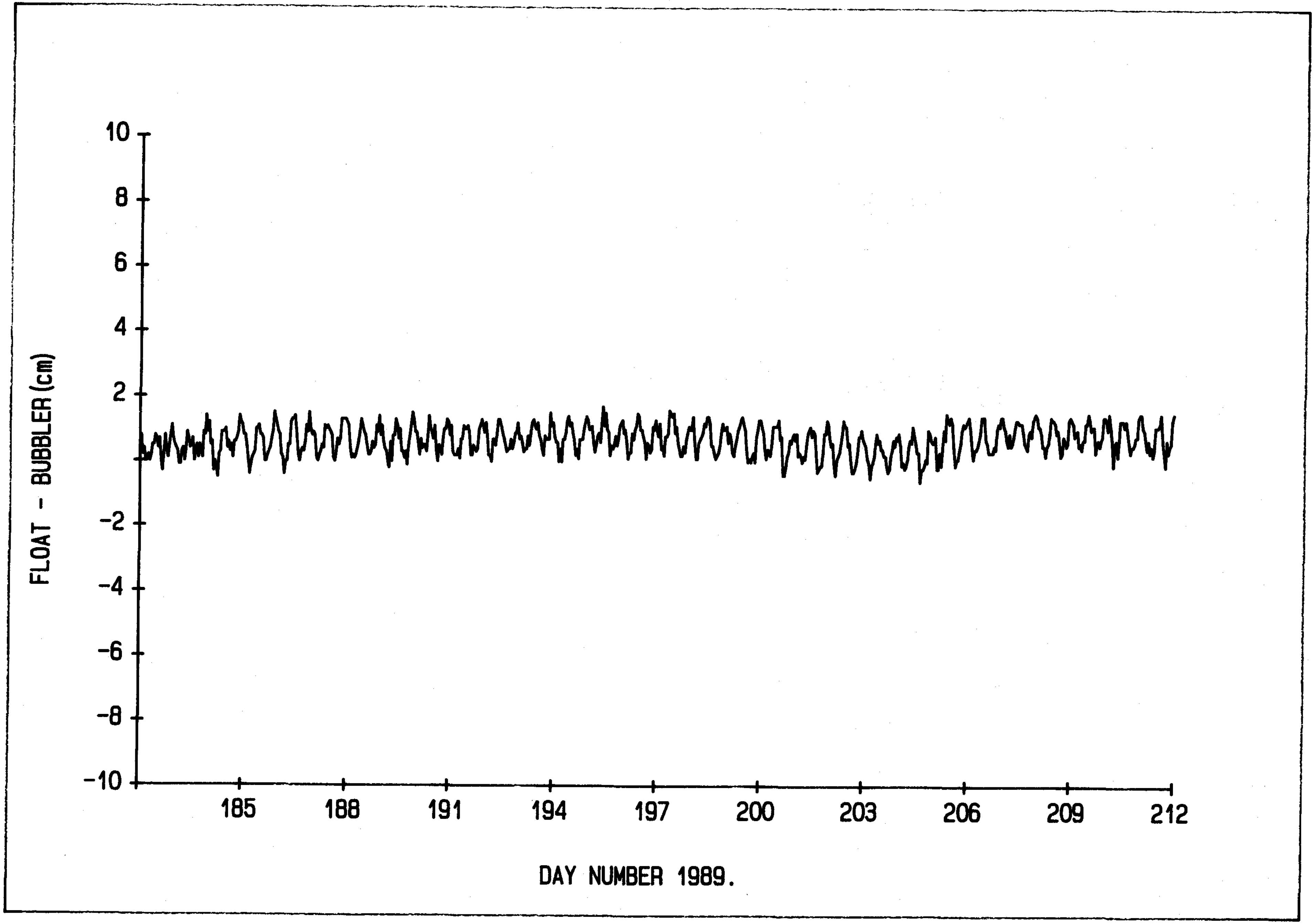

HOLYHEAD 30 MINUTE DATA: MONTH 7, 1989
TEMPERATURE 1 - TEMPERATURE 2
DIFFERENCE IN DEGREES
TEMPERATURE 1 = RED TEMPERATURE 2 = BLACK
TEMPERATURE IN DEGREES
DATARING - SUTRON DATA
DIFFERENCE IN METRES
DATARING = RED SUTRON = BLACK
HEIGHT IN METRES

Figure 4.



10
8
6
4
2
-2
-4
-6
-8
-10
FLOAT - BUBBLER (cm)
185
188
191
194
197
200
203
206
209
212
DAY NUMBER 1989.

Figure 5.

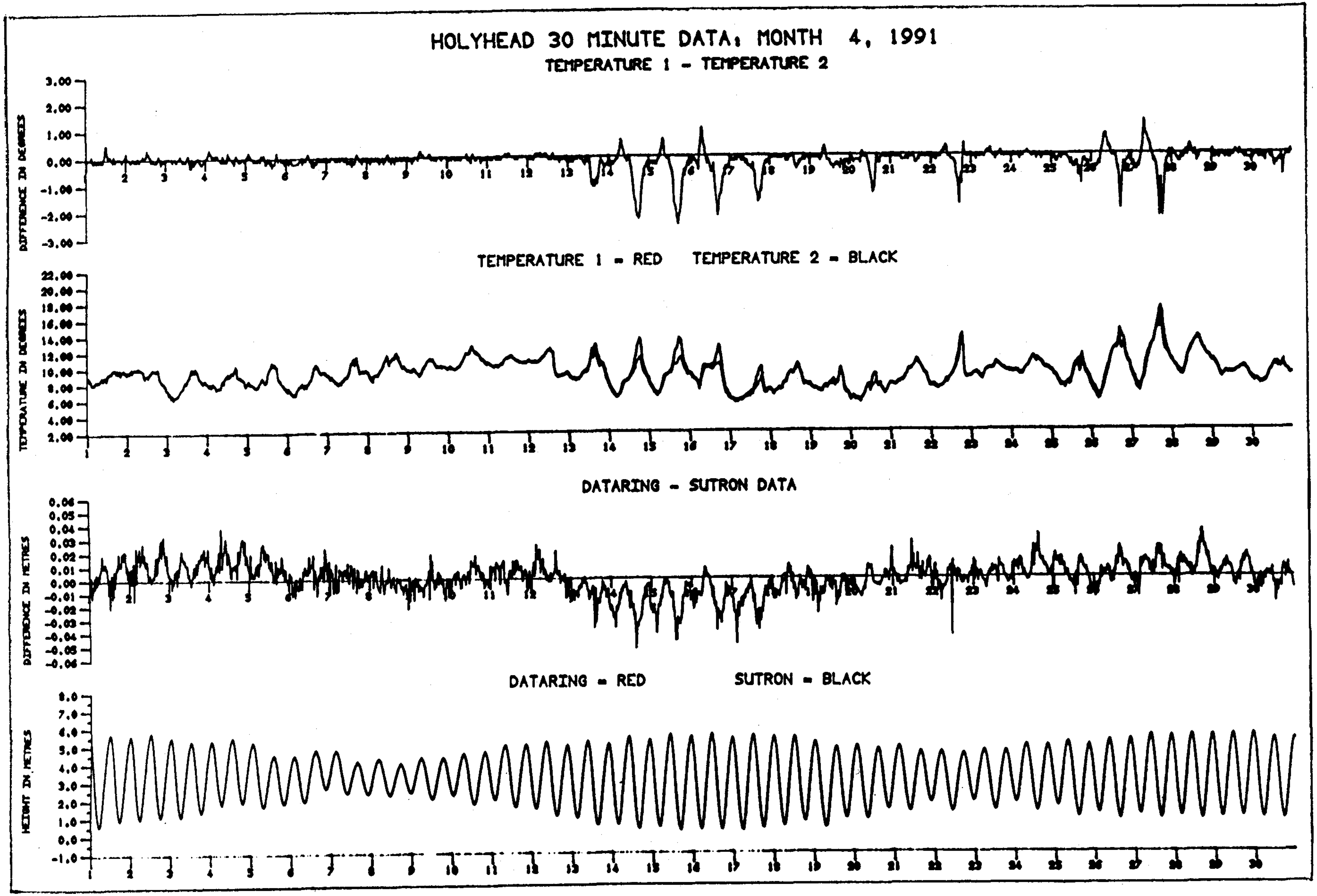

HOLYHEAD 30 MINUTE DATA: MONTH 4, 1991
TEMPERATURE 1 - TEMPERATURE 2
DIFFERENCE IN DEGREES
TEMPERATURE 1 = RED TEMPERATURE 2 = BLACK
TEMPERATURE IN DEGREES
DATARING - SUTRON DATA
DIFFERENCE IN METRES
DATARING = RED SUTRON = BLACK
HEIGHT IN METRES

Figure 6.

THE STILLING WELL - A HELP OR A HINDRANCE?

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1. INTRODUCTION

The conventional float-operated tide gauge, which uses a stilling well to attenuate the influence of surface waves, still remains as the work-horse of tidal measurements and in some areas even continues in use as a monitor of mean sea level for studies of climate change and sea level trends. Nevertheless it has long been known that the stilling well system suffers from inherent problems, including a non-linear response function. If concern is expressed at all, it is often assumed that tidal filtering on the one hand, and a focus upon long-period signals on the other, remove anxieties for all practical purposes. However it is here suggested that it would be imprudent simply to accept that the water level enclosed in a stilling well can be considered representative of the coastal environment which it presumes to monitor, and in consequence it is appropriate to re-examine stilling well performance and the implications for those interests which are relevant to GLOSS.

It is important to have in mind that the stilling well operates as a simple manometer, balancing pressure about the orifice, so that in its basic form, viz. a tube with a conical base where an orifice at the apex of the cone represents 1% of the cross-sectional area of the tube, the pressure of the water column above the orifice and external to the well is balanced by the pressure of the internal water column. This equilibrium will be maintained even where factors are present, other than the simple static pressure balance of homogenous water columns. The stilling well balances pressure and not elevation. Clearly dynamic processes which perturb the simple pressure field must be considered, and also any process which serves to differentiate density properties of the two water bodies.

It can be argued of course that an infinite range of natural features; embayments, promontories, estuaries, etc will display similar anomalies of sea level, but such features are considered to be a function of station siting. Given a selected site, the scientist should be assured that instrumentation will faithfully measure sea level at that location. Unfortunately such sentiments tend to be optimistic rather than realistic. The stilling well was first designed to assist in the measurement of tidal oscillations over several metres. As the evolution of science continues, and in particular as the target signal assumes a much smaller magnitude, such as the sea level response to climate change, perhaps three or four orders of magnitude smaller than the tidal signal, then it is necessary to examine more closely the performance of associated instrumentation.

2. THE HISTORIC RECORD

The subject is covered in a comprehensive fashion in the technical journals. The shortcomings of the stilling well, in the treatment of wave dynamics, were addressed a quarter of a century ago (Cross, 1968), while in the same era laboratory tests had been conducted on the performance of stilling wells in the presence of stream flows (Halliwell et al, 1969), and laborious attempts to observe the response function of the total system were seen to be underway (Lennon, 1968). Critical assessments of tide gauge performance were in hand at the time (Lennon, 1969) and within a further year, following surveys of temporal stability, plans for optimisation of performance were in place, but already the need to replace the stilling well by numerical filtering techniques had been established (Lennon, 1970). In the course of this testing procedure, several concerns had emerged other than those associated with the stilling well, and certainly it had become clear that digital, rather than analogue recording systems, were infinitely preferable. However, the basic imperfections of the stilling well response function remained a major problem area.

3. STILLING WELL CHARACTERISTICS

It is generally accepted that errors arise from three basic sources:-

3.1 From currents in the vicinity of the station

Water flow past the well intake, disturbed by the presence of the stilling well itself or by the structure to which the well is attached, can set up a disturbed pressure field which communicates to internal water levels. Where, as is generally the case, the well is clear of sea bed irregularities and also of surface phenomena, the effect is fundamentally a response to the Reynolds number and the invariable result is a "drawdown" of internal water levels. The magnitude of the effect is significant and its form is non-linear. Figure 1 (after Shih et al, 1991) shows the response of a variety of stilling well configurations to current exposure. Fortunately there are few tide gauge stations which are exposed to tidal currents of 2.0 $m.s^{-1}$ (4 Knots) and above, but tidal currents of 0.5 $m.s^{-1}$ do occur, and it can be seen that, given a conventional well design with a simple conical base, the drawdown can be approximately 4 cms.

3.2 From exposure to surface waves

Although the original purpose of the stilling well was to attenuate wave motion, in fact the design suffers from the asymmetry of flow into and out of the well, and in this sense has non-linear characteristics. Again this results in a "drawdown" of well levels in the presence of a wave field. The mechanism here is quite complex, and although the wave attenuation and phase lag can be readily computed in the ideal case from the relationship between orifice and stilling well diameters, other factors, notably the wave form, have a major influence. B.J. Noye (Noye, 1972) examined the physics of the system in some detail and addressed its non-linear characteristics. In fact he proceeded to postulate a design modification which promised to restore the well to a linear response. This, however, involved the replacement of the orifice by a very long narrow tube which had its own problems of a practical nature. The task of ensuring freedom from marine growth and marine biology, which otherwise implied a threat of temporal changes in the response function of the system, proved to be too demanding so that the design did not see common usage.

The wave-induced drawdown then remains a serious problem, together with the current effects, and in Figure 2 (Shih et al, 1991) it can been seen, from wave tank experiments that the magnitude of the effect could be approximately 7 cms in the presence of a 1 m, 7 second wave field.

3.3 The influence of local density changes

Here it is notable that many tide gauge stations, serving port operations, are sited in estuaries where there can be significant changes in density through the tidal cycle. In such circumstances water properties influencing the well at low tide are likely to show landwater influences with consequent low densities at this stage. The approach to high water tends to bring progressively more exposure to open ocean salinities with increasingly higher density water entering at the base of the well. Its inherent "stilling" properties then retain in the well a stratified system, with a lower mean water density of the water column contained within the well compared with that external to the system. In this manner the well progressively over-estimates the elevation of the ambient water as high water approaches.

Studies of a tide gauge stilling well at a particular riverine site on Merseyside, U.K., (Lennon, 1970) showed the presence of 8 cm anomalies at high water from this source and an overall bias to mean sea level of 23 mm.

In Figure 3 (from Lennon, 1970), typical tidal distortions of a stilling well are shown in the presence of a hypothetical tide with a 10 foot amplitude given certain common mechanical defects, plus density and extreme stream perturbations. Although the resultant tidal profile recorded by a gauge in these circumstances is smooth, and certainly not apparently anomalous, contributions are made in all the even-numbered tidal species with a major effect in species, 0, mean sea level.

4. THE IMPLICATIONS OF STILLING WELL PERFORMANCE

The above considerations clearly indicate that the signal recorded by a tide gauge in a stilling well is likely to be significantly different from the true signal of water level excursions at the well site. Because of non-linearity of the mechanisms concerned, the effect is likely to be noticeable at the high frequency end of the sea level spectrum. However it is also apparent that currents, waves and steric stratification produce a bias in mean sea level. As modern interests produce increasing focus upon the low frequency band, particularly in matters of climate change, this is a subject of serious concern.

Take for example a conventional stilling well exposed to a hypothetical semi - diurnal tidal current, say M_2 = 1 knot, S_2 = 0.5 knot. At Spring Tides then a tidal current of 1.5 Knots would be in force with a drawdown related to that condition. This would take the form basically of a quarter-diurnal drawdown signal peaking at approximately 8 cms. The position at Neap Tides would result in a similar periodic signal peaking at approximately 1 cm. Consequently the gauge would provide a negative bias to mean sea level, varying within a 14 day period, with an amplitude of approximately 3.5 cms and a mean sea level offset of approximately 4.5 cms, although the non-linear characteristics would provide further complication.

Although not truly periodic, the offset due to waves will respond to the return cycle of weather patterns but will have a similar signature.

One may then suggest the following:-

The spatial scale of these anomalies is centimetres (stilling well wall thickness), but the tide gauge data is used to interpret marine signals associated with the scale of the observing network, 500 kms and larger.

The drawdown due to currents might well be associated with a negative sea level offset of some centimetres in a period of 7 days, and longer due to aliasing.

Wave pumping also gives a negative mean sea level offset of similar magnitude associated with the time scale of weather patterns, again typically 7 days and longer.

Where present, steric stratification provides a positive bias to mean sea level in periods of hours, days and longer.

There is a strong danger of aliasing into seasonal and the all-important inter-annual time series.

Should an instrument be commissioned and remain thereafter unattended, one might expect that the station might still produce the long period trends in a relatively faithful manner. However one would need to have confidence that aliasing was under control. But in reality the practice is to conduct repeated surveys, tide staff checks or equivalent with frequent adjustment of the record. Such practices have the potential to introduce excessive noise in the mean sea level signal. Given the need to target greenhouse rising sea level trends of order 1 $mm.y^{-1}$ such anomalies cannot be tolerated.

Although work on inter-annual variability, where the sea level signal is of a magnitude +/- 40 cms, may still proceed with caution, it is clear that where the interest is in the long term phenomena,

and the sea level trend in particular, then there is a strong argument that a stilling well system should not be used.

5. RECENT SOLUTIONS

Although it is relatively easy to criticise, the search for a solution is much more difficult and in this context it is necessary to acknowledge the exhaustive tests conducted by and for NOAA/NOS in connection with the design and planning for the Next Generation Water Level Measuring System (Shih et al, 1991), and also adopted in the Australian SEAFRAME arrays. In the course of this work many configurations of the mechanical design were examined and tested in flumes, wave tanks and in the real world at a complex test site at Duck, North Carolina.

It rapidly became clear that although the new technology of the acoustic sensor would seek to avoid the perils of the stilling well, some compromise would need to be reached. Other considerations, for example of temperature profiles and their effect on the speed of sound, argued for a protective enclosure of some type and although the responsibility for wave attenuation was shifted towards numerical integration of rapid samples, some minor degree of mechanical filtering was recommended so as to reduce the perturbation of the acoustic returns. In response the philosophy of a protective well has developed. In particular the orifice to well diameter ratio has been selected as 1:3 as opposed to 1:10 of the conventional stilling well, and in view of the non-linear principles already discussed, a major step towards the elimination of the conventional problems is therefore made. The experimental and theoretical studies then focused upon the two major problems of exposure to currents and waves.

\# *Currents*

Figure 4 (after Shih, 1982) illustrates a selection of stilling well designs aimed to minimise the effects of currents in the vicinity of the well. The exercise identified the need to concentrate upon systems which attempted to ensure a condition of laminar flow in the vicinity of the orifice. The optimum design achieved this by the use of parallel horizontal plates near and below the base of the protective well and in Figure 1, the version (g), which represents the design in current use, is seen to deal effectively with current-induced drawdown for current speeds less than 4 knots.

\# *Waves*

Figure 5, from the same report, illustrates some designs evaluated in the exercise in the attempt to reduce errors due to wave-pumping. In view of the fact that the problem arises from the asymmetry of flow into and out of the well, it is not surprising that the approach to symmetry, by using double opposing cones about the larger orifice, achieved a remarkable improvement, approaching 100% by comparison with the conventional stilling well.

This brief survey does only rough justice to a very comprehensive study of stilling wells exposed to a range of exposures to laboratory and coastal conditions. However, it is important to illustrate the design (from Shih et al, 1991) which is the current operational solution to a long-endured series of hazards in the monitoring of sea level. This is given in Figure 6.

The matter of steric stratification is not so easy to avoid or to treat by technical means. This must remain a matter of site selection and certainly it would be imprudent to adopt a gauge, exposed to such effects, in any study which requires both high resolution measurements and a high degree of datum stability.

6. PERFORMANCE

In Figure 7 there is represented a comparison of the performance of a conventional tide gauge with respect to a new SEAFRAME system on the Australian baseline array which in a graphic manner indicates a significantly improved performance. The following comments are noteworthy:-

The vertical scale is logarithmic.

The new gauge shows significantly less background noise in the inter-tidal bands.

The latter is most marked at the high frequency end of the spectrum stressing that noise is contributed by the non-linear aspects of the conventional stilling well.

The tidal bands are much more clearly identified in the SEAFRAME data.

BUT # There is clear evidence of a significant reduction in noise in the low frequency cusp also which promises much improvement in the determination of the links between sea level and climate.

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Shih, H.H. 1982 Studies on Float-wire tide gauge stilling wells; ADR error model validation and engineering development. Internal Report NOAA/NOS.

Shih, H.H. & Baer, L. 1991 Some errors in tide measurement caused by dynamic environment. in Tidal Hydrodynamics. Parker, B.B. (Ed), John Wiley and Sons, Inc., 1991.

FIGURE CAPTIONS

Figure 1. Current-induced drawdown models (after Shih et al, 1991).

Figure 2. Wave-induced drawdown of a conventional stilling well from theory and from wave tank experiments (after Shih et al, 1991).

Figure 3a. Typical cycling of errors from a conventional tide gauge due to maintenance problems, steric stratification at a riverine site and extreme exposure to tidal streams (after Lennon, 1970).

Figure 3b. The mechanical analogue and harmonic signatures of the errors illustrated in Figure 3a (after Lennon, 1970).

Figure 4. Some of the stilling well designs examined by NOAA/NOS in attempts to reduce current-induced error (after Shih, 1982).

Figure 5. Some of the stilling well designs examined by NOAA/NOS in attempts to reduce wave-induced error (after Shih, 1982).

Figure 6. The "improved" design of the protective well in current use (after Shih et al, 1991).

Figure 7. Power spectrum of annual sea level time series from Darwin:
a) unshaded - from long-established float operated/conventional stilling well gauge.
b) shaded - from newly-commissioned SEAFRAME gauge in protective well.

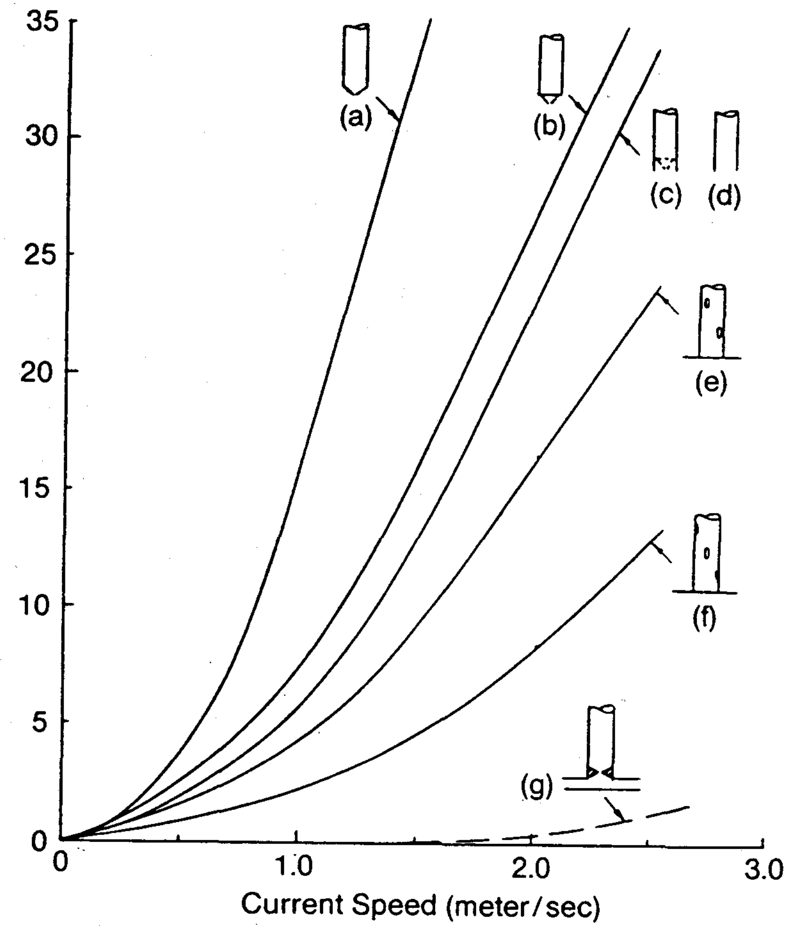


Figure 1

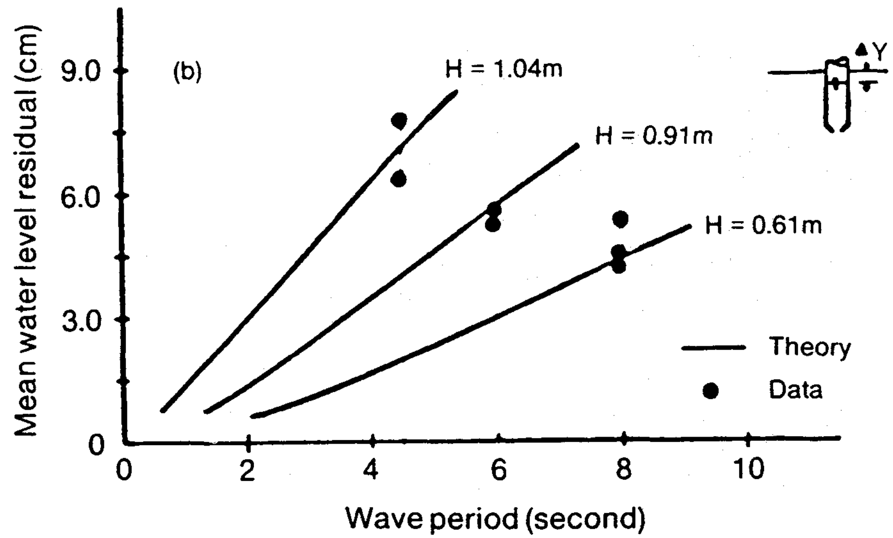


Figure 2

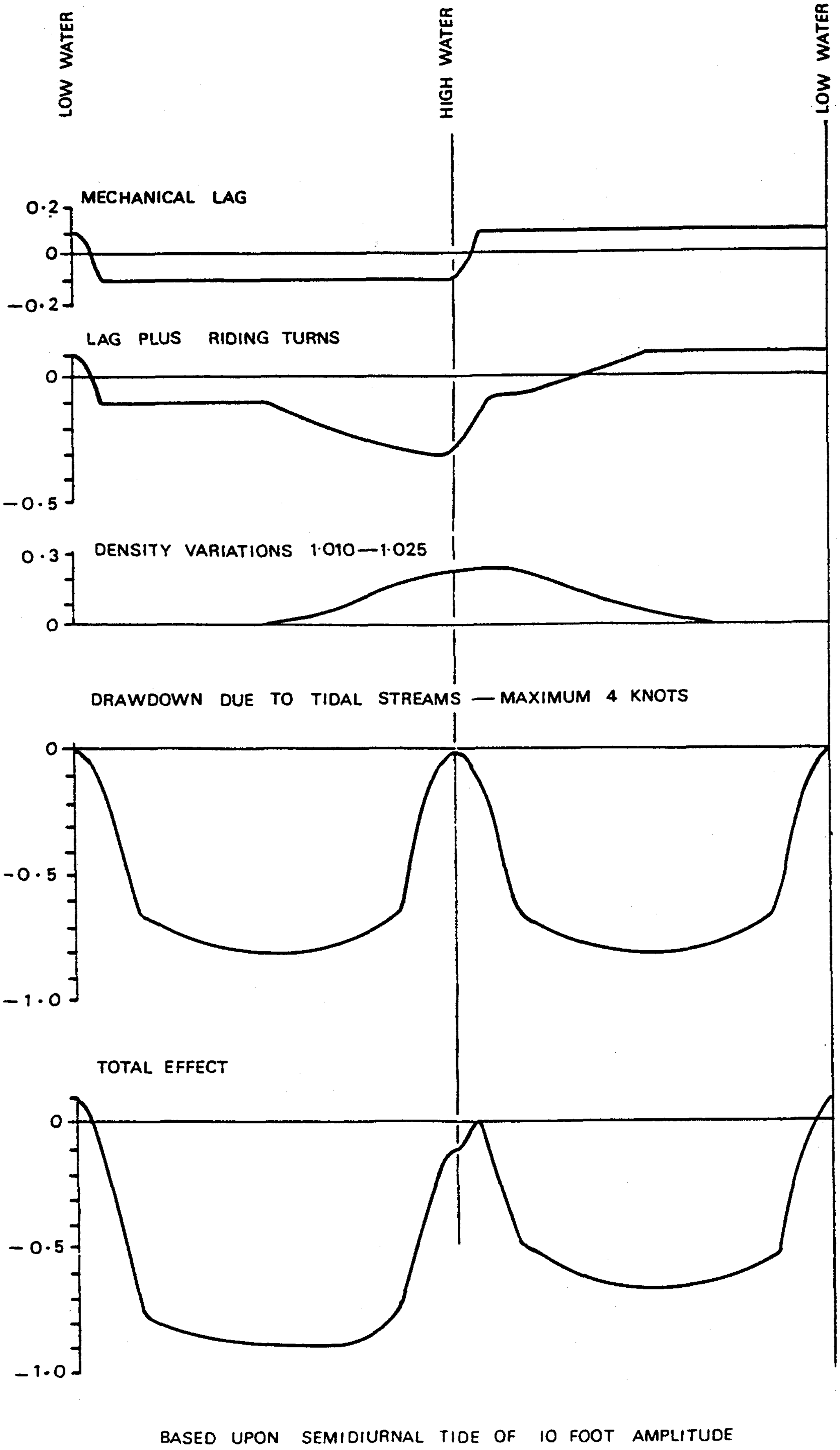
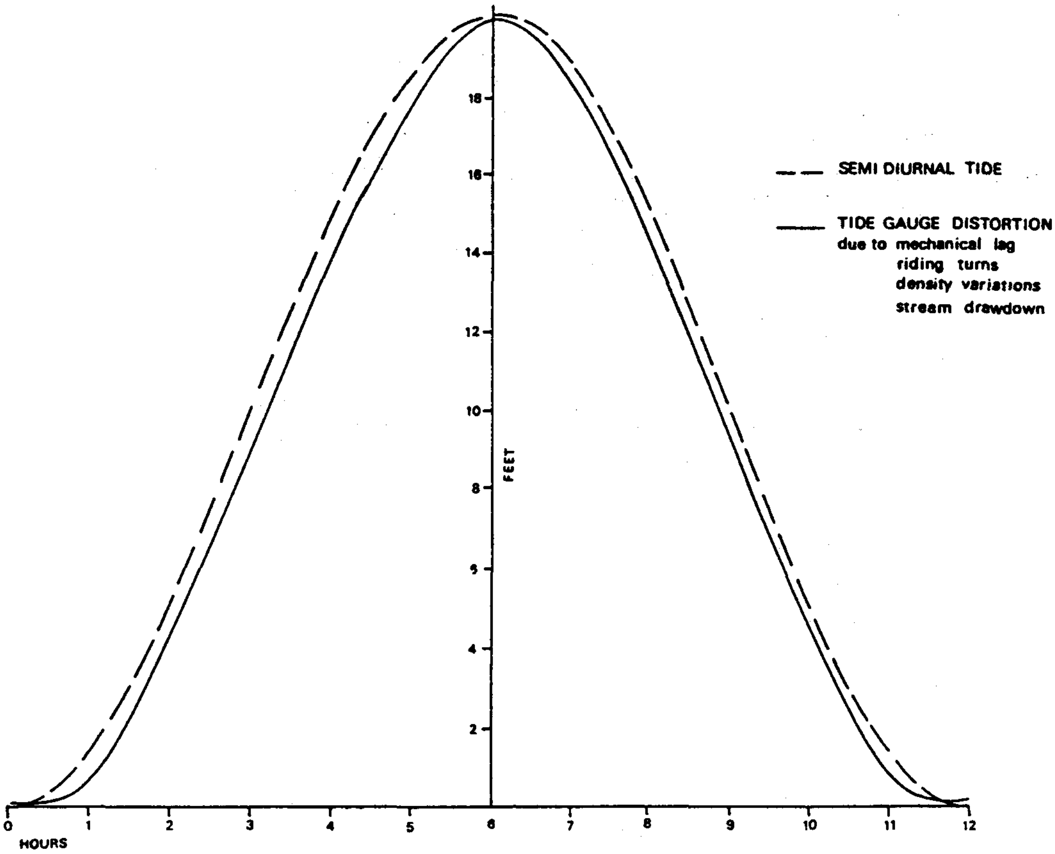

LOW WATER
HIGH WATER
LOW WATER
MECHANICAL LAG
0·2
0
−0·2
LAG PLUS RIDING TURNS
0
−0·5
DENSITY VARIATIONS 1·010—1·025
0·3
0
DRAWDOWN DUE TO TIDAL STREAMS — MAXIMUM 4 KNOTS
0
−0·5
−1·0
TOTAL EFFECT
0
−0·5
−1·0
BASED UPON SEMIDIURNAL TIDE OF 10 FOOT AMPLITUDE

Figure 3a



Comparison between the hypothetical open water tide and the curve produced by a gauge.

Harmonic Analysis of Typical Tide Gauge Errors Amplitude of Correction in feet

Species Number	0	2	4	6	8	10	12	14
Undisturbed tide	10.000	10.000	-	0.001	-	0.001	-	-
0.1 ft Gauge lag	9.999	9.983	0.002	0.043	0.001	0.025	0.001	0.016
Gauge lag plus riding turns effect	9.937	9.885	0.042	0.043	0.008	0.024	0.004	0.018
Density variation 1.010 to 1.025	10.076	10.100	0.036	0.011	0.004	0.005	0.004	0.002
Stream drawdown 4 knot maximum	9.399	10.000	0.322	0.001	0.168	0.001	0.096	-
Density variation plus stream drawdown	9.476	10.100	0.355	0.011	0.164	0.005	0.093	0.002
All above effects combined	9.420	9.986	0.315	0.049	0.175	0.024	0.092	0.018

Figure 3b

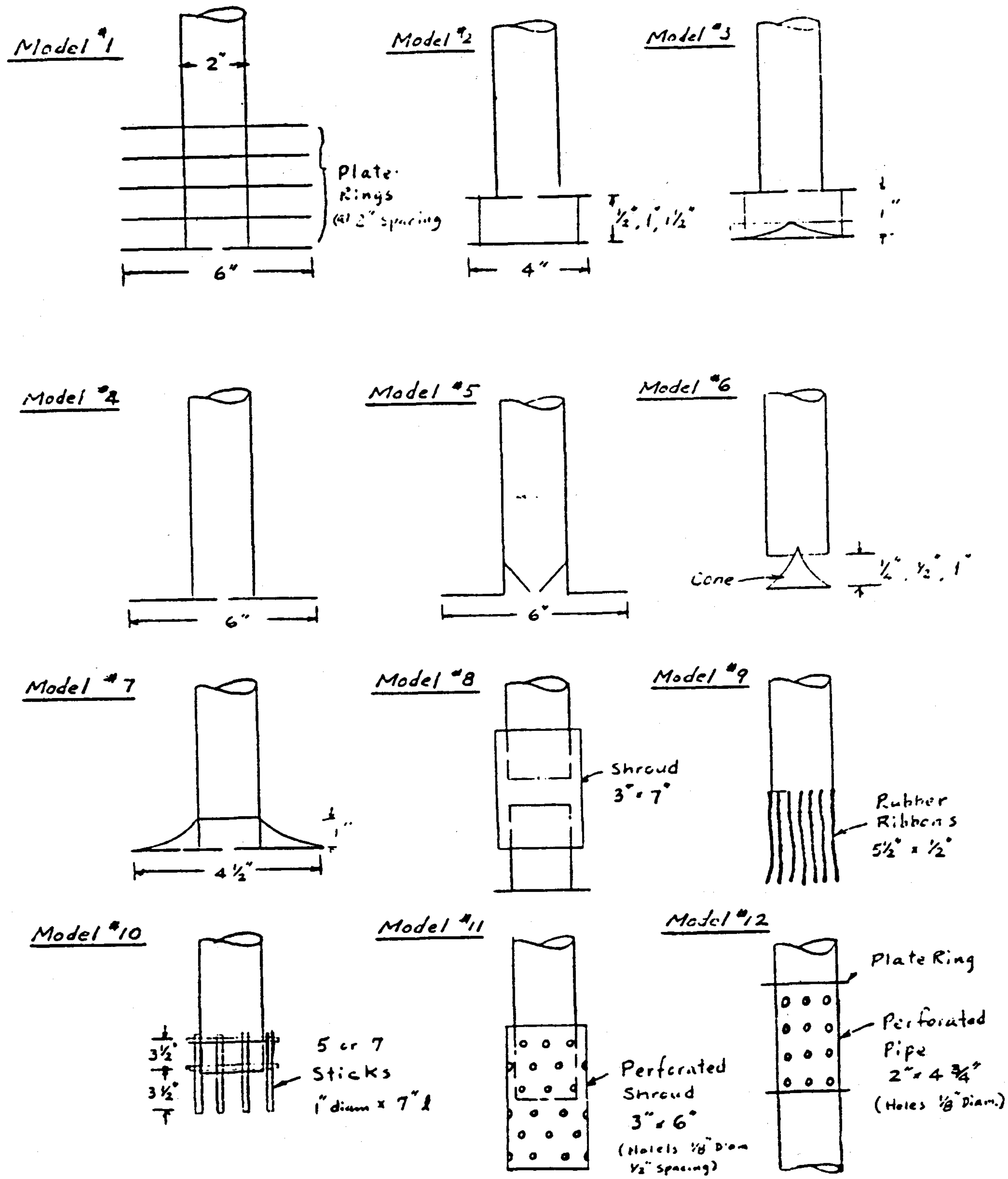

Model #1
2"
Plate Rings (4) 2" spacing
6"
Model #2
½", 1", 1½"
4"
Model #3
1"
Model #4
6"
Model #5
6"
Model #6
Cone
¼", ½", 1"
Model #7
1"
4½"
Model #8
Shroud 3" x 7"
Model #9
Rubber Ribbons 5½" x ½"
Model #10
3½"
3½"
5 or 7 Sticks 1" diam x 7" l
Model #11
Perforated Shroud 3" x 6"
(Holes 1/8" Diam ½" Spacing)
Model #12
Plate Ring
Perforated Pipe 2" x 4¾"
(Holes 1/8" Diam.)

Figure 4

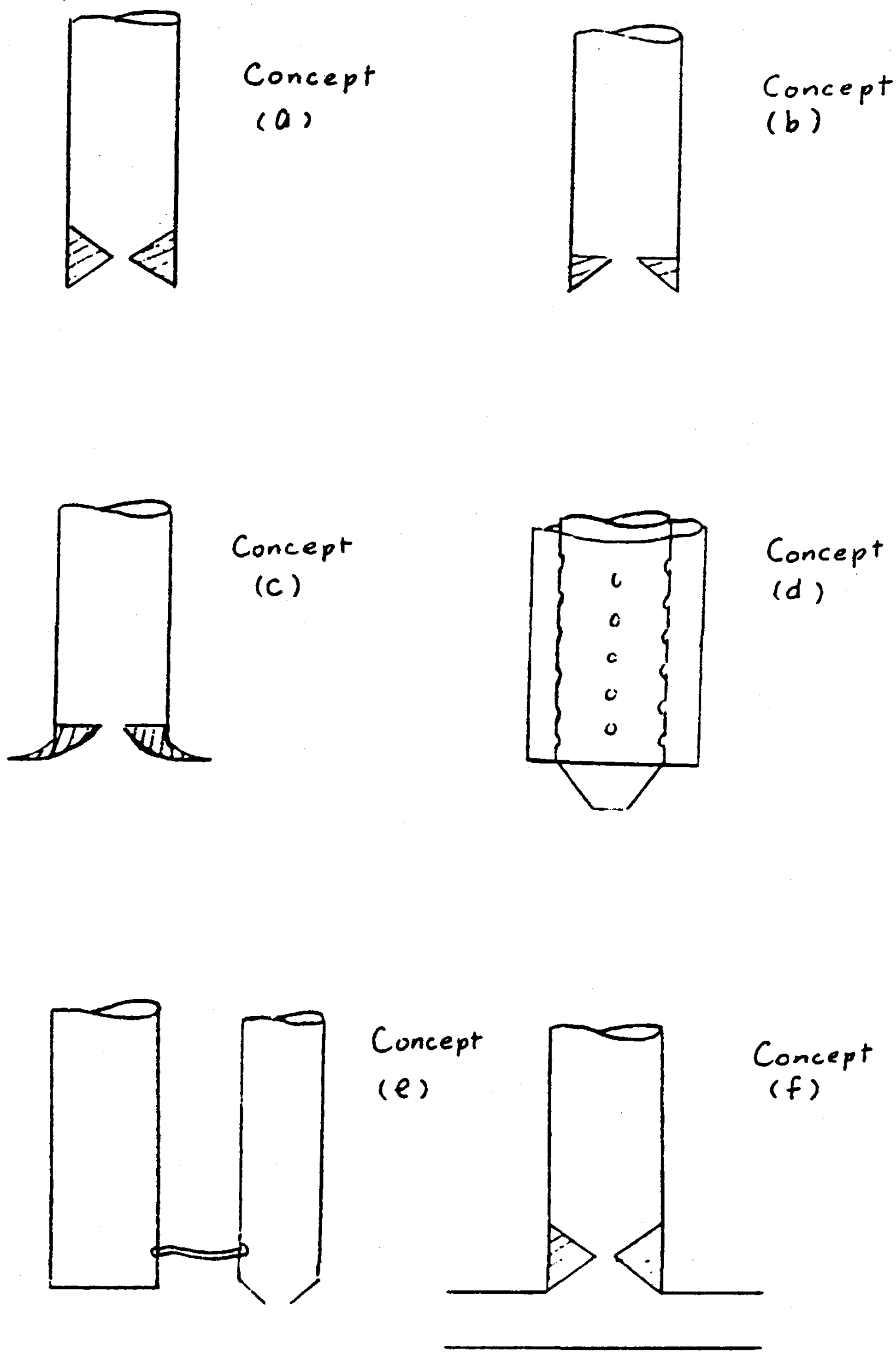


Figure 5

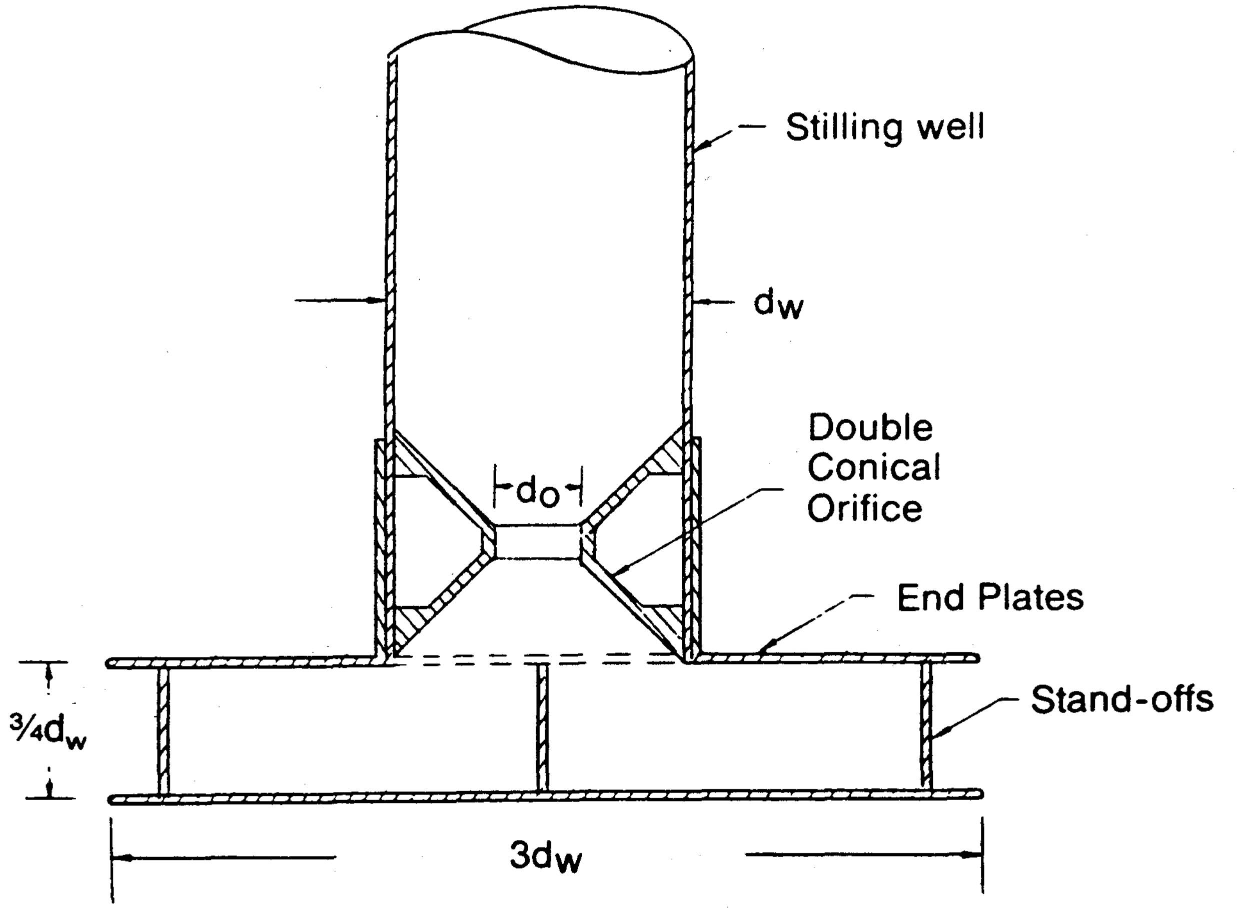
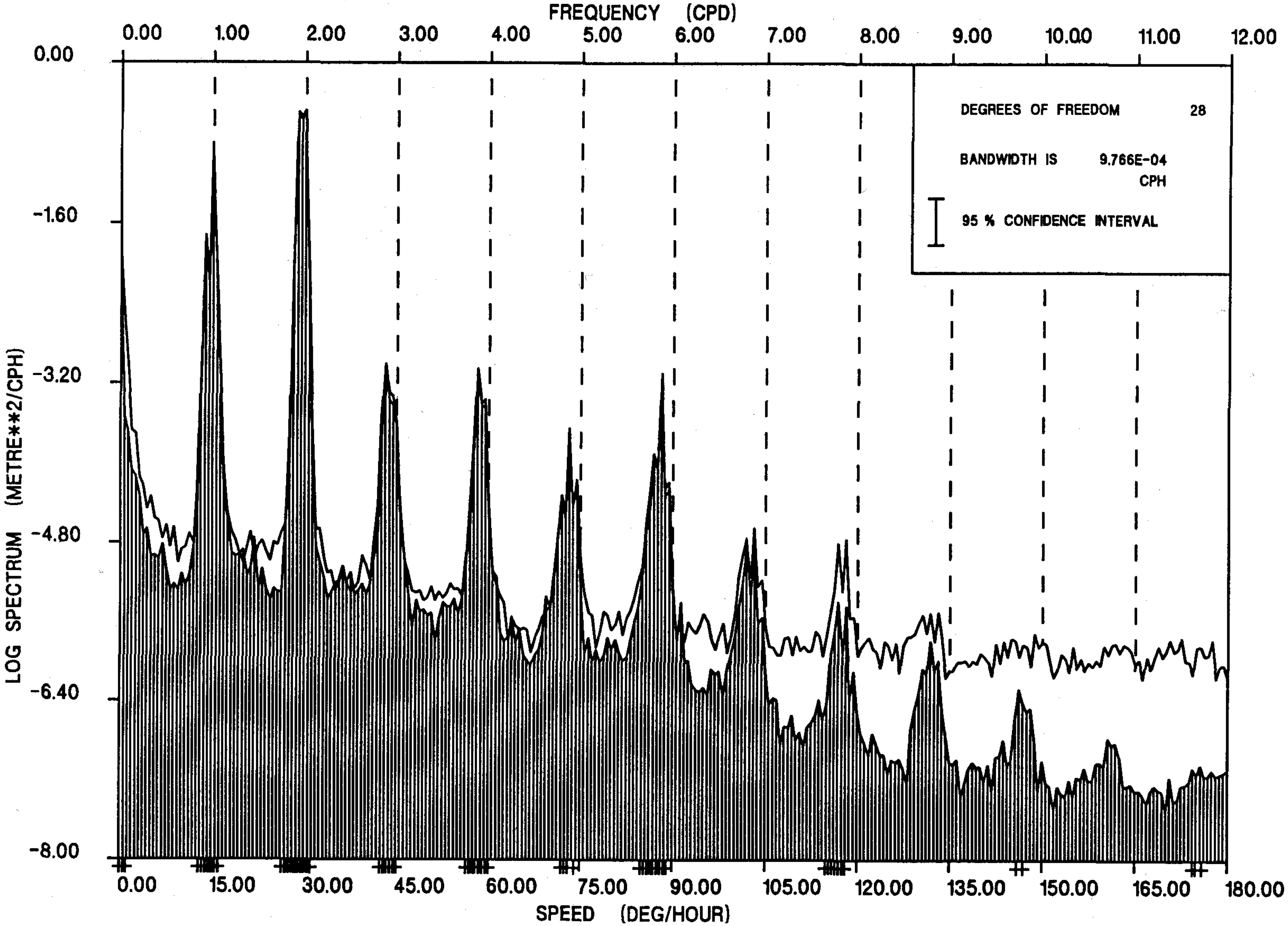

Stilling well
d_w
Double
Conical
Orifice
d_o
End Plates
Stand-offs
$\frac{3}{4}d_w$
$3d_w$

Figure 6

DARWIN ANALOGUE AND SEAFRAME SPECTRA



BLANK PLOT IS SPECTRUM OF ANALOGUE
SHADED PLOT IS SPECTRUM OF SEAFRAME
CENTERED SYMBOLS ARE TIDAL FREQUENCIES

Figure 7

PRECISE DATUM CONTROL FOR PRESSURE TIDE GAUGES

P.L. Woodworth

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1. INTRODUCTION

Many different types of tide gauge are now in use around the world. These include traditional float and stilling well gauges (Noye, 1974a,b,c; IOC, 1985; Pugh, 1987), acoustic gauges (Gill and Mero, 1990) and gauges based on the principle of measuring sub-surface pressure (Pugh, 1972). Pressure tide gauges are more convenient to use than others, especially in environmentally hostile areas, but their data are often difficult to relate to a land datum to better than a few centimetres. Methods used at present to impose a datum on pressure time series include simultaneous measurements at a nearby stilling well; tide poles or stilling tubes and observers; water level 'switches' in mini-stilling wells; and the use of 'comparators', or precisely calibrated reference pressure devices. Each of these has drawbacks.

The stilling well method probably produces usable results, as long as comparisons are performed over several complete tidal cycles to remove the effect of any lag in the well. However, a stilling well will not always be present and it will have its own systematic error sources (Lennon, 1971). A tide pole is very tedious for the observer and is useful only for first order checks in calm conditions. Switches show great promise and it is possible that reliable switch systems may eventually be developed. However, present ones do not entirely eliminate the effect of waves, even given the mini-stilling wells, and they are probably accurate to only a few centimetres, which is not good enough for long term recording. They also tend to foul in the dirty water often present in harbours. Finally, although the comparators used routinely by the UK Tide Gauge Inspectorate (UK TGI) appear to provide datum control of centimetre accuracy or better, they do not provide a near-continuous datum check, are clumsy to operate and are not well documented (CTG, 1986).

Pressure tide gauges already comprise a major subset of those in the GLOSS (Global Sea Level Observing System) network (IOC, 1990) and provide the best form of instrumentation for extending the network to environmentally hostile areas (IOC, 1988). Therefore, it is clear that a simple method is required to provide precise and near-continuous datum control to the time series from pressure gauges.

A method has been developed at POL for the precise datum control of sea level records from pressure tide gauges. By means of an additional pressure point at approximately mean sea level, it has been found that an effective temporal discrimination of the sea level record can be used to impose a datum upon itself. Two experiments, one based on bubbler gauge technology and one on pressure transducers installed directly in the sea, have demonstrated that the method is capable of providing millimetric precision datum control.

2. A BRIEF DESCRIPTION OF THE METHOD

A schematic pressure gauge setup is shown in Figure 1 with a pressure sensor in the water ('C') and another in the atmosphere ('A'). Around the UK national tide gauge network (called the 'A Class' network), the pressure difference C-A is usually recorded in a single channel of a differential transducer connected to a bubbler gauge (Pugh, 1972). At the South Atlantic sites of POL's ACCLAIM (Antarctic Circumpolar Current Levels by Altimetry and Island Measurements) network, C and A are separate absolute transducer channels (Spencer et al., 1992). In both cases, Paroscientific digiquartz sensors are employed (Banaszek, 1985). It is the difference C-A which gives sea level, after sea water density correction, and which must be constrained to a land datum. In practice, both C and A, or their difference, may measure pressure changes extremely well, but it would be common for their data to contain uncalibrated offset pressures and small low-frequency drifts specific to each individual pressure transducer. In addition, other parts of the apparatus may also introduce biases and drifts (e.g. through insufficient gas flow in a bubbler gauge) or the ocean itself may drift (i.e. through density changes).

In the present experiment, another pressure gauge 'B' is placed at 'datum B' (Figure 1) which is a datum approximately at mean sea level. Datum B would be geodetically connected to the local levelling network (Carter et al., 1989) and, it will be seen, will supply a sort of Tide Gauge Zero. The essential feature is that, while any pressure measured by a sensor at B will also contain an offset, and maybe a drift, the vertical height of its effective pressure point can be positioned at datum B very accurately. So, although it is not known absolutely HOW MUCH it is measuring to within perhaps a few mbar (i.e. to within a few cm), it is known WHERE it is measuring it to millimetric precision.

Figure 2(a) shows schematically the C-A record while Figure 2(b) shows the B-A record with the assumption of no waves. Initially, the datum of each record will be unknown. Of course, the latter is the same shape as the former, except that as the still water level drops below datum B the curve of Figure 2(b) bottoms out generating an inflexion point at the steepest part of the tidal curve at times 't1' etc. The flat part of B-A and its inflexion points will provide an extremely precisely defined shape which will be immune to any problems with datum offsets and low-frequency instrumental drifts. Our computation now involves overlaying the full curve of Figure 2(a) on to 2(b) using the top parts of the tidal cycles. Then the intersection of the flat line with the full curve can easily be computed, and the corresponding C-A values redefined to be at datum B. In other words, the datum has been transferred.

What about a more realistic situation with waves? Figure 2(c) shows that the sharp inflexion points might become rounded by waves, and it will not be until the wave crests have fallen with the tide below datum B that the curve will bottom out properly. However, this should not be a problem, provided that the waves are not too large, as Figure 2(c) can still be matched with 2(a) with the flat bit extrapolated on to the full curve. In practice, the matching can easily be done by least squares fit with a software algorithm designed to leave the area of the rounded inflexion points out of the computation.

This procedure is analogous to the function of the mechanical and acoustic water level switches used by the UK TGI. However, a switch acts at an instant and may go off prematurely with waves around. The 'software switch' here is the several hours of the bottom-out of B-A and is, in effect, a time-averaged discrimination of C-A. The rounding of the inflexion points due to waves will not bother the method in general but, as we are interested here in using B to establish a datum at regular intervals, rather than obtaining a continuous time series, the data of high wave days can simply be ignored. (Obviously we want a continuous record from C-A). High wave conditions might be identified from the degree of rounding at the inflexion points, or the digiquartz of C could be made to record at 1 Hz or higher frequency to measure them. 'B recording' may be intermittent at some sites owing to environmental or operational restrictions, and recording could be a feature of visits to remote islands or summer stays at polar bases. In our experience, such a procedure might be adequate to provide long term datum control to a continuous C-A record, as long as good (i.e. previously tested, relatively stable) transducers were used and the visits were at least once every year. However, where possible, it would be desirable to have the B sensor installed permanently as there is great appeal in being able to check the datum with every low tide (i.e. twice a day in most places).

In order to work properly, the method obviously needs a sizable tidal range so that B will be half the time in water and half the time in air. It will not work in lakes or microtidal areas but most coastal and many island sites have usable tidal ranges, even if only at springs. Clearly, 'tide' here means any real signal. 'Surge' will do quite as well as long as the same signal is observed in the top halves of B-A and C-A to enable them to match up. The method does not require the actual installed height of C or A to be known. Where it is difficult to install a fixed gauge C below the water, because of shallow gradients perhaps, then a pop-up, or bottom mounted and diver replaced gauge, could be used. Example locations where this might apply include the Tropical Atlantic, where POL and French groups have operated such gauges for several years, and Heard and Macquarie Islands, where the University of Flinders has made similar measurements. In fact, the height of A should be kept constant, with its readings compared regularly to a precise barometer, but that is for meteorological data purposes, not tide gauge considerations.

What do we expect the accuracy of the method to be? That depends on how flat the bottoming-out of B-A is. If completely flat, the method is theoretically perfect but there will be systematic errors depending on the hardware. Fifteen minute or higher frequency sampling would be better than hourly heights in order to clearly resolve the inflexion points but, whatever the sampling, it is important for A, B and C to record pressure simultaneously and in a similar fashion.

To summarise, the most important feature of the method is its ability to impose a datum as a function of time and its ability to handle slow drifts in any, or all, of the A, B and C transducers. As any drifts will manifest themselves as changes in the vertical conversion factor to impose the curve of Figure 2(b) on to that of Figure 2(a), they can be continuously adjusted for by constant constraint of C-A to the B datum imposed by the least squares adjustment.

3. EXPERIMENTAL RESULTS

In brief, the method has been shown to work well in two experiments at Holyhead (where the mean tidal range is 3.6m) using both bubbler and digiquartz-in-the-sea systems. An internal POL report (Smith et al., 1991), from which the above sections were extracted, gives further details and has been circulated to members of the GLOSS Experts group and to a number of tide gauge authorities. Additional copies may be obtained from the PSMSL.

Since the 1991 Holyhead experiments, purpose built equipment based on the same principle has been constructed for the digiquartz-in-the-sea technique for use at South Atlantic sites where the mean range is typically 1 metre. The first set will be installed at Tristan da Cunha in October 1992. The tidal range at Tristan is of the order of only 0.6m and, if the equipment works there, it should work in most places. Other sets have been constructed for Ascension and St.Helena and these will be installed later in 1992 or early 1993. Some of the 'A Class' bubblers around the UK will also be modified along these lines. POL would be interested in working with any group which might be interested in jointly developing this technique.

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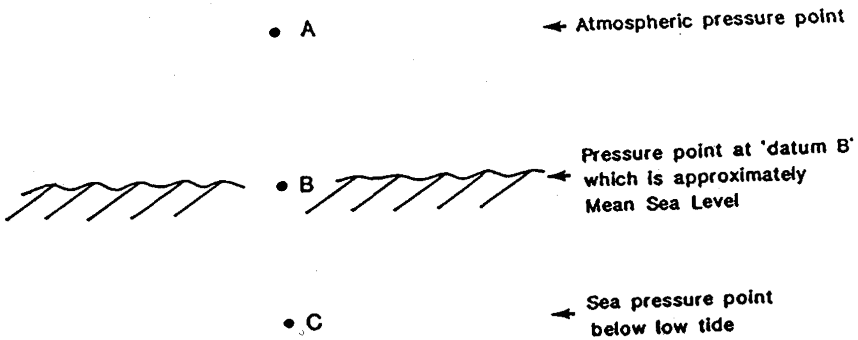
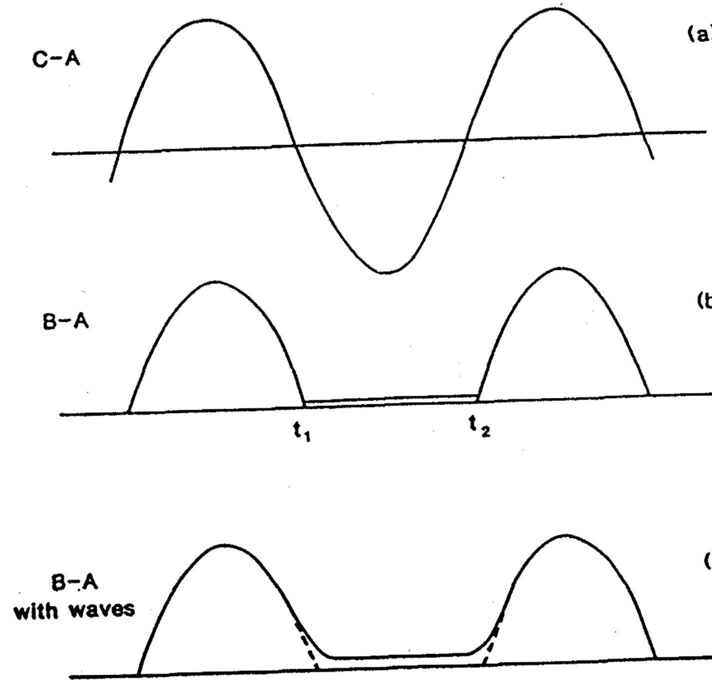
FIGURE CAPTIONS

Figure 1. Schematic illustration of a pressure gauge setup containing three pressure transducers: an 'A gauge', which measures atmospheric pressure; a 'C gauge' which measures sea pressure; and a 'B gauge' placed at approximately mean sea level.

Figure 2. Schematic illustrations of (a) the tidal curve produced from the C-A pressure time series; (b) the ideal B-A time series showing inflexion points 't1' and 't2'; (c) the B-A time series possibly distorted by the presence of waves.


A
Atmospheric pressure point
B
Pressure point at 'datum B' which is approximately Mean Sea Level
C
Sea pressure point below low tide


C–A
(a)
B–A
(b)
t1
t2
B–A with waves
(c)

ACCURACY OF SHALLOW PRESSURE GAUGES

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1. INTRODUCTION

That sea level be related with climate is evident, considering that the heat capacity of the upper 3 metres of the ocean is equivalent to that of the entire atmosphere. Actual climatic programmes observe sea level variations because sea level will have to provide much of the necessary empirical guidance to understand the importance of the heat storage transfer and variability in the oceans on basin-wide scales and for periods from several days to years. However, sea level alone is not sufficient and questions remain about the rate of energy leakage through the thermocline down into the deep ocean. Models with some degree of realism indicate that the description of sea level variability requires more than a single baroclinic mode (McCreary, 1981;1984). We expect that satellite altimetry missions coupled with tide gauges and surface to bottom density structure observations will play a key role in the present and future field programs.

Because classical tide gauges are difficult to maintain, particularly in remote areas, pressure recorders are now widely used. ORSTOM (Paris, France) has deployed eleven shallow pressure tide gauges from October 1982 through November 1984 (Verstraete, 1988). All our pressure recorders were manufactured by the Aanderaa company. Each instrument package is equipped with a digiquartz crystal sensor manufactured by Paroscientific Inc.

Since November 1988, this array was reduced to five sites at Praia (Cabo Verde), Dakar (Sénégal), Lomé (Togo), Sao-Tomé island and Cayenne (French Guiana).These five sites were implemented with the Argos telemetry system in 1989-1991. Each site is visited nearly every two years. At each recovery-redeploying operation, a diver put the new apparatus in its cradle exactly at the same level as the previous one (about 10m-deep).

2. COMPARISON BETWEEN DEEP AND SHALLOW PRESSURE RECORDS

A direct comparison between a shallow pressure record at Sao-Tomé island and a deep-pressure record 65 km apart, show a close agreement of the tidal signals (1,2 cpd) but low coherence over the whole spectrum 0-0.7 cpd. There is evidence of a strong baroclinic signal at subtidal frequencies in the near surface pressure record whereas the deep pressure record is practically unaffected (Cartwright et al., 1987). One concludes that at the seasonal and intraseasonal time scales, bottom deep pressure records alone are not a reliable measure of low-frequency sea level variations.

On the contrary, shallow (about 10m-deep) pressure records are able to give a reasonable measure of variations in sea surface elevation from bottom-mounted instruments. This is because the seasonal variations in sea level are essentially steric variations in the upper layers where strong currents advect warmer or colder waters.

3. THE SUBSURFACE PRESSURE AND THE BOTTOM PRESSURE

In an ocean at rest, the bottom pressure p_{-h} at depth $z = -h$ below the mean sea surface obeys the hydrostatic balance

$$p_{-h} = p_o + \int_{-h}^{o} \rho g dz + \rho_o g \zeta \qquad (1)$$

where ζ is the free ocean surface elevation above z=0, ρ_0 is sea surface density, $\rho(z)$ is sea density at depth z and p_0 the sea surface atmospheric pressure; g is the acceleration of gravity (exact standard value: g = 9.80665 m s^{-2}). This equation ignores vertical acceleration.

When the ocean is perturbed, the equation (1) is the hydrostatic approximation and the relation between the pressure just below the (detided) mean sea surface $\rho_0\ g\ \zeta$ and the bottom pressure at z = -h depends on the time and space scales of the forcing at the sea surface (wind stress, atmospheric pressure, heat gain...), the density structure within the water column, and the thickness of the water column.

We define the subsurface pressure at a fixed point as

$$SSP = p_o + \rho_o g \zeta \qquad (2)$$

The subsurface pressure is a useful index whose interpretation is quite distinct from that of its two components p_0 and ζ

For a homogeneous ocean , $\rho(z) = \rho_0$ and

$$p_{-h} = \rho_o g h + SSP \qquad (3)$$

In a single-layer ocean, the subsurface $\rho_0\ g\Delta\zeta$ and bottom pressure fluctuations p'_{-h} should be the same. This is nearly the case for the barotropic response of a stratified ocean. For barotropic waves, the ratio of SSP to bottom pressure is given by

$$SSP/p_{-h} = \cos(Nh/C) \qquad (4)$$

where N is a constant Vaisala frequency, h the depth of the ocean and C is the phase speed of a free progressive wave in a non rotating ocean. For barotropic waves, $Nh/C \ll 1$ and subsurface and bottom pressures are nearly the same.

4. SUBSURFACE PRESSURE IN A BAROCLINIC OCEAN

The relationship between bottom pressure and near surface pressure perturbations varies greatly according to the internal wave structure. Due to internal waves, there are perturbations in density $\rho'(z)$, pressure $p'(z)$ and vertical velocity $w(z)$ at depth -z below the mean sea surface z=0.

The relation between sea surface height and bottom pressure is not simple. In the simplified case of a fluid of uniform depth h with uniform density stratification $\rho(z)$, bottom and surface pressure perturbations are of very nearly the same amplitude, but out of phase for odd baroclinic modes and in phase for even-order modes. The changes in signs with mode number follow from the general property that a mode has n turning points in the vertical. As the interest is in the time varying part of p_{-h}, we consider usually the quantities p_{-h}, p_o, ρ and ζ in (1) as deviations from their time average. We define z=0 as the sea surface which makes the time average $< \zeta >$ equal to zero.

The rearrangement of (1) yields the free ocean surface ζ:

$$\zeta = \zeta_b + \zeta_a + \zeta_s \tag{5}$$

where $\zeta_b = p_{-h}/\rho_o g$, $\zeta_a = -p_o/\rho_o g$, $\zeta_s = -1/\rho_o \int_{-h}^{o} \rho dz$

In a homogeneous ocean, the steric term ζ_s reduces to -h , a constant.

In the general case of a multilayered ocean or a continuously stratified ocean, the free ocean surface is the sum of three terms:

ζ_b represents the barotropic response to changes in the wind stress field; this term is proportional to the change in bottom pressure. A variable eastward (westward) wind stress generates a meridional component of barotropic flow (Phillips,1966). The seafloor pressure spectrum is proportional to the wind stress spectrum. Numerically, the rms pressures (Hpa) are roughly equal to rms wind stress (dyne cm^{-2}).

ζ_a is called the surface elevation of an inverse barometer since it is equal to the depression that would be registered by a water barometer (about 1cm of water per hectoPascal (mbar) of pressure change). Such adjustment do not affect the pressure on the sea floor because the total weight per unit area of the column of air and water remains unchanged.

ζ_s is the steric sea level change caused by changes in density within the water column. These changes are due to horizontal advection, downwelling-upwelling, baroclinic waves, migration of fronts, eddies,... In a real stratified ocean, the amplitude of sea surface elevation is much greater than the variation in bottom pressure, particularly for the first baroclinic modes. Slow steric variations in the water column produce negligible signals in the seabed deep pressure records. This is because the total weight of the water column does not change. The thermal expansion from seasonal warming-cooling would not be associated with any change in the mass per unit area or resulting bottom pressure. Suppose a 4 km-deep water column. A 1°C increase of the sea temperature induces a decrease of density, an expansion of the sea water and a rise in sea level of about 0.6m. But the bottom pressure does not change.

On the contrary, shallow recorders detect any steric variation in the ocean water column. The contraction or expansion of a km-deep water column changes the weight of a 10m-deep water column because the change Δh is not compensated by the change in density within the 10m-deep layer. Steric variations produce clear signals in the SSP and subsurface pressure is a good approximation of the free ocean surface.

Therefore, observing the changes of the free ocean surface ζ necessitate not only bottom pressure observations but also **barometric sea surface pressure, sea surface winds and water density structure observations.** The observed bottom pressure is the absolute pressure (sum of atmospheric pressure and the weight of water column per unit area). In areas where the barometric pressure variations are small (Verstraete,1992), it is possible to compute the sea level as the difference of bottom pressure and a standard atmosphere ($P_0 = p_{0standard}$= 101 325 Pa), as far as the density of the water column is known.

$$\zeta = (p_{-h} - P_o) / \rho_o g + \zeta_s \tag{6}$$

where p_{-h} = 2 bar and P_0 equals nearly 1bar, 1 bar = 10^5 Pa. At the Atlantic stations, the difference between the absolute observed pressure p_{-h} and one standard atmosphere is therefore always close of one bar. The knowledge of the density structure is essential in hectometre-deep water columns, whereas it is possible to suppose that a 10m-deep water column is homogeneous. In the equatorial Atlantic, I have checked that the differences in density at z=0 and at z=10m over about 1100 hydrographic profiles are generally so small that this hypothesis is justified (Verstraete, 1988).

5. THE INVERTED BAROMETER PROBLEM

Changes in atmospheric pressure produce in the ocean depth-independent horizontal pressure gradients and, in an ocean of constant depth, depth-independent (barotropic) currents. Suppose now that an atmospheric disturbance ΔP_A propagates at speed C_A over a non-rotating ocean of constant depth D and density ρ. The resulting sea-level disturbance is

$$\Delta\zeta_a = - \Delta P_A / \rho g \, (1 - C_A^2 / gD) \tag{7}$$

The barometric factor is defined by the ratio $\Delta\zeta_a / -\Delta P_A$. The negative sign expresses the inverted barometer response, now enhanced by the factor $(1- C_A^2 / gD)^{-1}$. The term C_A^2 / gD is the square of the ratio between the speed of the disturbance C_A and the speed of a free progressive long wave C^2=gD. For long waves, the pressure perturbation is barotropic and in this case, the hydrostatic approximation (1) and the long-wave approximation are equivalent.

If $C=C_A$, there is a resonance and the dynamic sea level response is much larger than the static response, (the so-called inverted barometer response: -1cm in sea level / +1hPa increase in barometric pressure). In this approximation, changes in atmospheric pressure are compensated by equivalent sea level changes, so as to leave unchanged variations in bottom pressure. This is the static response of the ocean.

In a rotating ocean, where the Rossby radius of deformation of mode n is $\lambda_n = c_n/f$ (c_n is the phase speed of the baroclinic mode n and f the Coriolis parameter), free baroclinic planetary waves occur at very low frequencies, propagating eastward or westward. The **barometric factor** $\Delta\zeta_a / -\Delta P_A$ depends upon the ratio of the scale of the atmospheric perturbation over the Rossby radius of deformation. For large-scale atmospheric disturbances, $\Delta\zeta \to 0$ and the atmospheric pressure is geostrophically balanced. In the low-frequency limit, the sea level responds as an inverted barometer. If the atmospheric perturbations were propagating at the same speed as the phase velocity of free baroclinic Rossby waves, sea level would be in resonance. However, the phase speed of baroclinic Rossby waves is generally so slow in comparison with the speed of atmospheric disturbances that resonance is very unlikely.

In summary, as far as we are interested in seasonal or intraseasonal time scales, the inverted barometer approximation applies and we expect that $\Delta\zeta_a / -\Delta P_A$ be within a few percent of unity.

6. ABSOLUTE AND RELATIVE UNCERTAINTY

The sensitive element of the absolute pressure tide-gauges used in the equatorial Atlantic is a quartz crystal beam whose resonant frequency changes with applied axial force. The concept and design of this device was developed by Jerome Paros (1976) for flight applications. Paroscientific Digital quartz Pressure transducers utilize the inherent stability and precision characteristics of quartz resonators. Applied pressure is converted to a measurable force by means of bellows, lever and adjustable masses.

This force acts on the quartz beam, inducing a controlled, repeatable and stable change in the resonator's natural frequency which is measured as the transducer output. The quartz crystal resonator operates in an ultra-high vacuum in order to eliminate air damping and air molecular mass loading effects. This also eliminates effects due to temperature, pressure and humidity. With the beam vibrating in the vacuum, extremely high resonance is obtained on which the oscillator locks (mechanical Q of the quartz beam is in the order of 40 000). The output of the digital pressure transducer is a frequency which varies from its natural frequency (f_o = 40 kHz) at zero absolute pressure to some lower frequency (f_{min} = 36 kHz) at full scale pressure. The non-linearity of the beam frequency output signal with load is about 6%, which can be reduced to negligible levels by curve fitting methods. Calibration coefficients are fitted through the transducer output at pressures across the full scale range. The pressure model error is only a very small percentage of the full scale. For example, for a 15 psia pressure transducer, the error is at most .002% of the full scale. In the equatorial Atlantic, we use 100 psia pressure transducers. According to the Paroscientific specifications, the accuracy of the 100psia transducers is ± 0.01% of the full scale or 0.7 Hpa (± 0.7cm). The resolution is 0.001% of full scale (0.7mm).

One very important aspect is the pressure transducer stability. In general, the long term stability depends on the crystal aging, mechanical relaxation of machining and manufacturing stresses, and stabilization of the internal vacuum. The integrity and stability of the internal vacuum are essential because release of absorbed gasses or microscopic leaks have effects on the vibrating quartz beam: Air mass and air damping reduce the vibrating frequency or increase the output period. Aging techniques as used by quartz crystal manufacturers indicate that long term stabilization is enhanced by continuous crystal operation.

The instruments record bottom pressure and bottom temperature at hourly intervals. To compute the density of the water column at each site, it was initially planned to use hourly in-situ temperatures and only the two salinity observations obtained at the laying and recovery of each mooring. However, it turned out that the salinity of the water column varied greatly during the duration of a mooring. It was recognised that these two salinity measurements could be strongly aliased and introduce large errors in density computations. It was therefore decided to use one fixed mean value for salinity for all the records (35psu). The density of the water column at each site is then computed at hourly intervals by using the hourly in-situ recorded temperatures and a fixed salinity.

The equation of state for sea water $\rho = \rho$ **(t, S, p)** gives the density as a function of temperature, salinity and pressure. The equation of state for the ocean was defined by a Joint Panel of UNESCO (1981) and found by experiment and fits on available measurements. The standard error is estimated to 3.5 parts per million for $0 < p < 1000$ bars, $0 < t < 40$°C, $0 < S < 42$psu (Gill, 1982). Since ρ is always close to 1000 kg m^{-3}, the absolute error is 0.0035 kg m^{-3}. When combining all types of interpolations for temperature, salinity and pressure the error is less than 0.03 kg m^{-3} for 98% of the ocean. We use the polynomial approximations to calculate ρ ($t_{in\text{-}situ}$, 35, 0) to the accuracy to which it is known. We compute the density ρ in kilogram per cubic meter in terms of the observed temperature t (in °C) , with a salinity fixed at 35 (in practical salinity units or psu) and at one standard atmosphere (p = 0). Errors in the measurements of temperature, and bottom pressure must be evaluated to know the absolute and relative uncertainty of the computed sea level.

From (5), the absolute uncertainty in sea surface elevation is

$$\Delta\zeta = \Delta\zeta_b + \Delta\zeta_a + \Delta\zeta_s \quad (8)$$

Because we do not observe the barometric pressure, it is impossible to give error estimates on the atmospheric component of the sea surface height.

The relative importance of the steric term uncertainty $\Delta\zeta_s$ depends on the thickness of the water column. To evaluate the steric term , it is necessary to know the changes in density within the water column for any change in temperature and in salinity. At this point, it is necessary to introduce two coefficients :

the <u>thermal expansion coefficient</u> $\alpha = -\rho^{-1}(d\rho / dT)_{p,s}$ (in units of $10^{-7} K^{-1})$ and the <u>salinity expansion coefficient</u> $\beta = \rho^{-1}(d\rho / dS)_{p,T}$. (in units of psu^{-1}). The subscripts p, s, T denote that the partial derivatives are taken at constant pressure, constant entropy (or constant salinity for the case of sea water) and constant temperature. An error ΔT in temperature (ΔS in salinity) generates an error $\Delta\rho$ in density and an error Δh in sea level given by $\alpha h \Delta T$ ($\beta h \Delta S$).

<u>Temperature errors</u>

An error ΔT in temperature creates a relative uncertainty in the thickness h of a water column

$$\Delta h / h = \alpha \, \Delta T \tag{9}$$

which increases not only with the error, but also with the temperature and the pressure. The coefficient α nearly doubles from 10° to 31°C, or from 0 dbar to 4000 dbar. At 0dbar, an error of 1°K induces an error $\Delta h = \pm 1.7$ mm at 10°C and ± 3 mm at 25°C in the thickness estimate of a 10m-deep water column. According to the manufacturer, the accuracy in temperature is ± 0.1°C and the resolution is 0.04°C. An absolute error of 0.1°C over a 10m-deep water column at 25°C gives an error of ±0.3 mm.

<u>Salinity errors</u>

An error ΔS in salinity creates a relative uncertainty in the thickness h of a water column

$$\Delta h / h = \beta \, \Delta S \tag{10}$$

which is proportional to the error in S. The coefficient β is nearly constant for $2° < t < 31°C$. An error ΔS of 1 psu induces an error $\Delta h = \pm 7.4$ mm in the thickness estimate of a 10m-deep water column. According to the manufacturer, the sensibility in salinity in new tide gauges is 0.1psu (or 0.1 g/l). Suppose that the salinity is measured with an uncertainty of 0.1 psu, the error would be ± 0.7 mm.

<u>Pressure errors</u>

The full scale of the tide gauges in the equatorial Atlantic is 100psia, or nearly 7 bar and the accuracy is ± 0.01% of the full scale or 70 Pascals (0.7 Hpa which is 0.7 mbar or ± 0.7 cm). The resolution is 0.001% of full scale (0.7mm). The relative error Δp_{-h} in the bottom pressure estimate on the full scale is

$$\Delta p_{-h} / p_{-h} = 70 Pa / 7 \; 10^5 \; Pa = 10^{-4}$$

If $p_{-h} = 2$ bar or $2 \; 10^5$ Pa , the relative error is $3.5 \; 10^{-4}$

In the equatorial Atlantic, for tide-gauges with the above specifications, working in 10m of water at 15-25°C, the absolute uncertainty in sea level is estimated as the sum of the uncertainties due to temperature uncertainty (±0.3mm), salinity uncertainty (±0.7mm) and pressure uncertainty (±7 mm). All included, the absolute uncertainty is of about 8 mm. In a 100m-deep water column, the same <u>errors in density alone</u> would generate an error of nearly 10mm. Supposing that the gauges work with the same accuracy, it is clear that in hm-deep water columns, the main source of error raises from the uncertainties in the density structure within the water column.

All these results suppose that the calibrations of the gauges are done properly. In this hypothesis and on the basis of our in-situ observations, the absolute accuracy of the sea surface height computed from the shallow pressure gauge observations in the equatorial Atlantic ocean is estimated as

$$\text{Absolute accuracy} = | \text{Estimated value} - \text{Real value} | < 1 \text{ cm}.$$

For long-term or permanent observing system, this accuracy is attainable as far as the transducer outputs are checked across their full scale ranges in pressure, temperature and salinity and their calibration coefficients checked accordingly. In other words, permanent observations require routine calibrations of transducers, before and after each deployment at sea. The repeatability of the pressure observations must be checked particularly on aging quartz, because leakage in the ultra-vacuum chamber where operates the crystal beam will reduce its frequencies systematically or progressively. In the first case, all the pressures will be systematically overestimated; in the second case, an artificial positive trend will appear in the pressure time series.

Concerning the barometric term, corrective terms due to barometric pressure changes must be added to bottom pressure data, particularly in high latitude areas. In the equatorial Atlantic ocean, the amplitude of the seasonal variation in barometric pressure is small (about 2hPa) and the inverted barometer approximation applies at these time scales.

Deep pressure gauges being blind to steric variations, it is necessary to observe simultaneously the density structure in order to get reasonable estimates of the steric term in sea level, probably the most significant term in climate related programmes. **Although shallow pressure gauges are able to record the baroclinic signals as classical tide gauges, the observation of the density structure is necessary as well, in order to be able to relate the baroclinic structure to the sea level observations.**

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DEVELOPMENT OF A MULTI-YEAR BOTTOM PRESSURE RECORDER

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1. INTRODUCTION

Part of the POL Technology Development Project is MYRTLE (Multi Year Return Tidal Level Equipment). This is a deep ocean, self-contained sea level instrument for long-term deployment on the sea bed. It contains several releasable, buoyant data capsules which are used to recover the data thereby meeting the demands for obtaining the data in a reasonable time scale.

Measurements of pressure, temperature and some housekeeping parameters are stored, software processed and transferred to the releasable capsules for recovery by surface ship. A possible scenario would be to deploy the instrument for four or five years and recover the data each year on command from the surface vessel. Under development is a system to transmit the data contained in each capsule by satellite link at preprogrammed time intervals. The capsules would then be disposable, and the data recovered without the need for a ship recovery. This has a great advantage for operation in remote areas where access by ship is often difficult for logistic reasons. At the conclusion of the deployment the complete instrument can be recovered complete with central logging system and all the data.

2. BACKGROUND

POL has for many years used Bottom Pressure Recorders (BPR) for the measurement of oceanic tides (Cartwright et al 1988) and low frequency sea level variations (Cartwright et al 1987). During this time there has been a continuous assessment of the performance of the instruments. The design and operational duration of BPR's has improved but one of the main objectives has been to increase the accuracy of the pressure measurements.

It is known (Filloux 1980) that the major problem with pressure sensors is instrumental drift caused by operating the sensors at a large hydrostatic pressure (Figure 1). Other effects such as temperature sensitivity or instability in the clocks can be corrected or improved. It was shown (Spencer et al 1985) that the drift diminished with time after deployment but that each deployment incurred a similar magnitude of initial drift. There is some advantage therefore in keeping the pressure sensor at the same water depth for long periods. MYRTLE attempts to achieve this through long deployment periods and therefore minimises any change in the datum of the measurements.

At the present time POL is involved in 'climate' programmes such as WOCE (World Ocean Circulation Programme) through its ACCLAIM (Antarctic Circumpolar Current Levels from Altimetry and Island Measurements) project. This requires the operation of BPR's in the Southern Ocean for periods of 5 to 10 years to measure pressure gradients across the ACC. Yearly retrieval of the instruments places heavy logistic constraints on the programme and a longer deployment interval would be advantageous. However the primary reason for long operation at a fixed depth is to minimise instrumental drift which contaminates low frequency oceanographic signals.

3. DESCRIPTION OF INSTRUMENT

3.1 Mechanical Detail

Figure 2 shows a schematic of the instrument. Its dimensions are approximately 1.6 meters diameter and 1.8 meters high. It locates on a disposable steel ballast frame which is jettisoned for final recovery and is connected by a twin action titanium release assembly. The complete system free falls from the sea surface on deployment from a ship.

The main data logger, electronics and power supplies are housed in an aluminium tube. At the top are four separately releasable data capsules housed in what looks like an egg cup. When the capsules are released a transponder is activated to enable its ascent to be tracked and a recovery strop is payed out from the "cup". Each capsule carries a radio beacon and flashing light to aid recovery.

Data is transferred from the main logger to the capsules by an infra-red optical link operating through its protective glass sphere. Each capsule has the capacity to store all four years of data thereby ensuring that the data can be recovered if one or more of the capsules is lost. This is also true of the main logging system. For security each capsule is capable of being released from two independent release systems, as is the main frame.

3.2 Instrument Electronics

Sea pressure and temperature signals are recorded in the central logger on magnetic tape. A pack of lithium batteries provides sufficient power for operation up to five years. One of the main improvements has been the integration of a microprocessor into the system to control many of the functions. This is generally in a quiescent state and is 'woken-up' shortly before the main logger is due to record data. This data is also placed in the microprocessor memory and translated into ASCII characters which together with a 'time-tag' is sent to all four data capsules. Immediately after transfer the microcomputer returns to its quiescent state to conserve power. In this manner the microcomputer is only powered up for approximately four seconds each hour, a considerable saving in power.

Because it is not possible to have any electrical connections from the main logger to the releasable capsules the data is sent by infra-red optical link. Each capsule has an infra-red receiver that decodes the data and passes it to a solid-state logging system which then stores it in EPROM (Erasable Programmable Read Only Memory) of 2 Megabyte capacity. Low power operation is critical inside the data capsules and current consumption must be at least a factor of 10 below that of the central logger. This is achieved by having only the infra-red receiver operating continuously and by activating and de-activating the solid-state logger as required. The complication is alerting the data capsules that data is about to be transferred. Time has to be allowed for the power supplies to stabilise before logging can commence.

The microcomputer in the main logging system, is used for this function. The wake-up is achieved with a pulse-length detector on the receiver circuit. If a short pulse-length character is detected the data capsule power supplies are turned on and the capsule will stay active for a predetermined length of time (2 seconds). Longer pulse-length characters are ignored and the capsules will not power-up. The different pulse lengths are generated by changing the baud rate on the serial port of the microcomputer. A character baud rate of 2400 or greater will power-up the data capsules and a baud rate of 1200 or less will be ignored. Once the capsule has powered-up the data is transferred at the lower data rate of 1200 baud. This allows time for the EPROM's to be programmed reliably.

4. TEST DEPLOYMENT

The ship recoverable system was test deployed in a flooded quarry at Stoney Cove, Leicestershire, on the 1st October 1991. The aims of the test were as follows:-

1. To weigh in air and water all the component parts to check the buoyancy.

2. To deploy the system in water with the data being transferred to the podules via the infra-red sensor interface.

3. To tilt the main assembly on the quarry bottom then, with the aid of divers, check that the podules released from the main frame without fouling.

4. To release the complete instrument from its ballast weight and determine whether the surface recovery strop uncoiled correctly.

5. Check the attitude of the data podule during ascent and on the surface.

The above tests were completed successfully and all the objectives were achieved. A photographic record was kept of the various mauoeuvers as it is normally impossible to observe how the instrument behaves when used in fieldwork. It is now intended to use MYRTLE in the Southern Ocean and obtain data from the Drake Passage over a suitably long deployment. Development work on a satellite telemetry link is still progressing.

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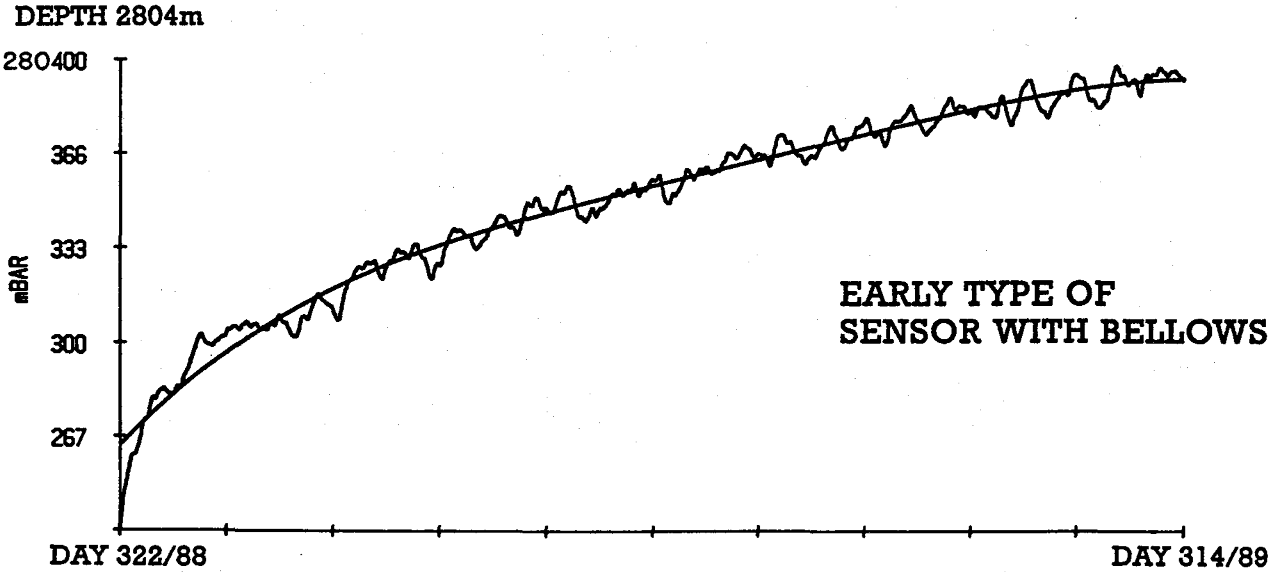
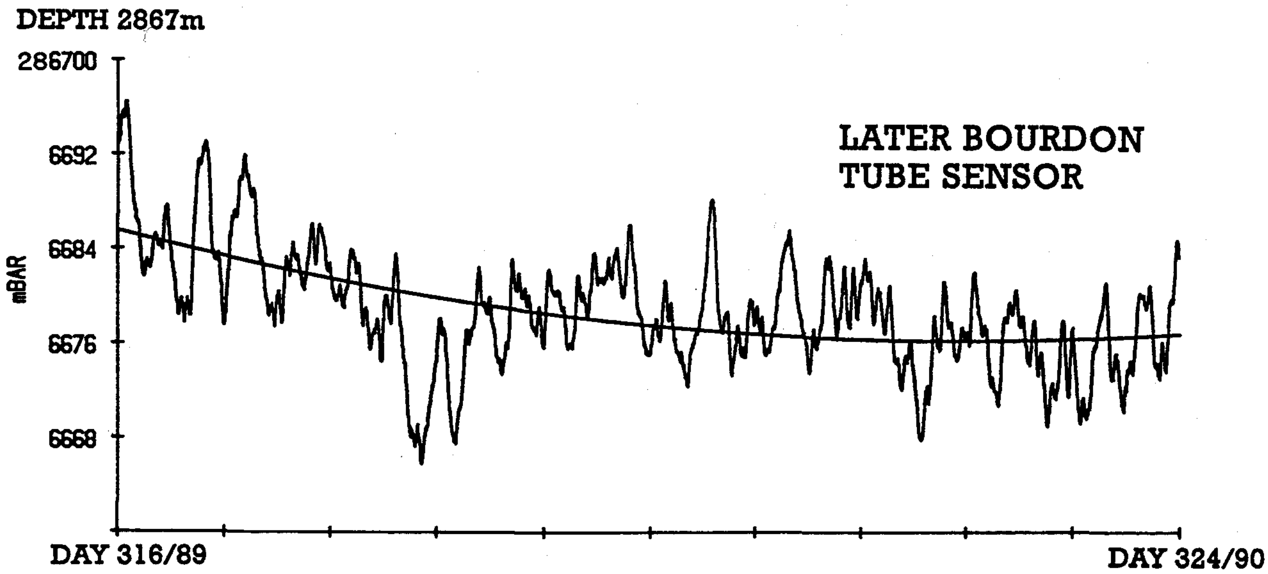
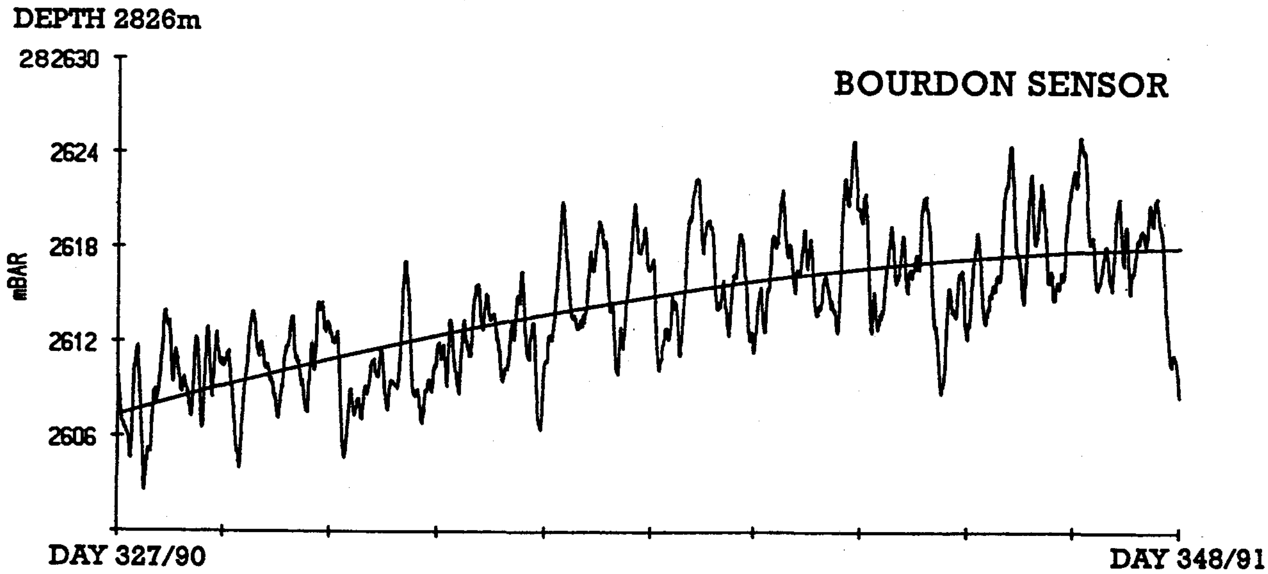
FIGURE CAPTIONS

Figure 1. Instrumental drift from high pressure sensors.

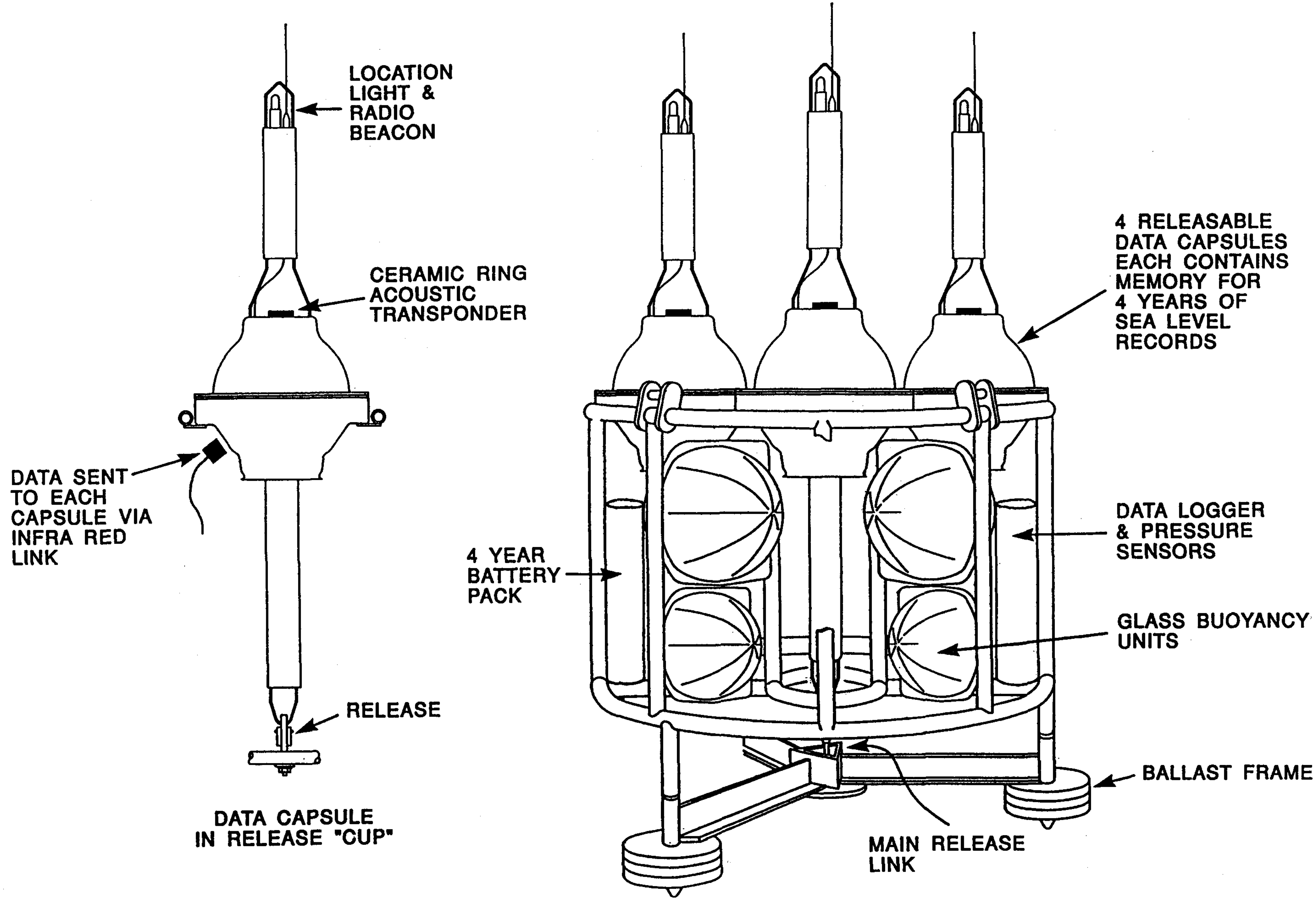
Figure 2. Schematic diagram of MYRTLE.







Pressure Signals from DIGIQUARTZ SENSORS with Tidal Signal Removed
ACCLAIM Site A in the Scotia Sea: Lat 53° 32' S , Lon 57° 00' W
All 3 records show the drift is initially large and reduces with time



"MYRTLE" - MULTI YEAR RETURN TIDE LEVEL EQUIPMENT

GPS MEASUREMENTS FROM MOORED BUOYS

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1. GENERAL

Early 1989 IAPG proposed ESA/ESRIN to use observations of the Global Positioning System (GPS) in floating buoys for the calibration of the ERS-1 radar altimeter. Since at that time all funds for the CAL/VAL budget were gone, the German Space Agency (DARA: Deutsche Agentur für Raumfahrtangelegenheiten GmbH) took up this proposal and realized it as a national project. The following is a brief summary of the first results.

1.1 Principle

The technique GPS in buoys uses the carrier phase observations of the NAVSTAR Global Positioning System to determine relative three-dimensional positions of moving sensors with centimeter accuracy. This was verified for the positioning of an airborne photogrammetric camera at the time of exposure and the precise positioning of measuring devices on survey ships, hovercrafts, aircrafts, etc. (Hein et. al. 1989, 1990).

A buoy has to be equipped with a geodetic GPS receiver and an antenna on top of the mast. A second GPS receiver tracks in a static position on land. The analysis of the phase observations, done in differential mode, results in a 3d-positioning of the antenna relative to the position on land. The tie to an absolute geocentric ellipsoidal reference system (e.g. WGS84 / laser coordinate system) can be easily done measuring (in static mode) the baseline vector to a fixed laser station where geocentric coordinates with highest accuracy are available. The reduction of the moving antenna on top of the mast to the vertical can be achieved using observed angles of two tilt sensors installed in two horizontal components within the buoy. The vertical antenna height of the buoy over sea surface can be determined beforehand. Final products of such an observation scenario are the ellipsoidal coordinates of the instantaneous sea surface with a possible sampling interval of up to 0.5 sec and an accuracy in the centimeter range in an absolute reference system like WGS84 or ITRF89 (International Terrestrial Reference System 1989). It is obvious that when putting more buoys with GPS receivers at representative places in an ocean area, through further computations ...

(i) the instantaneous (and/or mean) sea surface of the covered area can be determined,

(ii) discrete as well as mean wave heights (with respect to time and location) can be derived through the corresponding differencing, and

(iii) the direction of ocean (tidal) currents in this area can be computed, since the buoys are forced to move in the corresponding direction (until they reach the end of the anchor chain).

1.2 Overall design

1.2.1 General Considerations

Before the measurements could start several reflections due to possible environmental influences had to be done. The used buoy is shown in Fig. 1. Buoyancy effects were estimated by computing the dip-in volume of the buoy and the possible forces which were acting at the buoy. For the buoy part that is in water an average volume V = 7.5 m^3 can be assumed.

The antenna heights over sea level of the buoys in exact vertical position were determined in the harbor area of Wittdün. The dip-in of the buoy and thus, the antenna height is dependent on the total mass, including the mass of the anchor chain hanging from the buoy to sea floor. Therefore the length was estimated beforehand (dependent on the sea floor depth and the curve of the chain) and it was calculated that a different length of 3.00 m is necessary to change the dip-in depth by 1 cm.

At the buoy location water masses move with a velocity of 1 to 2 m/s. Because of that mass transport the buoys are forced to move in the direction of the current, but at the end of the anchor chain they are pulled down. We estimated that a current of 1.5 m/s speed produces a downward drag of 3.4 cm. This change of the dip-in depth was taken into account as a bias.

Effects due to the difference in salinity between the harbor area where the before mentioned dip-in depth determination was carried out, and the buoy location were negligible.

There is a bottle filled with liquid gas to fire a signal light on each buoy. The gas content decreases with time and thus, the total mass of the buoy changes. This causes a change in the dip-in of the buoy. But after three months the difference in mass was to small to produce any significant change.

1.2.2 Instrumentation

To obtain the instantaneous sea surface at a single point in the footprint of ERS-1 (diameter approx. 5 to 7 km in calm sea state) one single buoy would do the job. But for getting redundant measurements and for a proper averaging of the instantaneous sea surface over the footprint three buoys seemed to be appropriate. The goal was to determine the instantaneous sea surface with an accuracy better than 5 cm. Therefore GPS differential positioning with carrier phases was absolutely necessary. The requirements for the observations using GPS receivers (three floating and one static reference station) were the following:

- The distance between buoys and reference station was about 15 km. At such a distance the ionospheric impact on GPS measurements is still small or even negligible during night, so that single-frequency receivers can be used. However, in order to be on the safe side we used on one buoy and the reference station dual frequency GPS receivers. The other two buoys were equipped with single-frequency GPS receivers.

- For open water buoy positioning GPS observations with a sampling rate of 1 Hz were required. The used GPS receivers were two ASHTECH dual frequency receivers with twelve channels for L1 and L2 at the reference station and in one of the buoys. In the other two buoys there were MAGNAVOX 4200D card modules with six L1 channels where carrier phases and C/A code pseudoranges with 1 Hz could be observed.

- The high observation rate required a large memory which could be part of the receiver or of the logging device. As the buoys had to be operated unattended for more than 3 months, data logging systems used in the buoys and at the reference station consisted of core modules IBM compatible XT 256 KBytes and harddisks of 105 MBytes.

- Since the observations were taken in certain time windows, a timer for switching on and off according to the schedule of the ERS-1 overfly during the three-day repeat orbit was built in.

- Power consumption was provided by dry-fit batteries.

- The instrumentation had to stand the rough environment of the open sea. GPS electronic modules had no problems with that. Only the antennas had to be protected from corrosion. This was simply done using plastic hats.

- At sea the buoy was swinging from one side to the other. Therefore special devices had to measure the tilt in order to reduce the slant antenna height to the vertical. We modified SCHAEVITZ Accustar inclinometers, which are based on a cell filled with liquid and gas and a capacitive measuring principle. The electronics of the modified clinometers provide continuously (>100 Hz) an analogue tension to the parallel interface of the data logger, which is transformed to angles. The modified tilt sensors provide an accuracy of 0.1 degrees for single tilt measurements. Taking the slant antenna height of about 5 m and an angle of 30 degrees one gets the antenna reduction to the vertical with an accuracy better than 1 cm.

- It was important to establish a precise time tagging of the GPS observations and the tilt measurements. This could be realized by reading the angles from the parallel interface directly after obtaining the raw GPS data from the receiver interface. Thus the time delay to the referred GPS time was 56 msec (50 msec to store the position data string of GPS + 6 msec to get the angles of the tilt sensors) which could be neglected at tilt magnitudes less than 30 degrees. This was the case most of the time with the exception of stormy days.

1.3 Field Work

The IAPG buoy scenario took place in the North Sea, approximately 15 km west from the island of Sylt, near the Danish border (Fig. 2). The ascending ground track of ERS-1 was identical to the one used also for the Venice Tower experiment. Thus, it could be assumed that the orbit of the satellite was carefully determined using laser tracking from Middle-European laser sites. An array of three buoys was used for this calibration experiment covering the footprint of the altimeter, so that averaging over the area was possible. The reference station in List (north of the island of Sylt) equipped with a GPS receiver was carefully collocated to the fiducial stations Onsala, Hearstmonceux, Wettzell and Madrid in a GPS field campaign. Using orbit improvement with the TOPAS software precise geocentric three dimensional coordinates of the reference station could be computed.

After the instrumentation was installed in the buoys they were placed into the harbor area of Wittdün to determine in-situ the height of the antenna's phase center over sea level. On Sept. 5, 1991 the buoys were shipped to the calibration area in the North Sea, where they operated unattended for three months realizing GPS observations during 25 ERS-1 overflies.

1.4 Data Analysis and Results

The kinematic GPS observations were analyzed by the TOPAS software system (LANDAU 1988, 1990). This system is able to process any kind of kinematic or static data. It works for this pure-kinematic experiment without a static initialization period; a special technique is used to solve for the carrier phase ambiguities during movement ("carrier phase resolution on-the-fly"). Convergence tests of this algorithm are described by LANDAU (1990). Ambiguities were derived in our buoy experiment by applying this technique in a sequential procedure and they were redefined each time a cycle slip occurred in one of the satellites.

As an example of the total processed data set the results of the September 20, 1991 are given in Fig. 3. The total tilts of the buoys from the vertical show magnitudes of about 15 degrees in maximum and an average of 5 degrees. Thus, the corresponding reduction to the vertical was in the range of up to 30 cm considering all corrections mentioned before. Since the data were collected once per second we got the instantaneous sea surface height and the magnitude of the wave heights. Applying a low-pass filter it was possible to remove the wave effects in the data resulting in the instantaneous sea surface height that was compared to the radar altimeter measurement.

The radar altimeter derived sea surface height was obtained using the preliminary orbit that was processed by the German Geodetic Research Institute in Munich (DGFI). Adding altimeter bias, ocean tide and solid earth tide to the corrected sea surface height one gets the instantaneous sea surface height. There are two values for the altimeter bias on 09/20/91; the ESTEC bias with 3.58 m and the DGFI bias with 3.65 m. The instantaneous sea surface height derived by the radar altimeter measurement fits perfectly to the GPS observations.

In this volume only one example was outlined because of limited space. Due to the fact that ERS-1 radar altimeter and short arc orbit data at observed GPS days were provided to IAPG only quite recently, final analysis of other days is still going on.

1.5 Further Activities

Calibration of the TOPEX / POSEIDON Radar Altimeter

The same technique is used for the calibration of the radar altimeter of the French/American satellite TOPEX/POSEIDON in the Mediterranean Sea (near the islands of Lampedusa and Lampione located between Sicily and Tunesia). The launch was mid of 1992 and the commissioning phase will last until the end of 1992.

Proposal for the orbit improvement of the ERS-1 satellite

As the instrumentation works in such a practical and easy way there is the possibility to apply the same method to determine the radial orbit error of the satellite at single buoy positions by adding the radar altimeter signal to the instantaneous sea surface height derived by GPS in buoys. The main advantage would be to place the buoy at cross-over positions and to apply the GPS instantaneous sea surface height in the cross-over analysis.

The next and better step would be to place more buoys to certain position in an ocean area where a mean sea surface is processed using altimeter data. This altimeter-derived mean sea surface has four unknowns (one bias, two tilts and a torsion). Placing at least four buoys at well distributed cross-over positions it is possible to give the absolute orientation to the mean sea surface. The colinear method of radar altimetry provides a very accurate sea surface variability. Adding this to the absolute orientated mean sea surface one gets the improved instantaneous sea surface over the whole area. Next step is to add the radar altimeter signal to the instantaneous sea surface to get the improved radial orbit. The method proposed here is based on real measurements. All other approaches used up till now have to assume certain hypotheses in order to separate the different influences contained in the cross-over discrepancies.

ACKNOWLEDGEMENTS

This project is funded by the *Deutsche Agentur für Raumfahrtangelegenheiten (DARA), GmbH*, Bonn, Germany. We acknowledge the assistence of Wasser- und Schiffahrtsamt Cuxhaven for providing a buoy, placing it with their ship into the North Sea and carrying out with us various measurements in the harbour area in August 1990. During the ERS-1 altimeter calibration (Sept. to Dec. 1991) we were supported by the Wasser- und Schiffahrtsamt Tönning, in particular by the people at the Tonnenhof Wittdün on the island of Amrum.

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FIGURE CAPTIONS

Figure 1. Standard Buoy

Figure 2. Location of the IAPG Calibration Scenario

Figure 3. Results of Sept. 20, 1991

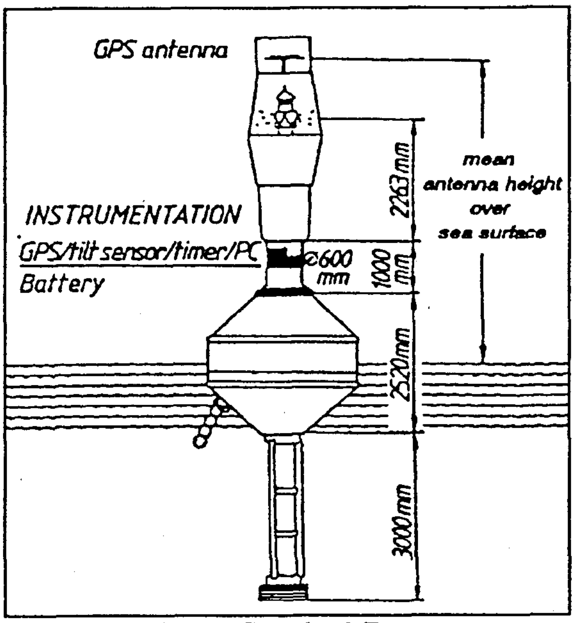

Fig. 1: Standard Buoy

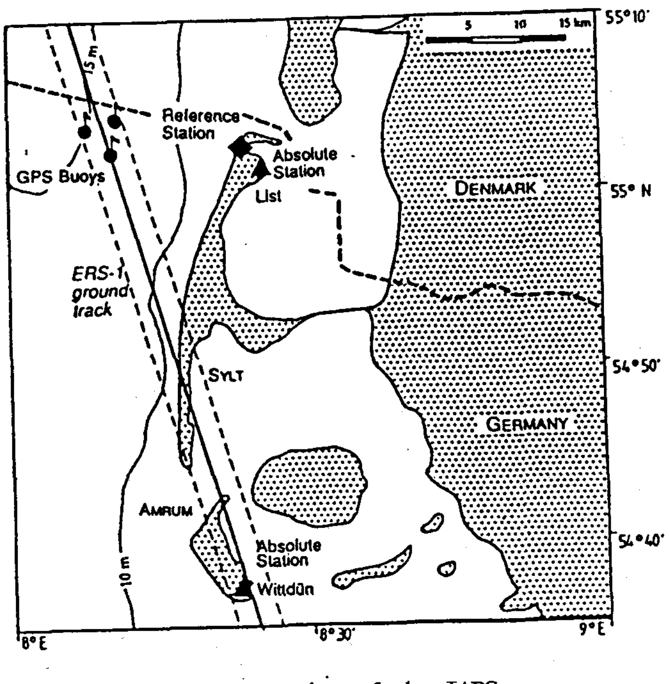

Fig. 2. Location of the IAPG
Calibration Scenario

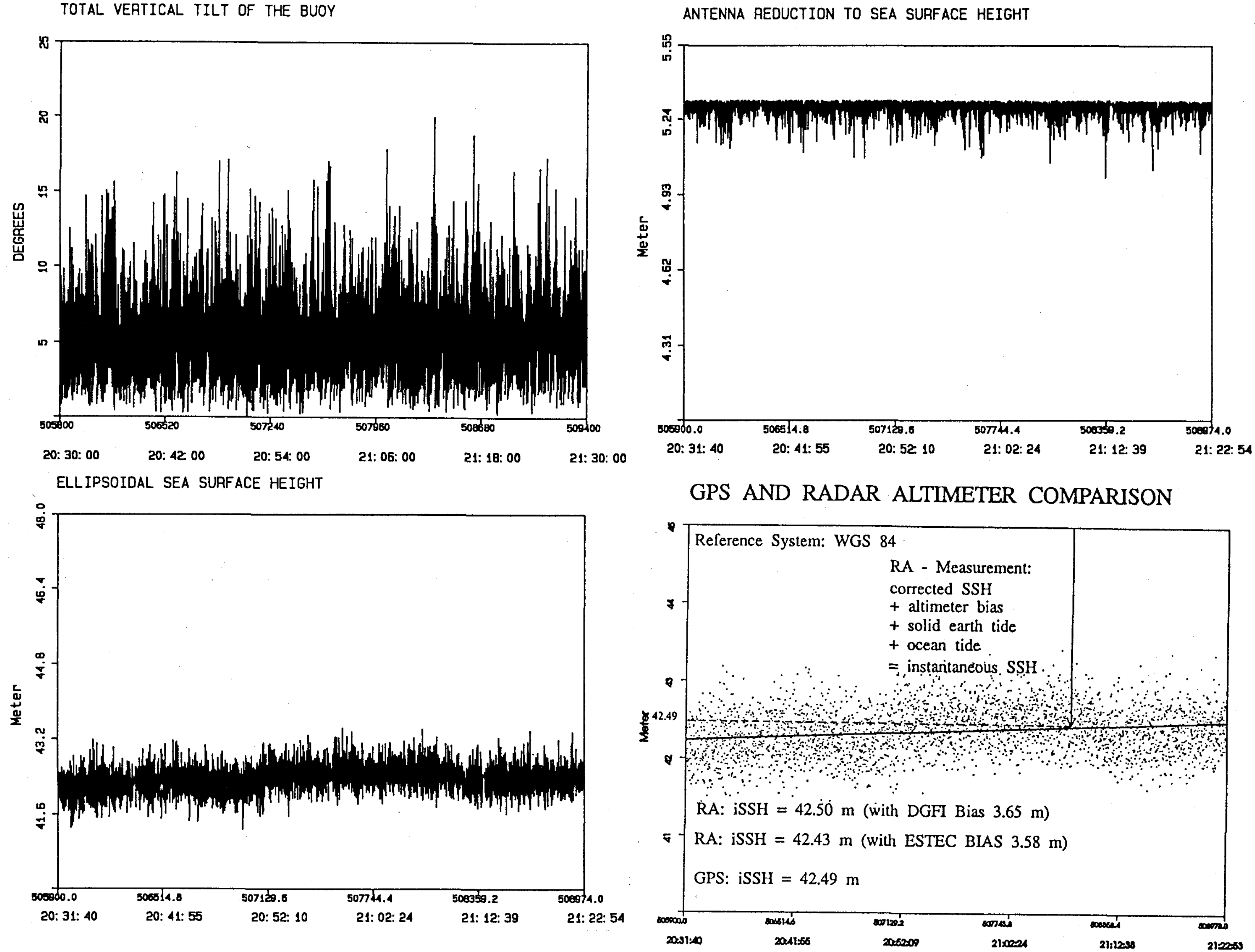

Fig. 3. Results of Sept. 20, 1991

THE RELATION BETWEEN ACOUSTIC TRAVEL TIME AND DYNAMIC HEIGHT ANOMALY OFF ABACO ISLAND, BAHAMAS

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ABSTRACT

Inverted Echo Sounders (IES's) measure the round-trip acoustic travel time from the IES to the sea surface. These relatively inexpensive ocean-bottom-mounted instruments have been proposed for (a) monitoring long term change at a specific site of a dynamical variable of interest (*e.g.* heat content, thermocline depth, dynamic height anomaly, *etc.*), (b) for open-sea calibrating of satellite altimeters, and (c) for studying the difference in sea level signals between a coastal tide gauge and that offshore. For the purpose of sea level variations, particularly at the centimetre level of accuracy, precise relations between the travel time and dynamic height anomaly must be obtained. The usual assumption is that there are constant linear regression coefficients between dynamic height anomaly and travel time. Based on 77 hydrocasts over the depth range 0-3000 db during 1984-1987 in the offing of Abaco Island, Bahamas, the regression coefficients between travel time and dynamic height have been found to vary systematically from month to month. If not accounted for, this can add $\pm$ 10 dynamic-centimeters of additional uncertainty when applying IES data to problems of sea level variability.

1. INTRODUCTION

It is clear from reports on climate change and possible anthropogenic effects on enhanced greenhouse warming (*e.g.* IPCC, 1990), that much of the research effort is limited by the quality and quantity of data available. This is particularly true in the ocean, where few time series are observed, in great part due to the cost of such data acquisition. Inverted Echo Sounder (IES) units are being used more and more frequently because of their relatively low cost and simplicity for many purposes in dynamical oceanography, but their effectiveness for long term monitoring has not been assessed. As we shall show, IES data have interesting calibration signal variability not reported in the literature (*cf.* Eden, 1990), and these lower frequency signals need to be explored. In addition, since we have selected the northeastern Bahamas for the initiation of this investigation, we can address other issues of interest to climate and global change, in particular the relationship between IES estimates of dynamic height anomaly, island sea level from a tide gauge, and volume transport.

Often times, an IES is coupled with a quartz pressure gauge (PG) and a thermometer. The combined IES/PG can then measure both the baroclinic and the barotropic components at a given site. Unfortunately all PG's have a long-term drift, and although they are valuable for determining the deep-sea gravitational tides, the combined IES/PG costs almost double that of the IES only (a typical cost for an IES is approximately $5,000; D.S. Bitterman, personal communication). In addition, since an IES measures time, there is an intrinsic stability (*i.e.* no standardization variation) in the measurement. For these pragmatic reasons, we will concentrate herein on the application of an IES (only) for several purposes in dynamical oceanography and marine geodesy.

2. BACKGROUND

Time series in deep water are quite rare, but the ones off Bermuda and Abaco are well known and have contributed greatly to our knowledge of the ocean (Schroeder and Stommel, 1969; WHOI & BBSR, 1988; Maul *et al.* in Eden, 1990). At monthly and lower frequencies the coherence squared between dynamic height anomaly at Station "S" and Bermuda sea level is typically 0.9 and higher (Roemmich, 1990), but there are interesting phase differences that are not readily explained. Similarly, Roemmich shows that the annual-averaged steric depth signal (0-2000 db) varies $\pm$ 10 dyn-cm year-to-year, but that this annualized signal is influenced by variations in different regions of the water column. We are unaware of any extensive investigation of the vertical acoustic travel time at Station S or of its relationship to the hydrographic causes.

We have studied acoustic travel time in the offing of Abaco Island, the Bahamas, where there has been monitoring of the Deep Western Boundary Current. Acoustic travel time (τ) and dynamic height anomaly (ΔD) respectively are calculated from the vertical distribution of temperature (t) and salinity (s) by

$$\tau = \int dz/C \quad \text{and} \quad \Delta D = \int \delta dp$$

where C(t,s,z) is the *in situ* speed of sound between the ocean bottom (z = Z) and the surface (z = 0), δ(t,s,p) is the anomaly of specific volume, and p is pressure. In consideration of the hydrostatic equation, $dp = \rho g dz$, the terms $C(t,s,p)^{-1}$ and $\delta(t,s,p)$ are assumed to be negatively related. The usual practice is to statistically correlate τ and ΔD and to suppose that the relation between them is fixed for a given locale.

3. RESULTS

Figure 1 is from the area east of Abaco Island (26.5°N, 76.0°W), based on 77 hydrocasts taken between 1984 and 1987. It shows the relationship between τ calculated from hydrocast (CTD) data and ΔD calculated from the same data over the depth range 0-3000 db. The ensemble (n = 77) linear correlation coefficient between τ and ΔD is r = −0.84, with the mean slope estimated to be −39.9 dynamic-meters/second; the intercept is 161.8. Contrary to our experience with $\tau/\Delta D$ data in the tropical eastern Pacific (Maul *et al.*, 1988) and off Cape Canaveral, Florida (Maul *et al.*, 1986), these data suggest that there are variable biases to the correlation.

We illustrate this $\tau/\Delta D$ variability further in Figure 2, which shows the regression coefficients (slope and intercept) from the linear correlation between τ and ΔD as a function of the month of the year. There does seem to be a regularity to the relationship, but it does not appear to be dominated by an annual signal. At first glance there seems to be a significant semiannual component to the correlations, but the spacing of the crests is not 6 months. We will investigate the statistical significance of these results in future work with the Abaco data, and will extend the study to include Bermuda.

Table 1 summarizes the calculations from which Figure 2 was plotted. Note that the linear correlation coefficients (r) for the ensemble of months during 1984-1987 are typically less than r = −0.9, and that for those months where it is greater than −0.9, the data are tightly grouped (*q.v.* Figure 1). At this time we are unable to rationalize the relations shown in Figures 1 and 2, but we are expanding our analysis to include the 1988-1992 data and are investigating the *t-s* properties of the water column for hints of the cause.

IES results off Abaco Island however, have shown significant correlation (r = 0.66) between acoustic travel time and north-south volume transport, as can be seen in Figure 3. The Abaco IES was located on the east end of a 50 km - wide oceanographic section that was instrumented with current meters; there also was a shallow-water PG on the island. Sea level from the PG at Abaco (not shown, but covering 684 days in 1986-1988) is statistically unrelated to τ in the sub-tidal to monthly frequency band (r = −0.11). Further, a multiple linear correlation between the IES, the PG, and volume transport did not include the PG data at 95% confidence. As with τ, these transports also lack a coherent annual and semiannual signal. The geophysical reasons as to why the IES and transport are related have not been elucidated, but we do know that data from the shallow water PG on Abaco Island 50 km to the west is largely unrelated to the IES values.

Contrarily, the Bermuda tide gauge data and the serial oceanographic data offshore are rather well related as noted above. Station S off Bermuda is closer to land (20 km away) and in a different hydrographic regime than the Abaco Island IES site, in particular the Deep Western Boundary Current is far to the west of Bermuda. But as Roemmich [1990] and others have shown, Station S is related to sea level on the island in a somewhat complex fashion, but the daily-to-monthly frequency coherences are not known. That brings us to one of the other interests we have *vis a vis* IES's and sea level on short time scales, namely the value of island tide gauges in satellite altimetry.

4. DISCUSSION

Satellite altimeters require verification information in order to maintain the centimetre accuracies needed for inclusion of their data in global monitoring of sea level (Stewart, *et al.*, 1986). Comparisons between island tide gauges and altimeters have been made (*e.g.* Wyrtki, 1987; Miller *et al.*, 1988), and the problem of how many tide gauges are required has been addressed by Wunsch (1986). Except to note that the signal in some island tide gauges and in offshore observations have significant dissimilarities at high frequency (Chiswell, *et al.*, 1988) but not at low frequencies (*cf.* Schroeder and Stommel, 1969; Roemmich, 1990), the question of how to transform the tide gauge record into the optimal altimeter comparison record is largely unanswered.

Based on the results shown in Figures 1 and 2, we began to question the role of an IES as a satellite altimeter verification instrument and as a means of monitoring climate change on interannual time scales in association with island tide gauges. Wimbush (in Eden, 1990) and E.J. Katz (personal communication) were unaware of the extent to which variability between τ and ΔD such as illustrated above showed up in the western Atlantic. For very precise work in marine geodesy and altimetry, the non-constant $\tau/\Delta D$ relationship we have calculated is an identifiable error source that can be taken into consideration.

However, there may be effects on the results reported herein due to using the 0-3000 db 1984-1987 CTD data to calculate τ and ΔD. First, CTD data have errors, into which we have not inquired; we do not expect these errors to be large however. Second, 3000 db is near, or slightly above, the velocity maximum of the Deep Western Boundary Current off Abaco, whereas our IES data are from 5000 db farther offshore. Third, the $n = 77$ ensemble of CTD's are from a 10° latitude by 10° longitude square off the Bahamas. Each of these factors could contribute to the variations in the $\tau/\Delta D$ relationship, and these are topics of future research.

With respect to the altimetry/tide-gauge/IES relationship, the problem definition could be accomplished by (a) locating an IES at an altimeter sea surface height (SSH) crossover site near an island tide gauge and making simultaneous observations, (b) constructing a time series of SSH at the crossover site, (c) determining whether a constant frequency response function H(f,x) exists in a conceptual model such as

$$S(f,x) = H(f,x)I(f) + \epsilon(f,x)$$

where the complex quantity S(f,x) is the frequency (f) partitioned SSH or IES response at distance (x) from the island tide gauge with input I(f) and residual error $\varepsilon(f,x)$, and (d) studying how the transform of S(f,x) is affected by a varying altimeter footprint or sea state, respectively, and distance. Another calculation should use S(f) for the altimeter and I(f) for the IES, with the frequency response function H(f) and error $\varepsilon(f)$ determined between them.

Observations of the ocean from aircraft and spacecraft have revealed that many islands have complicated circulation patterns (*e.g.* Gordon and Hughes, 1981; Pattiaratchi *et al.*, 1987): vortex streets in the downstream direction have been observed in LANDSAT data (Maul, 1977), and shadowing of surface waves from winds show up as calmer areas downwind (Cram and Hanson, 1974); upwelling and frontal activity is observed in colour imagery (Wolanski and Hamner, 1988); SAR images show complicated eddies on the 5-25 km scale in channels between islands (Fu and Holt, 1982); AVHRR images often show hints of circumferential flow around some islands which is somewhat substantiated by observations (Hogg, 1972). These observations, coupled with the fact that an island tide gauge situated in a harbour will be affected by local winds and runoff, suggest that using a tide gauge to calibrate an altimeter or to correlate with a deep-water IES is not a trivial problem.

5. CONCLUSIONS

We have shown that the relationship between the acoustic travel time calculated for an inverted echo sounder and the dynamic height anomaly over the depth range 0-3000 db east of Abaco Island varies systematically, perhaps seasonally. For the very precise work associated with calibrating a satellite altimeter or measuring long term change at a particular oceanic site, this imposes an additional error of $\pm$ 10 dynamic-centimeters. The problem of using island tide gauges to infer altimeter sea surface height for instantaneous comparisons is seen to be fraught with uncertainties, and is largely unexplored. Similarly the role of vertical acoustic site measurements to study interannual and lower frequency changes has not been critically evaluated, but locations where there are serial oceanographic stations (such as off Bermuda and Hawaii) are candidates for such investigations. We argue for a program to initiate such studies, particularly juxtaposed to tide gauges at which vertical motion can be measured by space-based geodetic techniques.

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FIGURE CAPTIONS

Figure 1. Relationship between dynamic height anomaly and acoustic travel time calculated from CTD data collected east of Abaco Island, the Bahamas. The numbers represent the month (1 = January, *etc.*) in which the CTD data were obtained for all years from 1984-1987. Note that the winter months lay near the lower portion of the ensemble, and summer along the upper portion. For 1986 for example, the slope of the regression line between dynamic height and travel time in March is −35.1 dyn-m/sec, and in October it is −47.4 dyn-m/sec.

Figure 2. Temporal variability of the slope (*) and intercept (+) in the linear correlation between acoustic travel time (τ) and dynamic height anomaly (ΔD) off Abaco Island. Although the values of slope and intercept change significantly with the time of year, the $\tau/\Delta D$ error introduced is of the order of $\pm$ 10 dyn-cm because the linear parameters co-vary.

Figure 3. Relation between volume transport in the oceanographic section from Abaco Island to a point about 50 km offshore from moored current meter data (solid line), and dynamic height anomaly from acoustic travel time (dots). The dynamic heights are least squares fitted to the volume transports for display purposes and are scaled to sverdrups (1 Sv = 1 gigaliter/sec = 1 x 10^6 m^3s^{-1}).

Table 1

Summary Statistics of Linear Regression between Dynamic Height Anomaly calculated from Vertical Acoustic Travel Time off Abaco Island, Bahamas for 1984-1987

Month	Number of Samples	Slope (dyn-m/s)	Intercept	r
1	5	−24.9	101.7	−0.99
2	5	−21.0	86.4	−0.76
3	18	−32.7	132.8	−0.91
4	12	−37.7	152.8	−0.93
5	3	−41.6	168.7	−0.99
6	0			
7	6	−36.0	146.1	−0.97
8	6	−32.4	132.0	−0.98
9	8	−26.8	109.5	−0.83
10	8	−43.1	174.4	−0.96
11	6	−36.5	148.0	−0.91
12	0			
ALL	77	−39.9	161.6	−0.84

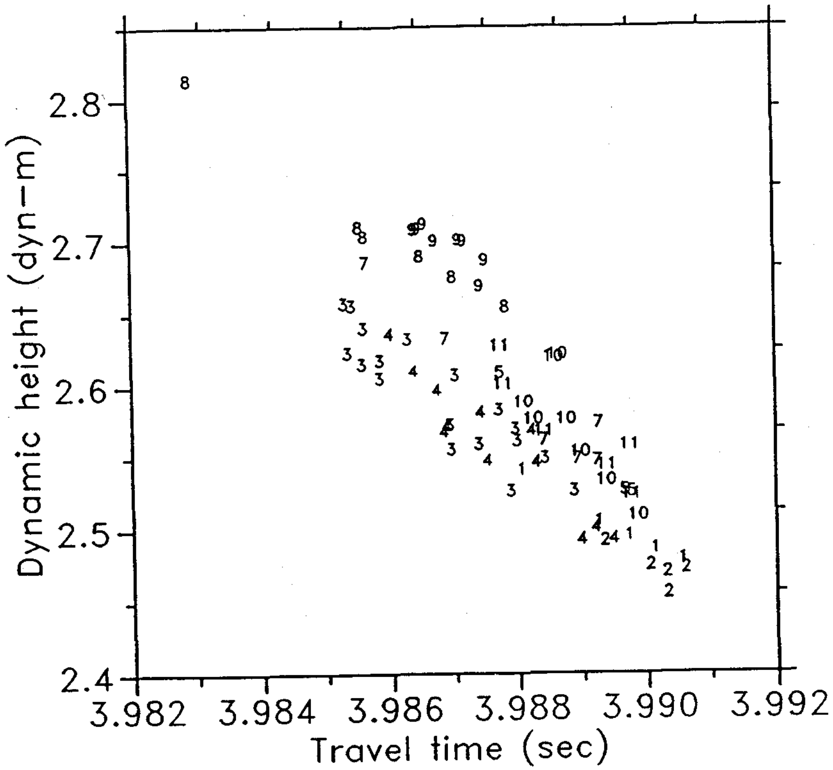

Figure 2.

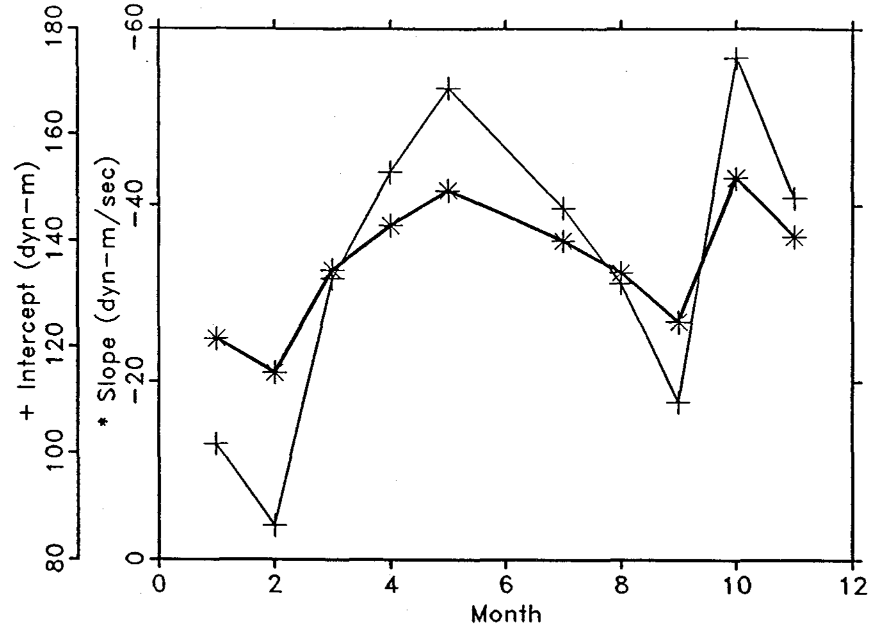

Figure 1.

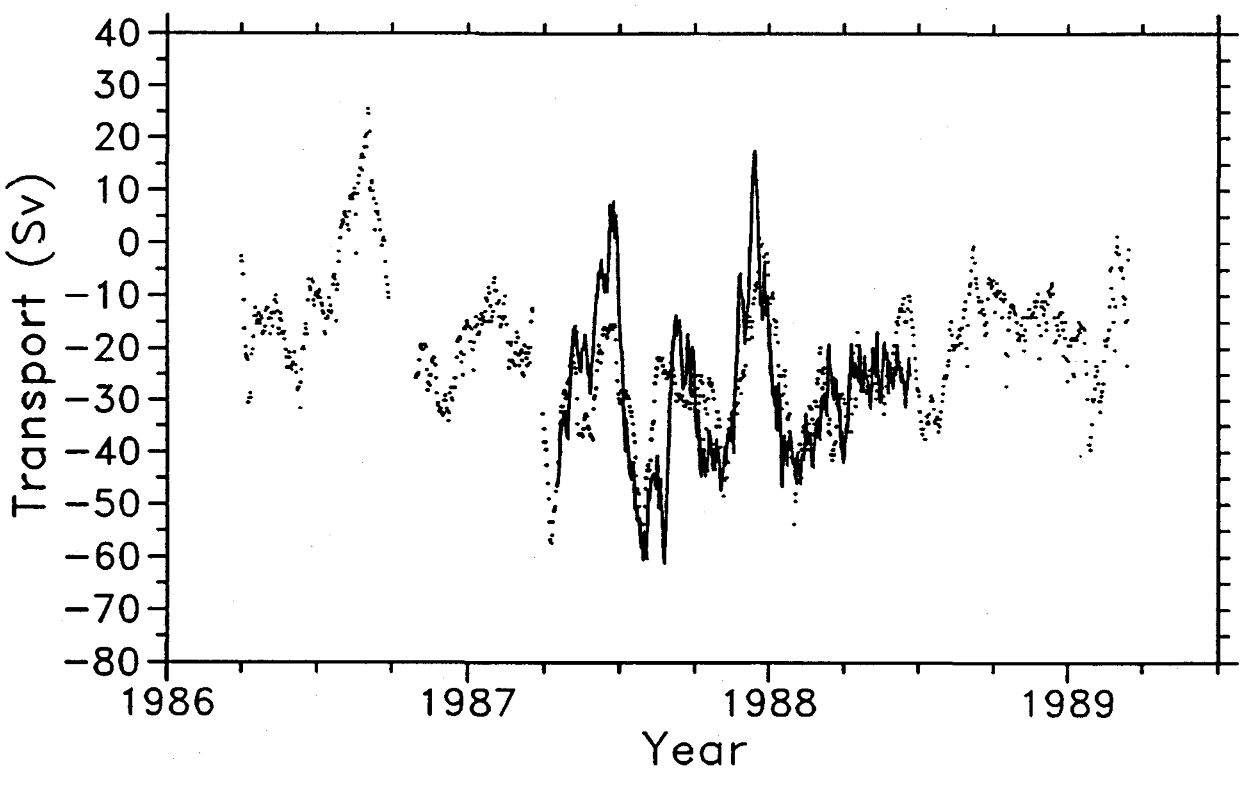
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−70
−80
Transport (Sv)
1986
1987
1988
1989
Year

Figure 3.

SATELLITE ALTIMETRY
CALIBRATION AND PERFORMANCES

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1. INTRODUCTION

The utility of satellite altimetry for measuring sea level and ocean topography has been demonstrated by a series of altimeters of increasing accuracy and precision flown successively on Skylab, Geos3, Seasat, and Geosat (see for references the special issues of J. Geophys. Res., 1983, for SEASAT, and J. Geophys. Res.,1990, for GEOSAT). Presently, two new missions are underway : ERS1, launch in 1991, supporting, among other sensors, an altimeter, and TOPEX/POSEIDON, launch last August 1992, specifically designed to observe large scale ocean circulation with an unprecedented accuracy.

Measuring the sea surface topography with a satellite altimeter system results from the combination of two techniques : radar altimetry and precise orbite determination. Radar altimetry is the precise measure of the distance between the satellite and the ocean surface. Precise orbit determination is the measure of the satellite's orbital distance from the center of mass of the earth. The difference between the two measurements gives the height of the sea surface (average over the footprint of the altimeter) in a coordinate system relative to the center of the earth (see figure 1). It must be noticed that to be useful for global ocean circulation studies, which are the main goal of the present mission, this measurement has to be combined with a precise knowledge of the geoïd and the ocean's density field, for providing a way to access the three dimensional structure of the ocean currents.

2. FUNDAMENTALS OF SATELLITE ALTIMETRY

To achieve the above mentioned goals, sea level measurements with an accuracy of a few centimeters over spatial scales of hundreds of kilometres are required. This implies the reduction of errors of a variety of sources : altimeter instrument error, range delay of the radar pulse in the atmosphere (ionospheric and tropospheric corrections), interaction of the radar pulse with ocean waves (called electromagnetic biais), determination of the satellite orbit, ... As an illustration of the order of magnitude of the different errors considered in the presently ongoing missions, we give on table 1 the error budget estimated for TOPEX/POSEIDON before launch. This satellite included six science instruments (see Figure 2). Four sensors are considered fully operational: a dual frequency radar altimeter ALT, a microwave radiometer TMR, a laser retroreflector array LRA (from NASA), and a Doppler Tracking System receiver DORIS (from CNES). And two sensors are experimental: a single frequency Solid State Radar Altimeter SSALT (from CNES), and a Global Positioning System Receiver GPSR (from NASA). The ALT is the primary instrument of this mission, the measurements of the two frequencies allowing for corrections for errors caused by ionospheric free electrons. The TMR is here to estimate the total water vapor content in the atmosphere along the beam of the altimeter and thus allows to correct the altimeter measurement from this source of error (tropospheric correction). The LRA is to provide the NASA baseline tracking data for precise orbit determination, and calibration of the radar altimeter biais (as we will present later). The DORIS tracking system provides the CNES baseline for an all-weather global tracking of the satellite. The two experimental instruments are intended to demonstrate the feasibility of new technologies : the SSALT for low power, low weight altimeter for future earth observing missions, and the GPSDR using a new technique of GPS differential ranging, for precise continuous tracking of the spacecraft. It can be pointed out from table 1, among other numbers, that the expected instrument noise is 4.1 cm for the ALT and 2.0 cm for the SSALT, and that the orbit error is the most significant part of the total budget of the order of 10 cm as deduced from the DORIS/SPOT2 experiment (Laudet, 1991), leading to a global RSS of the order of 14 cm for TOPEX and 11 cm for POSEIDON measurements based on a one per second sampling rate, which corresponds to an along track resolution of 6 km.

However, these numbers have been estimated before launch from the expected performances of the instruments and orbit determination. Past experience from the prelaunch altimeter missions has indicated that in flight height calibrations and height stability verifications are essential, and that verification of the performance of the satellite and the instrument, together with the progress of the induced science, are part of a continuing process leading to the improvement of the all systems.

3. THE CALIBRATION PROCEDURE

Several papers have been published recently on this subject of satellite altimeter calibration (see for instance Kolenkiewicz and Martin, 1990 ; Wakker and al, 1991). As defined by Wakker and al, the most simple formulation of the altimeter calibration procedure is :

1. to determine the satellite's altitude from an orbit computation based on tracking data h_{orb},

2. to measure simultaneously the sea level height h_{ssl} by a tide gauge of which the position is accurately known,

(These two quantities have to be taken above a reference ellipsoïd),

3. to measure the altimetric height of the altimeter above the sea surface, h_{alt},

The comparison of the difference between the two last quantities with the first one yields the altimeter biais.

$$b = h_{alt} + h_{ssh} - h_{orb} \tag{1}$$

with

b : altimeter height biais,

h_{alt} : measured altimeter height above the sea surface, corrected from instrumental and propagation effect, and center of mass offset,

h_{ssh} : sea surface height above the reference ellipsoïd, as measured by the tide gauge. This quantity includes :

h_t : the tide at the time of the satellite pass, above the geoïd,

Δh : the non tidal temporal sea surface variations

h_g : the geoïd height at the altimeter subsatellite point

$$h_{ssh} = h_g + h_t + \Delta h$$

thus

$$b = h_{alt} + (h_g + h_t + \Delta h) - h_{orb} \qquad (2)$$

Usually h_{orb} is obtained, as said before, by precise orbit determination, including laser tracking, DORIS tracking, and, for the future, other techniques like GPS. But, for calibration, only laser trackers located near by the calibration site are able to obtain orbit heights at the few centimetre accuracy level. The basic elements for satellite altimeter calibration are then:

- a tracking system by satellite laser ranging (SLR), with laser stations as close as possible to the calibration site,
- a sea level observing system based on tide gauge devices at the calibration site,
- a levelling system to tie the tide gauge and laser altitudes,
- a specific instrumentation of the calibration site for improving locally the different corrections to be applied to the satellite altimeter and laser measurements (sea state, troposphere,...).

4. THE CALIBRATION ACCURACIES

From (2), it results that the errors which affect calibration are:

$$\Delta b = \Delta h_{alt} + \Delta\ (h_g + h_t + \Delta h) - \Delta h_{orb} \qquad (3)$$

The ideal situation for calibration is when the laser site is just under the groundtrack of the satellite. Then :

$$h_{orb} = h_l + h_{gl} + h_{sl}$$

with

h_l: measured distance from the laser tracking site to the laser corner tube retroflectors corrected for instrumental and atmospheric effect propagation,
h_{gl}: the geoïd height at the laser site,
h_{sl}: altitude height of the laser station above the geoïd.

Then, as the laser is just under the altimeter subsatellite point, $h_{gl} = h_g$, and:

$$\Delta b = \Delta h_{alt} + \Delta\ (h_t + \Delta h) - \Delta h_l - \Delta h_{sl} \qquad (4)$$

This scenario has two advantages:

1) the tide gauge and the laser being adjacent, their altitudes can be tied one to the other by conventional surveying methods at the millimeter precision,

2) the laser height error is minimum when the satellite exactly overflies the laser site. Kolenkiewicz and Martin (1990) have estimated that the one sigma uncertainty in orbit height given by a laser measurement in these conditions (satellite flying at the laser zenith) is of the order of 7 mm, that this uncertainty is 1 cm for an orbit having a groundtrack point of closest approach (PCA) of 20 km, and that it increases linearly as the PCA distance increases.

This scenario needs to make use of a laser system and a tide gauge located on at the same place, for instance on a tower at sea. But this has practically never been the case up till now, for the previous and the on going satellite altimetric missions.

For SEASAT, the calibration site was Bermuda, with a tide gauge on a tower, at sea, and a nearby laser, both under the groundtrack of the satellite, but not at the same place. It was then necessary to use a levelling campaign to relate the tide mesurement to the laser site, which introduced an error of a few millimeters, and suffered also from the uncertainty of the geoïd topography between the two locations.

For ERS1, the calibration system uses also a tide gauge on a tower at sea, near Venice, but the satellite positioning is obtained from multiple lasers distributed over Europe. The closest laser site is Monte Venda, at a distance of about 64 km. The ties between the lasers and the tide gauge are done by GPS. In that case, the error budget must include an orbit height error of the order of 3 cm, and a GPS tie biais of some millimeters.

The TOPEX / POSEIDON mission includes two calibration sites. An US site has been chosen and instrumented on the basis of the same concepts: an oil platform (Harvest) located 19.5 km west of Point Conception, California. This site has a good laser coverage, by at least four stations, but located at several hundreds of kilometers away from the Harvest platform. The expected global error budget for the TOPEX altimeter calibration has been estimated of the order of 5.2 cm for one overflight, going down to 3.7 cm after 30 overflights (see TOPEX / POSEIDON Joint Verification Plan, 1992). A second site has been instrumented by CNES. Let us examine in details the calibration procedures and expected accuracies of this site, as a typical example.

5. THE POSEIDON CALIBRATION PLAN

Basically the concept is the same, with a tide gauge on a very small island, Lampione, less than 300 m wide and 40 m high, and located just under the groundtrack of the satellite, with a nearby island, Lampedusa, 18 km east of Lampione, part of the Wegener-Meldas geodetic laser network. The tide gauge and laser station are tied through GPS. The error budget estimated for POSEIDON calibration is presented on table 2. This budget is separated into a random part which can be reduced by the number of calibrated passes, and a biais part, which is incompressible, and which is mainly due to the GPS levelling between Lampedusa and Lampione. This error budget is given for H1/3 values of 1 and 2 m (the wave height averages during summer and winter respectively), and the electromagnetic sea state biais error is taken as 1% of the H1/3. The tropospheric error is estimated from a meteorological station and an upward-looking radiometer operating at Lampedusa. The ionospheric error is based on the processing of GPS and DORIS data collected on the site. The satellite position accuracy is based on a short-arc technique and the laser operating at Lampedusa: the estimated 1 cm biais and 1.5 cm random uncertainty are consistant with the numbers given precedently. As said before, the random error can be reduced by the number of calibrated passes: according to the weather statistics, a total of six passes is expected to be successfully tracked during the summer and three during the winter (these estimates are based on a total of 10 Lampione overflights with POSEIDON altimeter ON during 6 months of verification period, given the Antenna sharing plan between the US TOPEX and the French POSEIDON altimeters. As noted on table 2, this gives a total error of the order of 1.56 cm and 2.19 cm respectively for summer and winter periods.The launch having been made sucessfully beginning of August 1992, the number of calibrated passes is expected to be of five, leading to an estimated error (biais + random) of 1.74 cm.

However, as a backup solution for calibration of the CNES Topex / Poseidon Calibration Site, and in order to provide optimum local control of the altimeter system, including data on sea level, geophysical corrections and orbit, complementary equipements and model based interpolation procedure have been implemented. The full instrumentation of the site is presented on Figure 4.

It includes the following:

a) Sea level monitoring:

- Three coastal tide gauges are installed, one in Lampione, one southwest and the third southeast of Lampedusa. They are equiped with ARGOS station to allow automatic data transmission and high frequency sampling at 2 minutes intervals as the topex / Poseidon satellite passes overhead.
- A sea bed pressure gauge is also sealed just under the track of the satellite, 15 km southwest of Lampedusa.
- CTD hydrographic sections are performed once every 10 days, between Lampedusa and Lampione, and along the satellite groundtrack up to the sea bed pressure gauge. These data will provide during the whole calibration period a precise monitoring of the dynamic topography variability over the area.
- Two buoys equiped by IAPG with GPS receivers have been moored under the satellite track, one 7 km south of Lampione and the other 15 km south, just at the vertical of the sea bed pressure gauge. This system is intended to measure sea level heights within 1-2 cm with respect to GPS reference stations placed in Lampedusa and Lampione (see Hein and al, 1992, and Hein, this issue). These buoys are providing two more calibration points in addition to the Lampione tide gauge site. Moreover, they measure the wave heights.
- A sea level regional model (Sicilian strait, 38°N to 33°N) and a local Lampedusa model (36°N to 34°N) of sea level prediction including tides and wind effects have been developped (Fornerino and al, 1992). They are forced by the wind and atmospheric pressure fields provided routinely, every six hours, by METEO-France. Controlled by the tide gauges, the GPS buoys, and the CTD measurements, they are intended to determine, with a cm accuracy, the instantaneous sea level topography over the Lampedusa/Lampione area.

b) Geodetic Survey:

- GPS levelling campaigns has been achieved by IFAG, with the objectives, one to refer Lampedusa site to the surrounding laser sites (Grasse, Matera, Milo, Noto, Punta Sa Menta), second to locally refer the Lampedusa tide Gauges to the laser site, and third to tie Lampione tide gauge to the laser station. The standard errors have been estimated to respectively 4.0 cm and 4 mm in height for the two first campaigns. The results of the third are not yet available.
- A vertical deflection campaign has been acheived at four points (the laser site, the two gauges sites on Lampedusa, and the one on Lampione) to allow to calculate the geoïd slope.
- A local mean sea surface (1° square around Lampedusa) has been calculated by GRGS, using the altimeter GEOSAT data of the geodetic mission provided by the US Navy, with a data sampling between 1 and 5 km, giving access to the very short scales of the geoïd.

c) Satellite precise orbit determination:

- A mobile laser station from IFAG will stay at Lampedusa from August 1992 to November or December 1992 (if weather acceptable).
- A mobile laser station from CERGA is installed in Milo (an ASI site located between Trapani and Sicilia) from August to November 1992, for tracking of the satellite in the vicinity of Marettimo (a backup site equiped also with a tide gauge), and contribution to short arc orbit computation.
- A DORIS beacon is installed on the island of Lampedusa, as part of the network of 47 beacons distributed around the world, for supporting the precise orbit determination of the satellite near the calibration area. It must be noticed that it is a dual frequency radio system, having the advantage,as said before, of being all weather operational, and, being bi-frequency, of allowing to determine the ionospheric correction which has to be applied to the altimetric data.
- The short arc orbit computation is achieved using all the data issued from the laser tracking (Lampedusa, Milo, Grasse, Matera, Herstmonceux, Wettzel, Grasse,...) and the DORIS tracking (at Lampedusa, Toulouse and Dyonisos). The expected accuracy on the radial component of the

orbit over the Lampedusa calibration site is 1-2 cm.

d) Meteorological-atmospheric survey:

- Two ionospheric dedicated GPS receivers are installed at Lampedusa, and are providing an estimate of the Total Electronic Content for the time delay correction of the altimetric signal propagation in the ionosphere, complementing the DORIS estimate.
- Upward looking radiometers are used to measure the water vapor content at the vertical of the site, to be able to accurately correct the altimeter signal propagation in the troposphere.
- A meteorological station is measuring continuously temperature, wind humidity, atmospheric pressure, in order to adjust the meteorological models and correct the in-situ and satellite data.
- The meteorological fields (every 6 hours) of METEO France models Peridot and Vagmed, over the Lampedusa area, are available, for in-situ data corrections and local sea level model forcing.

The TOPEX / POSEIDON satellite has been launch beginning of August. The first altimeter data are just arriving now. It is thus premature to present any output of that redondant calibration system. However, the first data are very promising.

6. SOME INFORMATION ON THE FIRST TOPEX / POSEIDON DATA

From the French side, several very positive checks have been made. In term of precise orbit determination, based on laser tracking and DORIS tracking (including, beginning of October, 47 stations, i.e. a global coverage of the order of 85% of the whole world), the computed orbit error is 11cm, without any effort made on the improvment of the gravity field. Such an already low value let us hope to go down to 5 cm precision for the orbit. The analysis of the first POSEIDON altimeter signals reveals that the noise level is, as expected, of the order of 2.1 cm, with a resolution of oceanic scales down to 5 to 6 km along track. The dependance of the altimeter noise to the sea state (H1/3) is linear as usual, but with a much smaller slope than the previous altimeters. The data for Cycle 1 will be available by the end of October for the 38 selected PIs of the programme. This data distribution is planned to follow by one month the data acquisition of each new cycle.

7. SUMMARY

To acheive the centimeter accuracy required for global ocean circulation studies, satellite altimetry faces extreme constraints, and implies thus the reduction of errors of a variety of sources. In order to give numbers, we have analysed, as an example, the expected error budget of the TOPEX / POSEIDON mission. Putting together all the error sources, it has been noticed that, for this dedicated altimeter mission, the global RSS is estimated of the order of 14 cm for the TOPEX altimeter system, and 11 cm for POSEIDON.

To verify the expected performances of an altimeter mission, calibration experiments need to be implemented during the first months of the mission, and verification experiments have then to be maintained during the life of the satellite, for checking the continuity of the observed performances, and the detection of any drift. The usual procedure for altimeter calibration have been described, involving precise orbit determination with nearby laser tracking, observation of the sea level variations by a tide gauge carefully levelled by reference to a basic ellipsoïd, and also tied to the laser stations, and acquisition of a set of environmental parameters necessary for improved local corrections of the altimeter measurements. The basic elements of the three altimeter missions which have, or are, including calibration have been briefly presented: SEASAT, ERS1, and TOPEX / POSEIDON.

For the last altimeter mission, dedicated to oceanography as previously noticed, two calibration experiments have been implemented. The one developped by CNES at the Lampedusa site, south of Sicily, is intensively instrumented: it has been presented in detail in this paper as an illustration of an intensive satellite altimeter calibration experiment. Error budget expected for this POSEIDON calibration at Lampedusa have presented, to illustrate the constraints to be satisfied in order to reach the very small 1 or 2 cm expected error levels.

Although results from this calibration exercise are still not available (the launch of the satellite was August 10, 1992), the first results from precise orbit determination allows to already estimate the present orbit error level at only 11 cm, and hope for 5 cm level after further improvements. And the first data from the POSEIDON altimeter data seem to confirm the expected 2 cm noise level, with an alongtrack resolution of 6 km. These performances have never been reached up till now, and are very promising for the scientific community waiting for these data.

ACKNOWLEDGEMENTS

The description of the TOPEX / POSEIDON Lampedusa calibration and verification experiments has been supplied by Patrick Vincent. The preliminary informations on the first Poseidon data are coming from a personnal communication with Michel Lefebvre. The author would like to acknowledge both of them.

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FIGURES CAPTIONS

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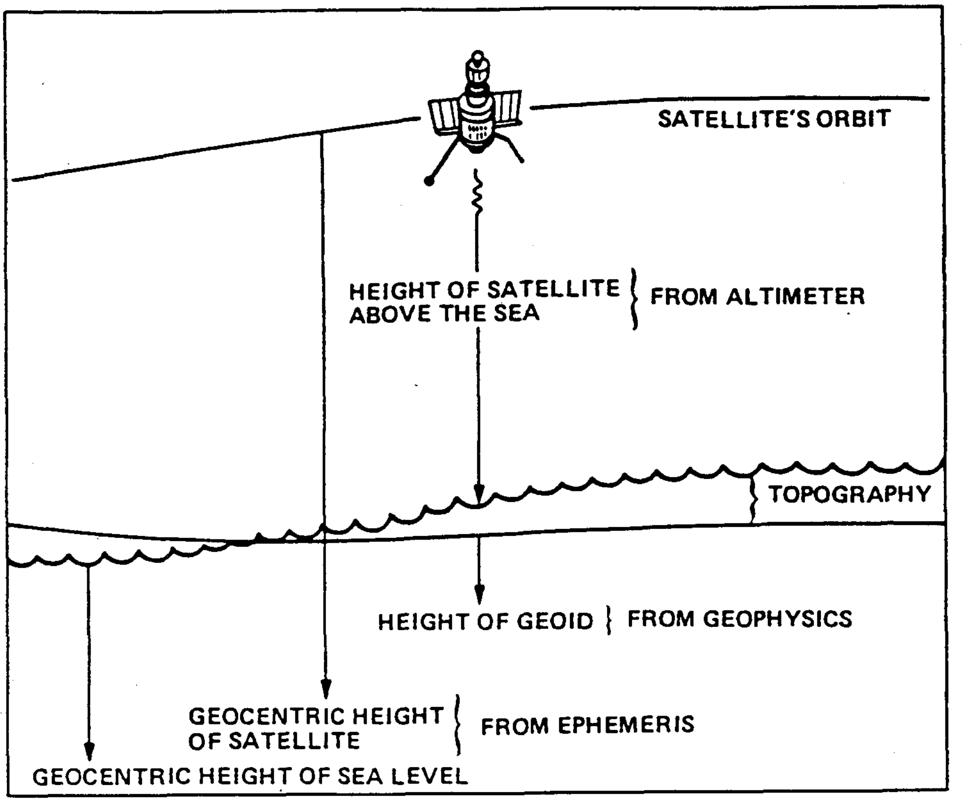

Figure 1: The basic geometry of satellite altimetry (from Stewart and al, 1983).

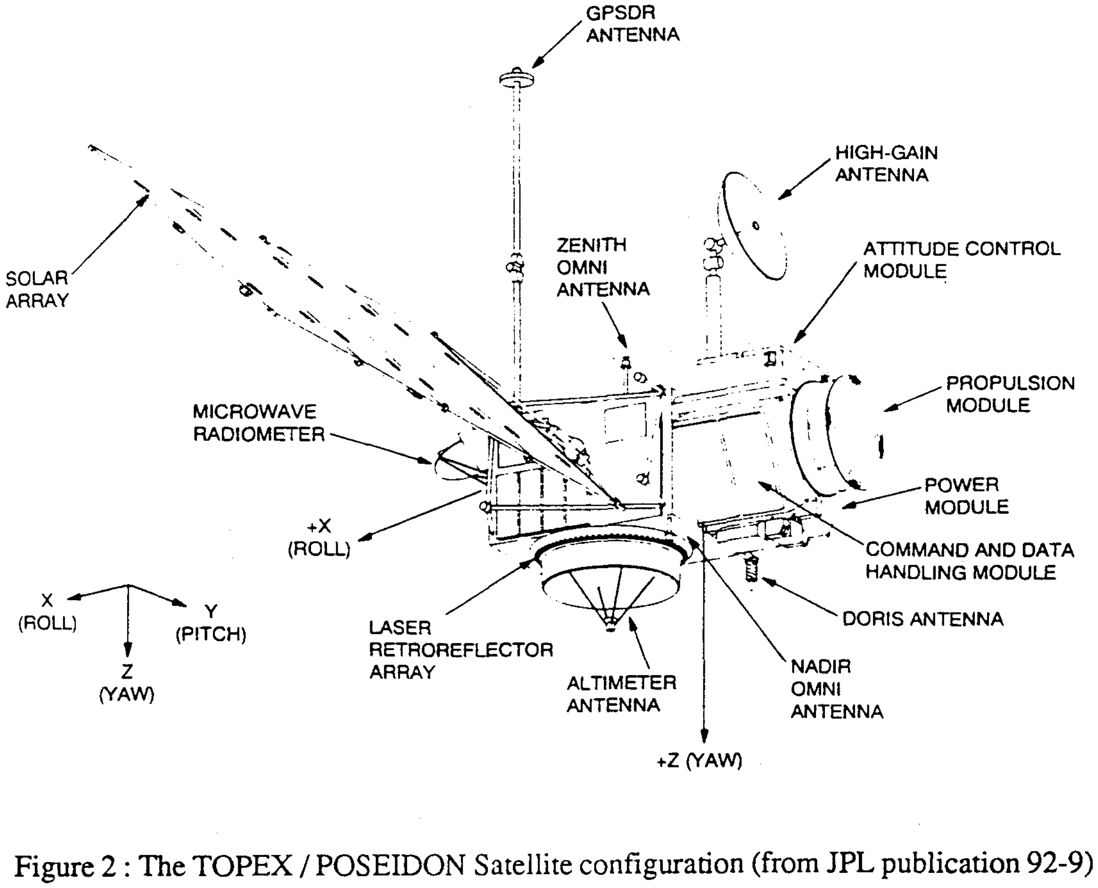

Figure 2 : The TOPEX / POSEIDON Satellite configuration (from JPL publication 92-9)

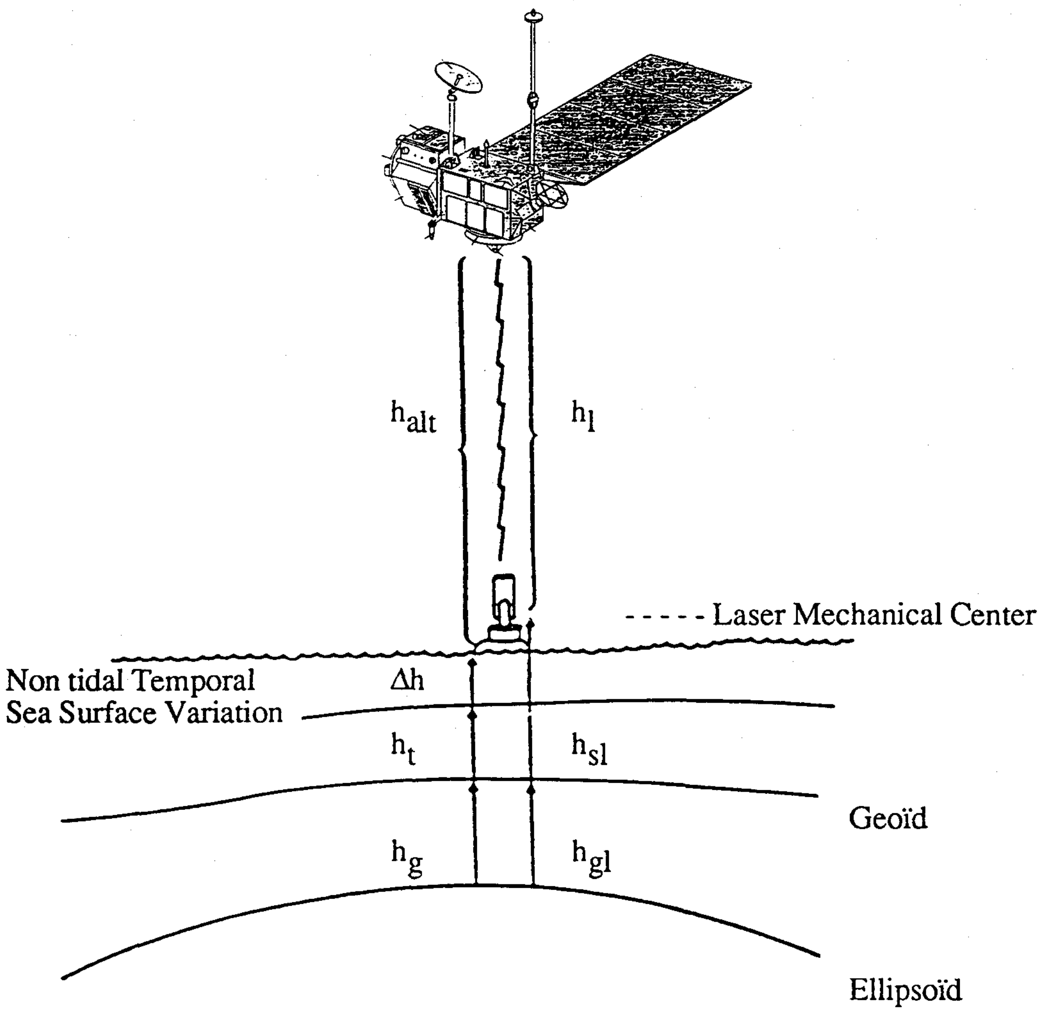

Figure 3: Calibration Geometry using laser station nearby the calibration site.

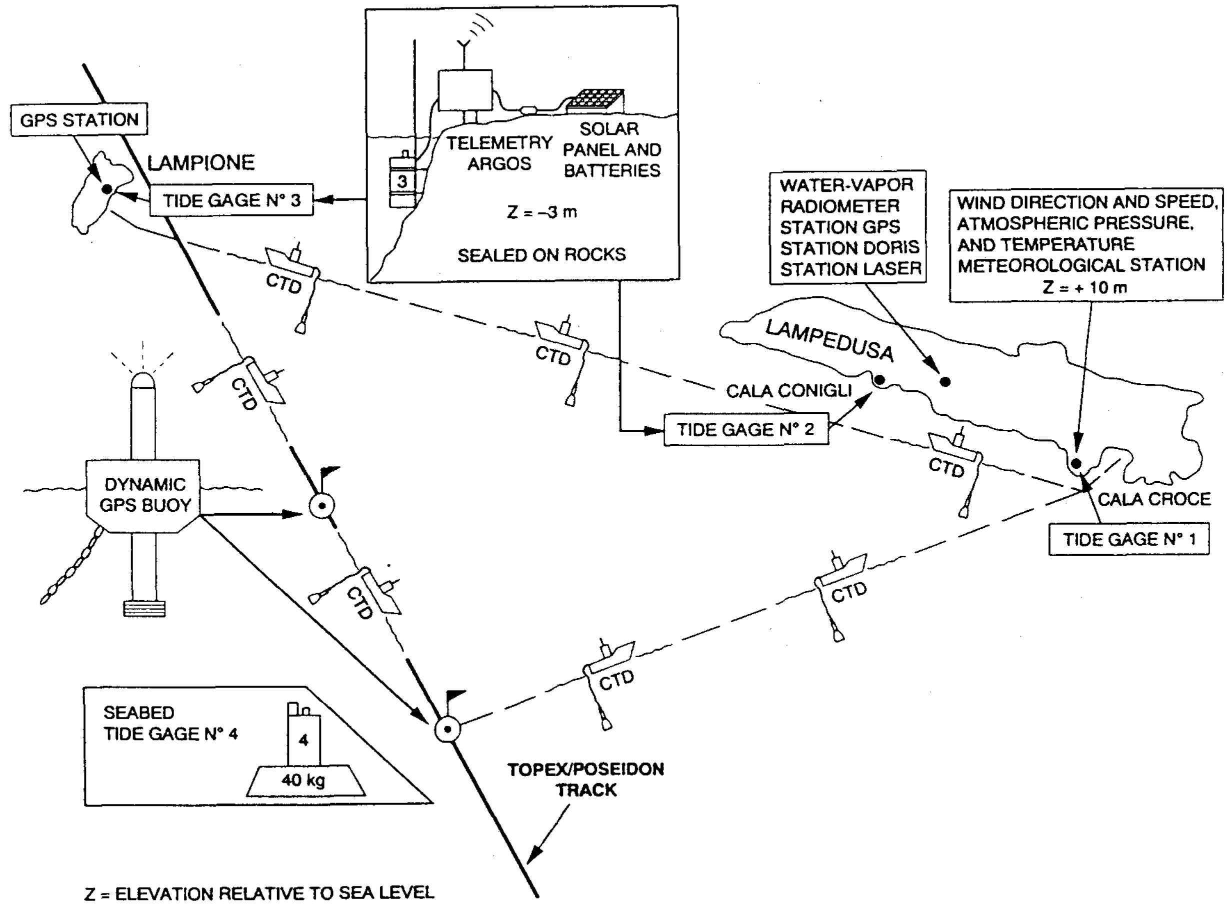

Figure 4: Instrumentation of the Lampedusa site (from JPL publication 92-9).

Error source	TOPEX component, cm	Decorrelation distance, km	POSEIDON component, cm
Altimetry			
Instrument noise	4.1[a]	6	2.0
Bias drift	2.0	>>10,000	1.7
Media			
EM-bias	2.0	50 to 1000	2.8
Skewness	1.0	50 to 1000	
Troposphere, dry	0.7	1000	0.7
Troposphere, wet	1.2	50 to 1000	1.2
Ionosphere			2.0
Orbit			10.0
Gravity	10.0	10,000	
Radiation pressure	6.0[b]	>10,000	
Atmospheric drag	3.0	>10,000	
GM (gravitational constant for mass of the Earth)	2.0	10,000	
Earth and ocean tides	3.0	10,000	
Troposphere	1.0	10,000	
Station location	2.0	10,000	
RSS absolute error	13.7		10.8

Major Assumptions for TOPEX:
1. Dual-frequency altimeter.
2. Three-frequency radiometer.
3. Fifteen laser tracking stations.
4. Altimeter data averaged over 1 s.
5. $H_{1/3}$ = 2 m; wave skewness = -0.
6. Tabular corrections based on wave-form tracker comparisons.
7. 1300-km altitude.
8. No anomalous data, no rain.
9. Improved prelaunch gravity field; adjustment postlaunch.
10. ±3 mbar surface pressure from weather charts.
11. 100-ms spacecraft clock.

Major Assumptions for POSEIDON:
1. Single-frequency altimeter.
2. Altimeter data averaged over 1 s.
3. $H_{1/3}$ = 2 m; σ_0 = 10 dB.
4. The instrument noise and drift estimates result from simulations and flight-model ground tests (Raizonville et al., 1991).
5. The EM bias and skewness error result from crossover analysis (Gaspar, 1990).
6. The troposphere wet error is deduced from the TMR error estimate.
7. The ionosphere error is deduced from the DORIS-based correction (Escudier et al., 1991).
8. The radial orbit error includes all the error sources and is deduced from the DORIS/SPOT2 experiment (Laudet, 1991).

[a]Including the noise in the ionospheric correction by the dual-frequency altimeter measurements.
[b]Solar, Earth, and thermal radiation.

Table 1: Estimated error budget for TOPEX and POSEIDON measurements of sea level (from JPL publication 92-9).

Error source, cm	Summer ($H_{1/3}$ = 1 m)		Winter ($H_{1/3}$ = 2 m)	
	Bias	Random	Bias	Random
POSEIDON altimeter		1.84		1.96
Satellite position	1.0	1.5	1.0	1.5
Troposphere (dry)		0.2		0.2
Troposphere (wet)		0.5		0.5
Ionosphere		0.5		0.5
GPS leveling	0.45		0.45	
Tide gage		0.5		0.5
Sea-state bias		1.0		2.0
Subtotal (rss)	1.10	2.72	1.10	3.30
Based on the number of calibrated passes out of a possible 10		6 passes, 1.11		3 passes, 1.90
RSS total error (bias + random)	1.56		2.19	

Table 2: Error budget for the POSEIDON calibration at Lampedusa (from JPL publication 92-9).

COMPARISONS BETWEEN ALTIMETRIC AND GLOSS TIDE GAUGE MONTHLY MEAN SEA LEVELS

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ABSTRACT

Monthly mean sea surface heights derived from precise global orbit recomputations for the first year of the Geosat Exact Repeat Mission have been compared to tide gauge data from 57 island and 71 coastal sites. In general, the monthly means from the different techniques are correlated significantly at island stations, especially in the Tropical Pacific, and the average standard deviation of the monthly mean differences between techniques is 5 cm. This provides a conservative estimate of the current accuracy of deriving monthly mean sea surface topography time series from altimetry. Coastal gauge data in general have a smaller correlation with the nearby deep ocean altimeter data, although groups of stations in the western Pacific do exhibit correlation.

The objects of the comparison were two-fold:

(i) to provide a 'ground truth' validation of the time series of the altimetric heights, and thereby of the computed orbits, through which an assessment of the current accuracy of the altimetric technique averaged over monthly timescales can be determined. In this analysis the altimeter was used as a virtual 'tide gauge in space' with no further ad-hoc orbit error removal treatments employed.

and (ii) to demonstrate with real data the utility of a well distributed global tide gauge network (i.e. GLOSS) in such a role.

We believe that the present analysis and that of Koblinsky et al. (1992) are the first to employ such precise global orbits and in which a geographically representative spread of tide gauge stations has been used. In addition, this is the first time that GLOSS, as such, has been used as the basis for selection of tide gauge sites. Although many more tide gauge stations exist worldwide, most are on continental coastlines and their usefulness for altimeter data validation remains to be tested.

A fuller report of this work can be found in the paper 'A comparison of monthly mean sea level variability determined from Geosat altimetry and a global tide gauge dataset' by S.A. Harangozo, P.L. Woodworth, R.H. Rapp and Y.M. Wang to be published in the International Journal of Remote Sensing.

MEASUREMENT OF MID-OCEAN SURFACE LEVELS TO ±3CM WITH RESPECT TO MID-CONTINENT REFERENCE POINTS USING TRANSPONDERS WITH THE ERS-1 AND TOPEX ALTIMETERS - A DEVELOPING TECHNIQUE

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1. INTRODUCTION

Several satellite altimeter/radiometer systems have been launched which have had the capability to measure the range of radar altimeter signals returned from the sea surface with a variance of about ±3cm for sea states of about Hs = 2m and only slightly worse for much higher sea states. However, our knowledge of the height of the satellite above the centre of the earth at the time when the measurement was made, and hence our ability to relate that sea-surface height to a fixed point on land, has usually been at least an order of magnitude worse than this. Altimeter-bearing satellites are usually tracked by laser or microwave tracking systems which measure range or doppler shift using signals which pass back and forth between the satellite and ground stations *along slant paths*. Coincident measurements from at least three such stations are therefore required if the 3D position of the satellite in space, and particularly its altitude, is to be known at the maximum resolution of the tracking system. The sparsity of tracking stations is such that 3D location is seldom possible. The data from an individual tracking system must be used with data from other stations, usually in Europe or America, to constrain a global orbit. This provides orbit knowledge generalised on a global basis. For example, several groups are deriving orbits for ERS-1 for which global accuracies of ±30 to 30cm rms are claimed. At a particular site and time this means there is a 32% chance that the inferred orbit altitude will be in error by more than these levels and a 5% chance that it will be in error by more than twice these levels.

It has been predicted[1] that altimeter measurements made over transponders can provide a different and complimentary sort of orbit measurement. *Direct measurements or orbit altitude* can be made at a particular location and time, with an accuracy as good as or better than, the accuracy with which the altimeter measures the sea surface. This should allow the altitude of orbit arcs several thousands of km in length and spanning major oceans to be located with the same precision (±3cm) so that, once every few days the height of the ocean surface under that arc can be measured, with respect to transponder sites on land, with an accuracy of about ±3cm. This paper concerns the development of the techniques required for such a measurement.

2. THE USE OF TRANSPONDERS WITH THE ERS-1 ALTIMETER

The resolution with which a mean delay can be assigned to pulses returned from any target to an altimeter depends critically on our ability to provide a mathematical model of that target. An active transponder provides an almost perfect point target, which can be modelled with very high precision. It can also be measured on a radar test range and the effective point of reflection related to a datum mark on the body of the transponder with sub-centimetre accuracy. It is therefore a very suitable precision target.

The technique of making altimeter measurements to transponders has been demonstrated over the last year using ERS-1. In order that the ERS-1 Altimeter should be able to measure targets which are in regions where its tracker would not normally operate it has been equipped with the capability to pre-set and hold its tracker parameters, including tracker window delay, rate of change of delay and AGC and to implement those preset values at a given time from its on-board memory.

In the latter part of the ERS-1 commissioning phase and throughout the first Ice Phase the process of commanding the altimeter in this way to view transponders was implemented and refined by the ESA Altimeter Project Team in co-operation with the Space Radar Group of the Rutherford Appleton Laboratory. The predicted orbit provided by ESOC was used to set the tracking window to view transponders deployed in Europe, Africa and North America. It has been found that the window can usually be set with a height accuracy better than ±2.5 metres in either the ice (120m window width) or the oceans (30m window width) mode. Operations were brought to a level where they were routinely successful.

When an altimeter passes over a transponder (i.e. the transponder is within about ±8km of the altimeter ground track) the transponder is illuminated for up to 4 seconds. In this time up to 4000 pulses are transmitted and received. The range between the altimeter and transponder varies in a highly predictable manner, and can be expressed as a simple parabolic function of time and satellite velocity.

$$r^2 = r_o^2 + [v(t = t_o)]^2 \qquad (1)$$

where

- r = range to the transponder at time t
- r_o = the range to the transponder at the time of closest approach, t_o, i.e. when a line from the satellite and orthogonal to the satellite orbit passes through the transponder position
- v = the apparent velocity of the satellite = $\sqrt{(RZ)}\omega$ where R is the radius of the orbit, Z is the radius vector from the centre of the earth to the transponder and ω is the orbital angular velocity of the satellite.

Of course a radar altimeter measures the delay, τ, between pulse transmission and reception which is related to range by $r = c\tau/2$, where c is the velocity of electromagnetic radiation. We should also note that $\tau = \tau_s + t_i + t_\tau$ where τ_s is the delay that would occur in free space, τ_i is the additional delay due to the dielectric properties of the ionosphere and τ_t is the additional delay due to the dielectric properties of the troposphere. $\tau_i + \tau_t$ can be assumed constant over the small time interval and scan angle involved in the measurement so that we can rewrite (1) as

$$\tau^2 = \tau_o^2 + [2v/c\,(t - t_o)]^2$$

Because we know the form of this function so precisely, we can use all of the measured pulses to calculate, with very high accuracy, the minimum of that parabola. That minimum corresponds to both the time of closest approach and the delay of pulses transmitted between the altimeter and transponder at the time of closest approach. In fact the altimeter data stream contains not individual returned pulses but waveforms which are the result of accumulating 50 returned pulses. Due to variation of the relative velocity of the satellite with respect to the transponder during the overpass the shape of the waveforms will vary being more spread out the further the satellite is from the point of closest approach (Fig. 1). It can be shown that the parabola defined by the individual pulses is the same as that defined by the centres of gravity of the waveforms so that the latter can be used as the measured data. The parabola fitting process most generally appropriate is an iterative, four parameter, v, t, τ, ρ (where ρ is the power under a waveform), least squares fitting process. However, for relatively clean data having little contamination by ground clutter, it has been found that a two parameter, t, τ, fitting process gives the same results and requires much less processing time.

Before launch, on the basis of the ERS-1 altimeter specification, the accuracy of measuring delay at closest approach with the ERS-1 altimeter in the Ocean Mode was estimated to be equivalent to ±0.5cm. To convert this delay measurement into a range measurement it is necessary to calculate $\tau_i + \tau_t$. This, in turn, requires that the total electron content, the ground level pressure, and the columnar water vapour content of the atmosphere in the region of the transponder are known. With reasonably good measurements of these quantities the delay in the atmosphere can be calculated with an accuracy of about ±1 to 3cm[2], the lower levels applying to dry high-latitude sites. To convert the range measurement into an orbit height it is necessary to have an approximate measurement of the across-track position of the satellite ground-track with respect to the transponder position (if the transponder is 1 to 8km off track a 1m uncertainty in across-track orbit position translates into 1mm to 1cm uncertainty in the measurement of orbit height above the transponder).

ERS-1 altimetry data has now been collected during ninety transponder overpasses. The data returned from the transponders has always been of good quality and shown the predicted characteristic parabolic variation (Fig. 1). Using the full four parameter least squares fitting approach and the simpler data filtering and two parameter analysis techniques illustrated in Fig. 2 it has been possible to make precise measurements in the presence of very substantial ground clutter. Measurement precision is about 4 times better than was predicted. When a parabola is fitted to data that has been collected in the high resolution Ocean Mode over a transponder that is in a site of low ground reflectivity the residuals produced are spread over only ±1cm. They show signs of a systematic structure symmetrical about the point of closest approach. This is thought to be due to the signal truncation that occurs in the accumulator of the altimeter data processor as fifty individual pulses are added to provide the waveforms that are transmitted to the ground. It is the interpretation of this effect that now limits the resolution of delay at closest approach to a level equivalent to about ±2 millimetres.

The measurement of the time of closest approach is also very precise (±28 microseconds). In 28μs the satellite moves along its orbit by about 20cm. In associating a position along the orbit with the time of closest approach we must consider the effects of doppler shift in the received signal and local orbit slope uncertainty. The altimeter processor maps frequency changes of its received signal into range changes. Hence, the doppler effect due to the component of the satellite motion in the direction of the transponder will cause the delay-time parabolic plot, and the calculated time of closest approach to be biased. This is a small and precisely calculable effect and does not impact on accuracy. A more important consideration in relating the orbit to the transponder location is that, at the time of closest approach, a line from the phase centre of the altimeter antenna to the mid-point of the transponder antennae will form a right angle with the orbit. Therefore, any uncertainty in the slope of the orbit will translate into uncertainty in locating the along-track position of the altimeter with respect to the transponder. A simple calculation of the uncertainty in orbit slope to be associated with an orbit which gives a global knowledge of radial position to ±30cm rms indicates slope uncertainty of < ±3mm in 20km so that a position on the orbit can be associated with a position on the ground to < ±3mm x 800/20 = < ±12cm. The accuracy of relating along-track timing to a position along the ground-track will therefore be dominated by the accuracy of determining the time of closest approach and it should be possible to locate the satellite position along its orbit track to about ±23cm.

A third important measurement simply uses the transponder as a receiver to compare the transponder pulses with timing pulses derived from a GPS receiver or some other ground-based timing system. This allows a very precise association of the altimeter data with a ground-based time standard. This measurement should not normally be necessary but it has been found in practice to be a useful local independent check on the satellite operator's system. In areas where the rate of change of altitude due to ellipsoid slope and orbit are high (24 m/s) precision timing of the data is essential.

The following quantities have been derived from transponder measurements with the stated precisions:

1.	Delay at the point of closest approach equivalent to	- Ocean mode	< ±2mm
		- Ice mode	< ±8mm
2.	Satellite along-track position	- Ocean mode	< ±0.2 metres
		- Ice mode	< ±0.7 metres
3.	Datation timing		< ±5 microseconds

Satellite along-track position determination and datation timing will be unaffected by the atmosphere, therefore, if the figures for delay at closest approach are increased to ±2 to 3cm to allow for uncertainties in estimating atmospheric delay, this table should also represent the accuracy of the measurements listed.

3. COMPARATIVE MEASUREMENTS

Experiments have been made in which altimeter measurements made to two transponders positioned about 140km apart along the ERS-1 ground-track at sites which differed in altitude by about 1000m were compared with GPS measurements of the transponder positions. Also, the height of the satellite orbit over a transponder has been measured coincidently by the transponder technique and by laser tracking. The data from these measurements is still being analysed but early indications suggest that the results will not conflict with the measurement accuracies stated above. Further measurements have been made on much longer arcs which it is hoped will confirm our estimates of the accuracy with which transponder measurements can locate trans-ocean orbit arcs.

4. POTENTIAL APPLICATIONS OF THE TECHNIQUE

The capability to measure orbit altitude and along-track position to this accuracy with devices as simple and low-cost as a transponder makes possible new techniques for altimeter calibration, the precision measurement of sea surface with respect to inland sites, direct measurement of signal penetration over the ice caps, land-based geodesy and orbit improvement. Given the quality of orbit knowledge available from a conventional tracking system (± 30 to 60cm radial), our knowledge that orbit error will be mainly a once per revolution effect[3], that the decrease in altitude of ERS-1 due to drag effects is only about 43cm per revolution and for TOPEX it will be much lower, it can be seen that the use of a single transponder will allow a very substantial improvement in orbit knowledge for positions ±2000km along track on either side of it. Deployment of a second transponder along the same track (Fig. 3) can potentially increase the length of precisely located orbit, certainly to 5,000km and quite possibly to much greater lengths. A small network of about 7 transponders (Fig. 4) may allow us to determine the height of about ten arcs across the major oceans wrt the centre of the earth to ± about 3cm once every 10 days. The value of such information, how it relates to other sea-level measurements and whether it is of sufficient value to warrant setting the transponders in place are matters for discussion in the ocean level monitoring community.

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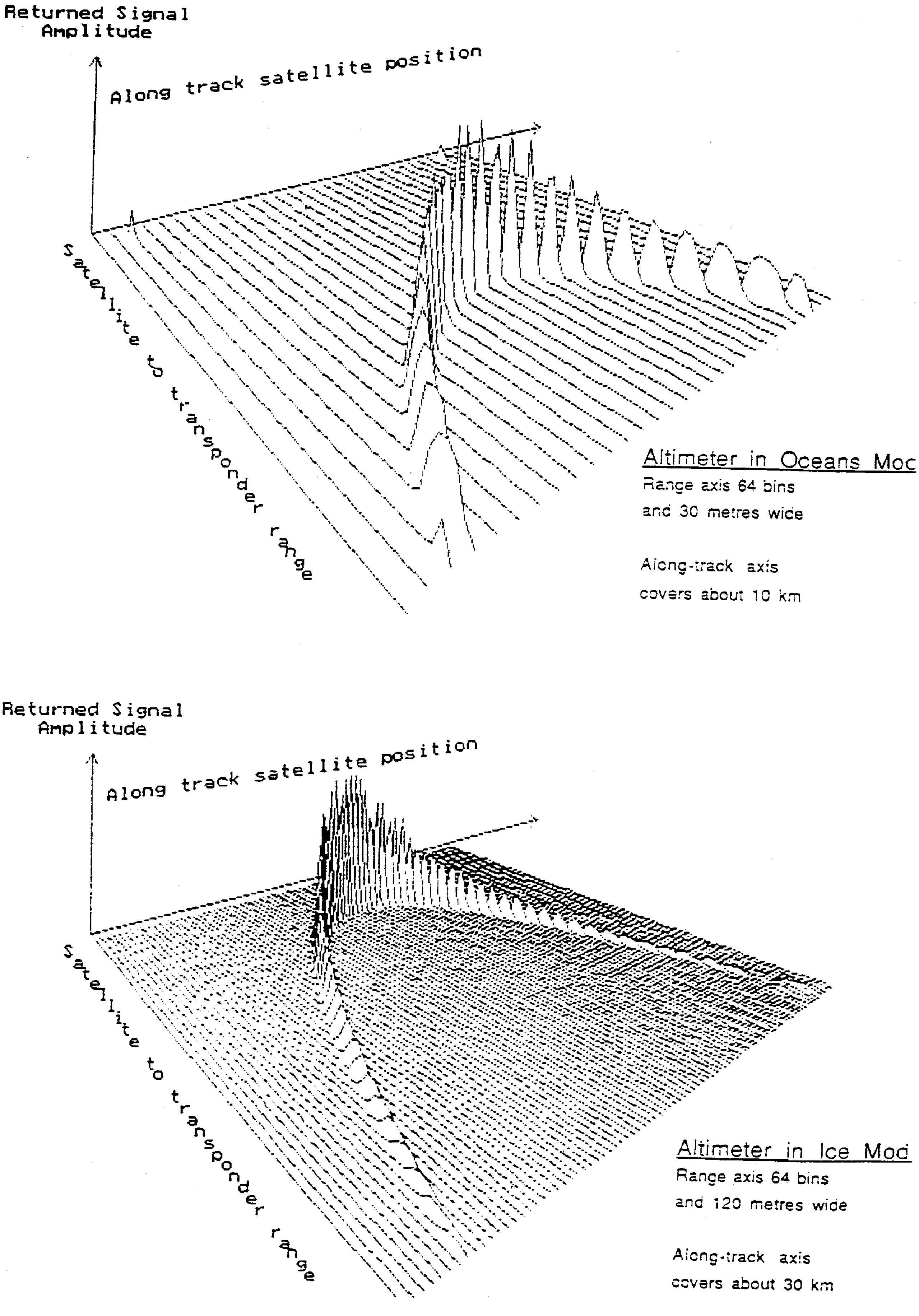
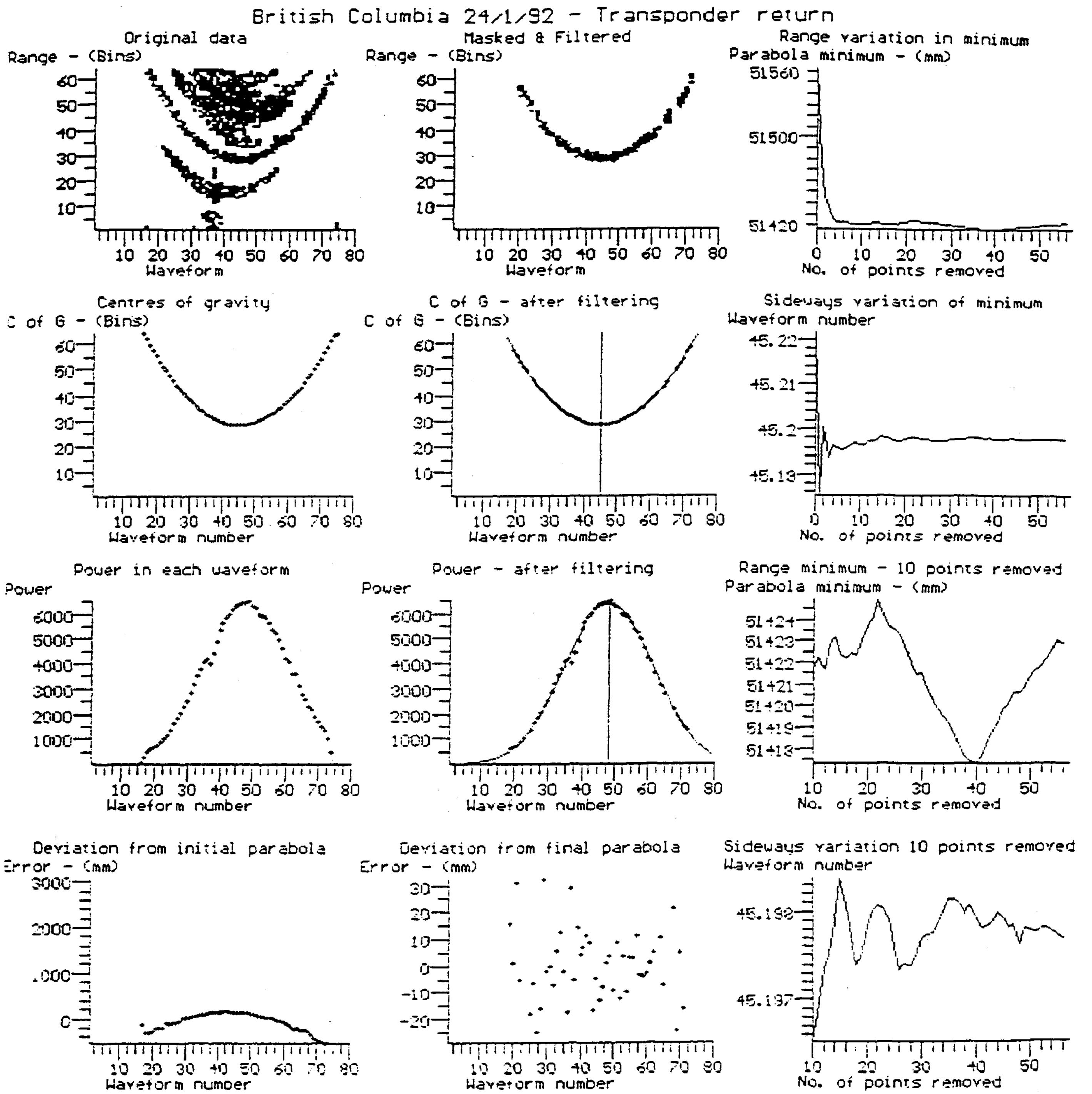


Fig. 1 Altimeter waveforms recorded over transponders



No of original points 80
No of useful points 60
No of final points 50

Residual Uncertainty +/-
Delay minimum 1.9 mm
Along track 0.1 M

Max of power curve 48.23 Waveforms
Min of range curve 45.20 Waveforms
Range - Power offset 3.0 Waveforms

Area under Power curve 213832

Fig. 2 The plots above illustrate the filtering, bad data rejection and curve fitting that is applied to determine the delay minimum from raw altimetry data collected in the low resolution "Ice Mode".

(Additional parabolea in the first plot are due to small lakes close to the transponder. "Bins" refers to the 64 bins across the altimeter tracking window. For this "Ice Mode" data each is equivalent to about 1.8 metres of range. "Waveform number" refers to the waveforms delivered in the altimeter data stream once per 1/20th sec.. As the satellite travels at about 7km/sec the interval between waveform numbers is equivalent to 350 metres.)

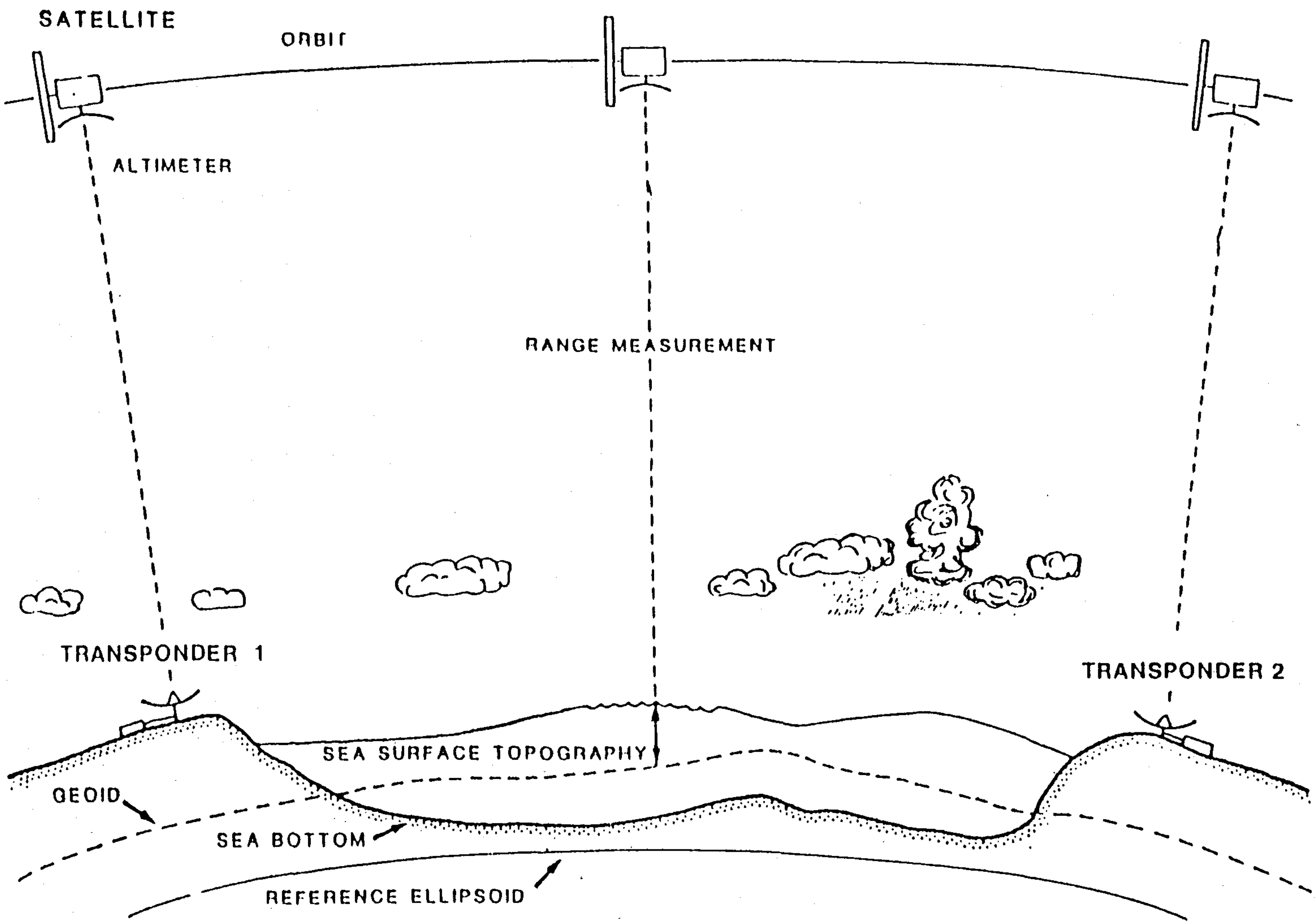


Fig. 3 The location of transponders beneath orbit arcs crossing major oceans can potentially provide very precise mid-ocean measurements of sea surface related to positions on land.

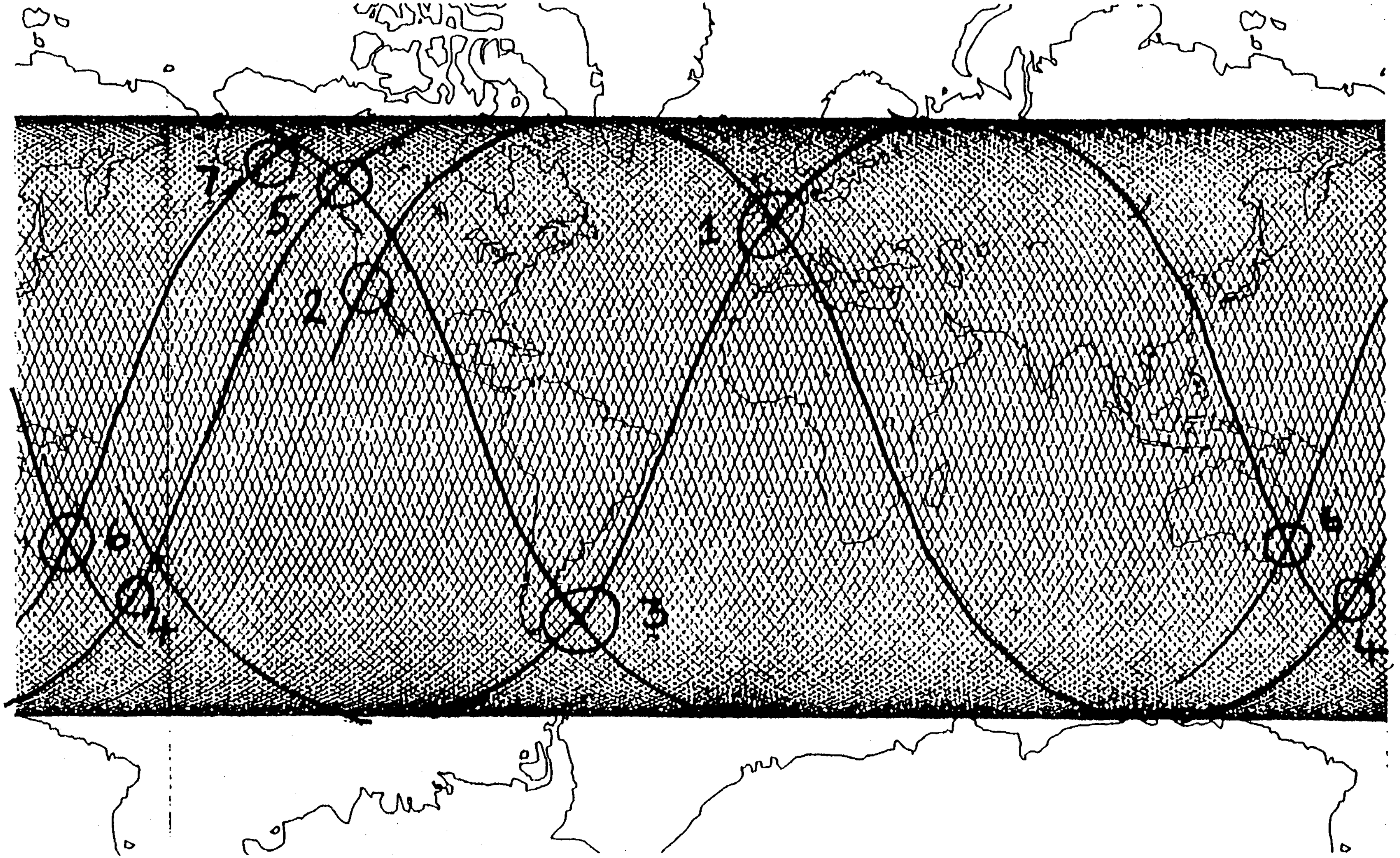


Fig. 4 A relatively small number of transponders would allow precision altimetry to be collected along about 10 arcs.

CHECKS ON DATA RECEIVED BY THE PERMANENT SERVICE FOR MEAN SEA LEVEL (PSMSL)

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1. DATA CHECKS

The following brief note describes the checks made by the PSMSL on data received from national authorities. Details can also be found in PSMSL publications (e.g. Woodworth, Spencer and Alcock, Int.Hyd.Rev., 67(1), 131-146, 1990).

In general, in years past the PSMSL has not received copies of original tide gauge hourly height measurements or continuous charts but has accepted monthly and annual mean sea level (MSL) values from national authorities on the understanding that these quantities have been computed accurately. Inevitably, this has always not been the case.

The PSMSL has devised a range of tests on the supplied MSL information which guards against gross errors in the dataset such as transcription errors or large unrecorded datum changes. Some of these tests are 'common sense', others are 'statistical':

(1) A check is made that the average of the quoted monthly mean values is consistent with the quoted annual mean.

(2) 'Common sense' consistency checks are made on the data including checking that the datum information is consistent with previous knowledge. This includes reference to back correspondence and simple time series plotting.

(3) A search for outliers is made on data for each calendar month of the year separately, and for the annual means, for all possible time-spans containing at least 20 years of data. A linear fit is made to the time series and any individual monthly mean value more than 4.5 standard deviations from the fitted line is flagged.

(4) A search is made for incorrect datum information by performing a set of linear regressions of RLR annual mean values against the supplied datum correction factors ('RLR factors' in PSMSL terminology) in all possible 20-year time-spans. A correctly adjusted RLR time series should be uncorrelated with the RLR factors.

(5) A search for jumps in the RLR time series is made for each calendar month of the year separately and for the annual means. The difference between a mean value and the corresponding value for the next year of data is histogrammed and any outlier more than 4.5 standard deviations from the mean-difference is flagged.

(6) A test is made for 'upside down' data. In several countries the main research interest is the study of vertical land movements, rather than sea level changes, with the result that MSL data are often quoted as the distance below a benchmark height rather than above it. The most sensitive test to guard against such an error is an inspection of the seasonal cycle which, for 'upside down' data, would appear opposite to that observed in neighbouring records and opposite to oceanographic and meteorological expectations.

(7) A set of 'buddy checking' is made in which the RLR data from one station is subtracted from

that of a neighbouring station (or 'buddy') which is less than 400km away. Over this short distance most of the MSL variability due to oceanographic and meteorological forcings in the two records should be similar and will cancel out giving a difference time series primarily composed of relative vertical land movements, instrumental and datum errors and any small spatially varying ocean and weather influences. The previous tests are then applied to the difference time series and any discrepancies are flagged.

These tests have been applied to the entire dataset and inconsistencies have been referred back to the national authorities, although the reasons for some apparent oddities are no doubt lost in history.

2. RELATED ACTIVITIES

(1) A year ago we started to send back to national authorities entire copies of our data holdings from their countries with a request that they be checked as far as possible. This can take a lot of work and the best benefit can be expected from those authorities which have responsibility for the entire national network and which have been in operation for many years. Copies have so far been sent to Australia, USA, Brazil, Canada, India, Sweden, Norway, Japan, Netherlands, Yugoslavia, Greece, S.Africa, Denmark, Peru and the TOGA Center, with replies received in most cases.

(2) The new Unix version of the databank has been expanded to flag station-years which appear odd (e.g. a data spike) but which are not so odd that we would want to reject them completely. The national authority may well have confirmed the oddity to be real (e.g. due to earthquake). The flag in most cases will be supplemented by a short entry in the documentation for the station.

(3) As Klaus Wyrtki and others have often pointed out, the best check on monthly mean data is to ensure good quality control of the original hourly values. Over the past year, we (Lesley Rickards) circulated GLOSS Contacts for a 'once only' submission of all original data from GLOSS sites which are in computer form. This will give a dataset from which the suitability of each site to the global network can be examined. However, an added benefit is that as the dataset is enhanced each year through WOCE, TOGA, ACCLAIM etc. activities, the PSMSL should be increasingly backed up by the original information.

(4) Probably the best data checkout comes from dedicated scientific analysis, and we are pleased that developments such as some increase in the amount of MSL analysis at Bidston, GLOSS related activities (e.g the IOC-UNEP Pilot Project in the Indian Ocean), and easier access to the PSMSL dataset (by public access Unix disk complementing the GF3 magnetic tapes) will all result in higher quality data.

DATA PROCESSING AND QUALITY CONTROL AT THE TOGA SEA LEVEL CENTER

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ABSTRACT

Data processing and quality assurance methodology applied at the TOGA Sea Level Center (SLC) is described for two data streams: those stations from the Indo-Pacific Sea Level Network, which is jointly operated by the University of Hawaii and various international agencies, and those stations from regional and national networks as contributed to the TOGA SLC by various agencies.

The TOGA SLC prepares scientifically valid, well-documented, standardized sea level data sets of hourly, daily, and monthly values for the international data banks. As of July 1992, 191 stations with 1772 station-years of quality assured data have been submitted to the World Data Center-A for Oceanography and the Permanent Service for Mean Sea Level.

1. INTRODUCTION

Time series records of sea level heights from around the globe have provided a wealth of information on the highly variable nature of the boundary between the land and sea. High frequency sea level variations with periods from seconds to hours are dominated by wind waves, seiches, tides, storm surges, and occasional tsunamis (Pugh, 1987). Slower movements of sea level height with periods from days to years are mostly associated with transient synoptic scale meteorological features, ocean circulation patterns, and seasonal and other short-term climatic fluctuations (Mitchum and Wyrtki, 1988). The longest sea level records show the influences of local land subsidence, plate tectonic movements, and climate variations (Emery and Aubrey, 1991).

The routine collection of monthly sea level values from international sources began in 1933 with the creation of the Permanent Service for Mean Sea Level (PSMSL). Tremendous effort was applied to rescue historic data sets, verify datum levels, routinely gather data and documentation, standardize the format, and distribute the data (Pugh et al., 1987).

In the 1970's, a network of sea level gauges was implemented on tropical Pacific islands as part of the North Pacific Experiment (NORPAX) specifically for the purpose of associating sea level variations with ocean circulation and short-term climate change (Wyrtki, 1973). As a result, the sea level records helped link several features of the large-scale ocean-atmosphere interactions (Wyrtki, 1979a; Wyrtki, 1979b).

The ocean-atmosphere coupling became the focus of scientists interested in the predictability of climate. The World Climate Research Programme (WCRP) was created by the World Meteorological Organization and the International Council of Scientific Unions (ICSU) with the objective to determine the extent of climate variability and man's influence on climate. A key activity of the WCRP is the Tropical Ocean Global Atmosphere (TOGA) Project, which has been organized with the joint support of the ICSU's Scientific Committee on Oceanic Research and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

In 1985, the TOGA Sea Level Center (SLC) was created at the University of Hawaii (UH) to concentrate the efforts of acquiring, processing, and archiving sea level data from the tropics. The

TOGA program requires daily sea level values from sites identified in the implementation plan (International TOGA Project Office, 1987). Originally, requests were made for daily values from various data collecting agencies. These values proved inadequate for quality control and requests were restated for hourly values. As the quantity of data collected by the TOGA SLC increased, expertise in data management was provided by the National Oceanographic Data Center (NODC) of the National Oceanic and Atmospheric Administration (NOAA) with the establishment of the Joint Archive for Sea Level (JASL) at UH in 1987. The JASL supports the TOGA SLC in the collection, quality assurance, management, and dissemination of the data.

The TOGA SLC prepares scientifically valid, well-documented, standardized sea level data sets of hourly, daily, and monthly values for the international data banks. As of July 1992, 191 stations with 1772 station-years of quality assured data (Figure 1 and 2) have been passed from the TOGA SLC to the World Data Center-A for Oceanography, which is co-located at the NODC in Washington, D.C., and to the PSMSL, which is co-located at the Proudman Oceanographic Laboratory at the Bidston Observatory.

In this paper, data processing and quality assurance methodology is described for two data streams (Figure 3): those stations from the Indo-Pacific Sea Level Network, which is jointly operated by the University of Hawaii and various international agencies, and those stations from regional and national networks as contributed to the TOGA SLC by various agencies.

2. DATA FROM THE INDO-PACIFIC NETWORK

Through efforts of UH, Pacific Tsunami Warning Center, and NOAA scientists, the Pacific Island Sea Level Network (Wyrtki et al., 1988) was established with over 35 sites in the tropics. The success of this network lead the UH scientists to place additional installations in the Indian Ocean, where presently 17 stations are operational. The TOGA SLC routinely processes data from 52 sites of the Indo-Pacific Sea Level Network, with 31 Pacific and 3 Indian Ocean stations relaying in near-real time via satellite to UH (Kilonsky and Caldwell, 1991). The TOGA SLC also routinely receives via satellite and processes 18 stations in the tropical Pacific from NOAA's Global Sea Level Network of New Generation Water Level Measuring Systems.

Quality assurance begins at the sea level station. Redundancy of instrumentation is vital for reducing data gaps and quality control. Typically, at least two separate float and stilling well configurations are established at each site, with usually more than one recording mechanism for a given well (Figure 4). Recently, secondary data loggers have been installed at a few sites. Each source of data is referred to as a data channel (Table 1).

The station is maintained by a local employee, who is trained by UH technicians and is responsible for tide staff readings, minor repairs, and monthly changes of data storage media. Due to the vastness of the network, regular site visits by UH technicians are not feasible, thus the local site attendants are crucial elements of the network.

Routine surveys of a network of vertical control points or fixed bench marks on land relative to the tide staff zero are performed during visits by UH technicians or other qualified personal. Each site has its own independent bench marks and local datum, the tide staff zero, which is used for referencing the measured sea level heights. This information is used to control the stability of the reference level, although subtle differences between the tide staff zero and the bench marks from survey to survey are not applied during the final calibration. The survey readings tend to be noisy and analysis over a long period of time is necessary to identify the vertical movement of a bench mark relative to the tide staff zero. However, the survey summaries are critical for maintaining an historic datum that can be used when replacing a destroyed station.

Beginning in 1988, a new feature was added to the installation configuration: a reference level switch. The switch is a triggering mechanism that is surveyed to the tide staff zero and mounted at a fixed position on a piling or a stilling well at about the mid-tide level. It is linked to a Handar Data Collection Platform (DCP) that measures the precise time when the sea level vertically passes the trigger in the switch. The switch information supplements the tide staff observations for calibration of the measured sea level heights. The Handar DCP relays sea level, switch, and technical data in near-real time to UH.

The near-real time data received at UH are continuously logged on a dedicated microcomputer and previewed daily to monitor the health of the installation. Spurious signals are noted and pointed out to the UH technicians. On a weekly basis, a status report of the entire near-real time network is provided to the Director of the TOGA SLC.

Primarily, quality control occurs on a monthly basis. For each station, a plot is made of the observed high-frequency data, which are digitized at either 4-, 5-, 6-, 10-, 15-, or 60-minute intervals for each data channel; the predicted tides, which are calculated from a routinely updated data base of harmonic constituents (Foreman, 1977); the residuals, which are defined as the observed data minus the predicted tides; and the differences among channels (Figure 5). These plots form the core of the quality control and are used for isolating spurious outliers, timing drifts, instrument malfunctions, and datum shifts.

Spurious outliers normally consist of one or a few consecutive points that are grossly out of the normal range of variance and are usually caused by telemetry, instrumentation, digitization, or processing errors. The obviously incorrect data are replaced by missing data flags.

Timing drifts are usually due to misinitialization of the instrument, processing errors, or drifts of the clock. The drifts are visible on the plots of residuals as periodic fluctuations similar to the tides. For shifts that are exact increments of the digitized sample interval, corrections are made by moving the entire questionable segment forward or backward in time by the appropriate number of time steps. For timing drifts that are not an exact increment of the digitizing interval, the data are not adjusted but the problem is documented in the final quality assessment.

The residuals can show a variety of other spurious signals. Sources of errors include the blockage of the stilling well by sand, overgrowth of marine organisms on the float and in the well, faulty float cables, and leaky floats (UNESCO, 1985). The errors are handled on a case by case basis and corrections are applied if warranted. In some instances, the data are not recoverable and the entire faulty time segment is removed from the series.

Datum shifts can be monitored by two methods for the near-real time data set: by inspection of plots of residuals and daily values and by analysis of the data from the reference level switch. Datum shifts appear as quasi-step functions in the plots and are easily identified. The switch data provide reference level calibration information with typically about 60 pairs of gauge/switch values per month per channel for analysis. The monthly standard deviation of the difference of the pairs is on the order of 0.01 feet. For the near-real time data, the switch provides a preliminary calibration constant and information on the stability of the reference level of each instrument. Datum shifts that are identified by the plots or switch data are documented and temporarily adjusted; however, the final calibration is not applied until the end of the year.

On a delayed-mode basis, as the tide staff observations and ADR paper tape gauge rolls are received by mail at UH, a separate analysis is performed. Data spikes, timing errors, and other spurious features are corrected.

For calibration, the tide staff readings are paired with ADR values for corresponding times and plotted on a scatter diagram (Figure 6). Normally about 28 pairs are available for analysis each month. Erroneous pairs are removed. A standard deviation and mean difference between the tide staff/ADR pairs is obtained. The standard deviation is on the order of 0.1 ft for most sites and the mean difference is the preliminary calibration constant for the ADR data based on the tide staff.

At the end of the year, the measured sea level heights from each channel are linked to a fixed datum, the tide staff zero. A final calibration constant is chosen for each extended time period, normally about a year, in which no physical changes occurred to the instrumentation, installation foundation, Handar software, tide staff, or the switch. The preliminary calibration constants of the ADR based on tide staff observations and of the ENC and ENB based on the switch are analyzed for stability (Figure 7). A final calibration constant is chosen for each extended period and for each channel such that comparisons between instruments using calibration constants from both the tide staff observations and the switch are internally consistent.

Finally, after each data channel is calibrated, a primary channel is chosen for each station. Historically, the ADR was selected, but since 1990 the ENC has been frequently designated as the primary channel due to its precise timing. The high-frequency data from the primary channel are decimated to hourly values with a three-point Hanning filter. This filter was chosen to minimize aliasing from subsampling and to minimize the attenuation of the tides. The procedure was tested with actual tide data as well as random data. Gaps in the primary channel are filled with data from quality assured data of the redundant channels. If the gap is less than 25 hours and if redundant data are not available, the gap is interpolated using the predicted tides. This consists of statistically comparing the predicted tides to the observed data and shifting the predicted tides in time to correct for timing differences. Then the linear interpolation between hourly values at the end points of the gap in the residual series is added to the corresponding corrected predicted tides to obtain interpolated values over the span of the gap. Interpolated gaps greater than 7 hours are documented in the final quality assessment, which includes information on the installation, processing, and other data characteristics. At this point, normally about 18 months after the year in which the data were collected, the data of the Indo-Pacific Network are available for distribution and are submitted to the international data centers.

3. DATA RECEIVED FROM REGIONAL AND NATIONAL NETWORKS

Hourly data are routinely received at the TOGA SLC from nearly 50 agencies collecting data in nearly 60 countries of the tropical and subtropical Pacific, Indian, and Atlantic oceans. Data holdings and processing techniques have been documented for the TOGA Pacific and Indian Ocean sets (Caldwell et al., 1989 and 1990) It is assumed that correction and calibration were applied by the originators and that the data are received in good quality. After applying a host of checks to ensure the scientific integrity of the data, hourly, daily, and monthly data sets are prepared for the permanent archive with scientific units in millimeters and the time in Greenwich Mean Time.

As each data set is received, the data are converted to the JASL standard format and the hourly values are plotted. This preview verifies the scientific units and completeness. For annual updates that have a common time span with previous submissions, comparisons during the time overlaps are made as tests of consistency.

A linear least squares tidal analysis (Foreman, 1977) is applied to calculate the harmonic constituents. From about a year of apparently good data, the harmonic constituents are used to calculate predicted tides, which are subtracted from the observations to form residuals. Plots of the hourly residuals are a primary quality control tool. For most island stations with deep adjacent waters, the tides contain very few high-frequency components (Figure 8a), the harmonic analysis reflects the observed tides to a high degree, and residuals have a flat signature. For regions with shallow coastal shelves, influences of rivers, or complex coastal or basin geometry, the tidal analysis may not completely resolve many of the higher frequency components, and the residuals will show the non-linear, shallow water tides (Figure 9a and b). The hourly residuals are inspected on a case by case basis to correct or flag only erroneous features in the observed data.

Data spikes and timing offsets are readily identified in the hourly residuals (Figure 8b). Data spikes are replaced by missing data flags and subsequently interpolated. Timing errors are adjusted if the drift is an exact increment of an hour; otherwise, the erroneous feature is not adjusted but is documented in the quality assessment file. Short gaps or grossly incorrect values in a span of 24 hours or less are interpolated using predicted tides. Interpolated values in a span greater than 7 hours are documented.

Plots of daily and monthly values and plots of differences among adjacent stations are used primarily for monitoring the reference level stability. For example, the plots of daily data for stations along the East Malay Peninsula (Figure 10) show high coherency and stable levels. Daily plots occasionally show erroneous spikes caused by incorrect data over a span of hours to a few days. When available, bulletins which provide summaries of storm tracks, such as the Mariners Weather Log (published by NOAA) or the Darwin Tropical Diagnostic Statement (published by the Bureau of Meteorology of the Northern Territory Region of Australia), are studied to verify if the extreme sea level heights are related to meteorological events.

Detection of datum shifts necessitates the use of all available tools described above. For non-subtle shifts, the hourly residuals clearly show quasi-step function signatures. When these jumps occur periodically in time, such as at the beginning of the month when the analog or ADR gauge rolls are changed, it is clear that the reference level shifts are erroneous. The original tide staff observation and station maintenance sheets usually provide the necessary information for correction; otherwise, the data are flagged.

In some cases, quasi-step function signatures are identified in the hourly residuals associated with natural events, such as the arrival of Kelvin waves or westerly wind bursts at Nauru in the Equatorial Western Pacific. For these cases, comments are added to the quality assessment.

There are other times when the lack of a change in sea level may warrant suspicion. In Figure 11a, a Kelvin wave was clearly monitored in the daily sea level as it passed through the Galapagos; however, it failed to show a signature at La Libertad. In Figure 11b, differences among adjacent stations show the sharp jump between the Galapagos and La Libertad, although, the difference between La Libertad and Tumaco, which is about 700 km to the north and has a much stronger annual cycle, does not clearly indicate a reference level change for La Libertad. Another method of detection is the comparison of the data from redundant sensors. Unfortunately in this case, the redundant data were suspicious as well. Because the La Libertad data were calibrated by the Ecuadorian authorities prior to submission to the TOGA SLC, the only means of confirming and/or resolving the shift is to ask the data contributors to investigate the original analog rolls and the tide staff comparison sheets.

Datum shifts are not corrected unless calibration information, such as tide staff observations and matching gauge values, are available. The originators of the data are asked to review their records to help resolve questionable features. If the originators do not have calibration data available, comparisons with redundant gauges and nearby sites may warrant the adjustment of a datum shift. All adjustments to the reference level and any suspicious signature is thoroughly documented in the quality assessment.

Other valuable tools for verifying data integrity include plots of detrended data for areas of extreme local vertical land movement and comparisons of monthly values with the annual cycle (Figure 12a and b). For this example, after the presently unexplainable trend of -21 cm/year was removed, the data appeared reasonable and the difference with its mean annual cycle did not show any obvious reference level jumps.

For historic data sets, comparisons are made with data held by the PSMSL. This provides a consistency test by ensuring that data originators have not adjusted the reference levels after submitting the data to the PSMSL.

The data sets from each agency are returned for their review. If necessary, unresolved features are highlighted for inspection of the original records and inquiries are made for specific information about the sea level station and processing techniques.

After quality control is complete for the hourly values, these data are filtered to daily values with a 119-point convolution filter (Bloomfield, 1976). The daily values in turn are decimated to monthly values with a simple average, which is archived along with a count of the number of days available for the calculation. If more than seven days are missing per month, the monthly value is not calculated and is replaced with a missing data flag.

For each site, a quality assessment file is maintained, which accompanies the data in the final archive. On an annual basis, the quality assured and documented data sets of hourly, daily, and monthly values are submitted to the international data banks and a new set of requests are sent to the data contributors.

4. SUMMARY

Data processing and quality control at the TOGA SLC has been described. The data are received at the TOGA SLC from the UH Indo-Pacific Network, which is mostly motivated through efforts of the TOGA Project, and from many national and international agencies that kindly contribute data and assistance without hesitation. The international data centers such as the World Data Center-A for Oceanography co-located at the National Oceanographic Data Center in Washington, DC and to the Permanent Service for Mean Sea Level at the Bidston Laboratory, ensure advertisement of the data availability and allow easy access for the scientific and public communities.

The TOGA stations as well as the recently designated World Ocean Circulation Experiment (WOCE) stations are active components within a larger endeavour, the Global Sea Level Observing System (GLOSS) (Wyrtki and Pugh, 1985) of the IOC. The efforts of GLOSS will help ensure permanency of the over 300 established and proposed sea level sites around the globe through international and regional guidance and assistance.

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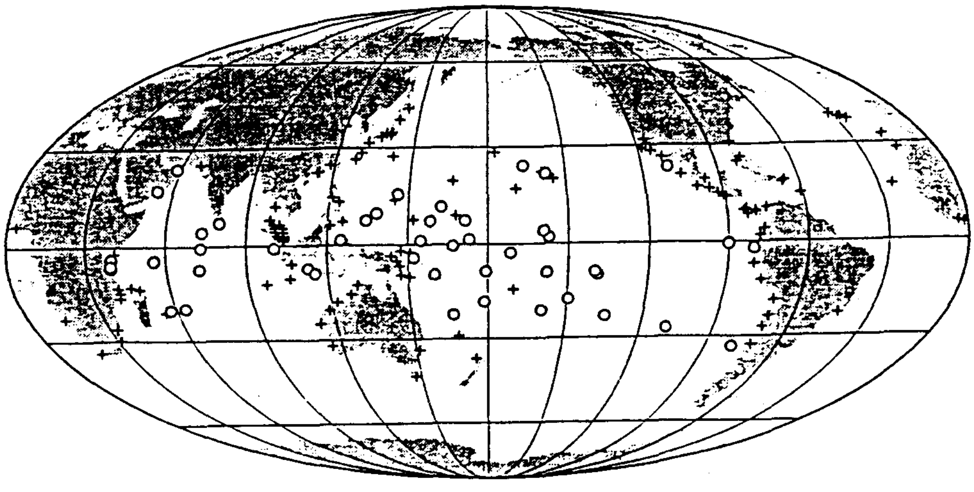

Figure 1. Sea level stations processed at the TOGA Sea Level Center and submitted to the World Data Center-A for Oceanography and the Permanent Service for Mean Sea Level.

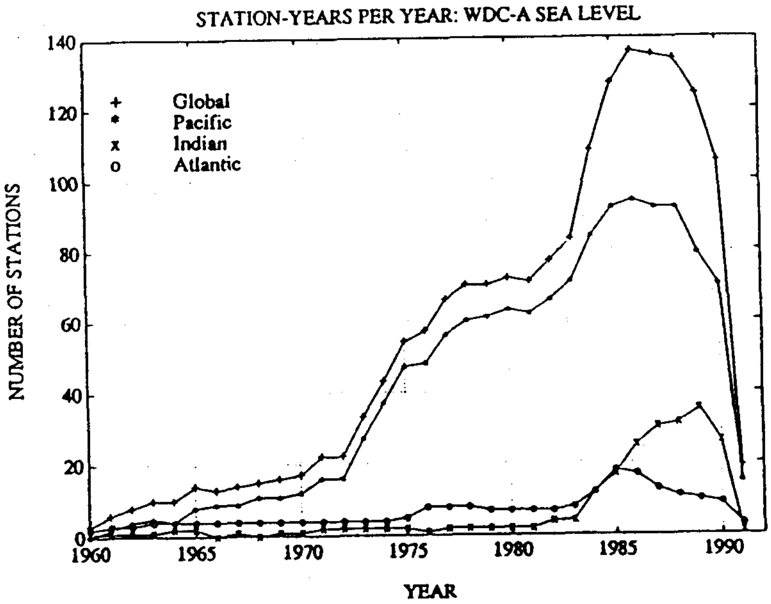

Figure 2. Data availability by year and ocean basin.

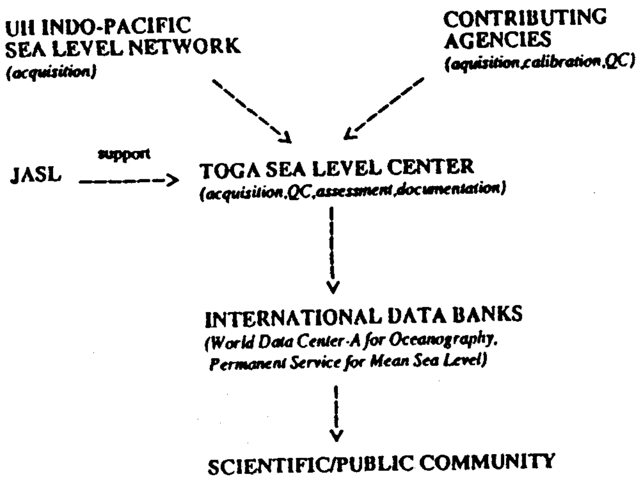

Figure 3. Data flow through the TOGA Sea Level Center.

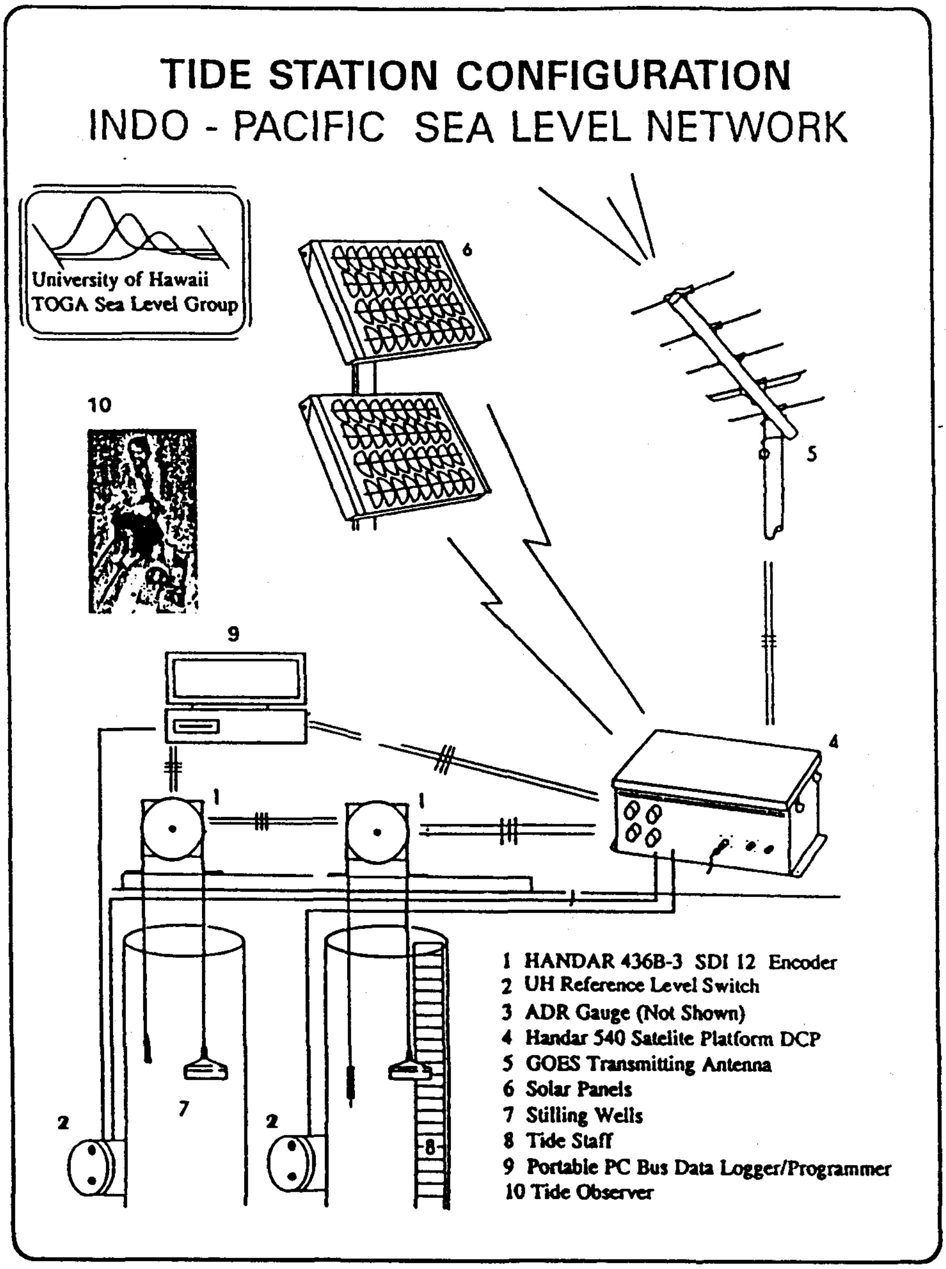

Figure 4. Typical installation designed by UH scientists.

Table 1. Sea Level Data Channels of the Indo-Pacific Network

CHANNEL	GAUGE/RECORDING MECHANISM
ADR	Analog-to-Digital Recorder
ENC	Handar Encoder
ENB	Secondary ENC
ENO	ENB linked to a data logger
BUB	Bubbler Pressure Sensor

Note: 1) each site typically has two float and well gauges 2) all channels are linked to float and well gauges except BUB which is pneumatic, 3) the ENC and ENB are independent with separate floats and wells, 3) the ADR, ENB, and ENO utilize the same float and well, 4) the ADR is optional and is not at all sites, and 5) all data are transmitted via satellite from a Handar Data Collection Platform except for the ADR punch roll, which is received at UH by mail.

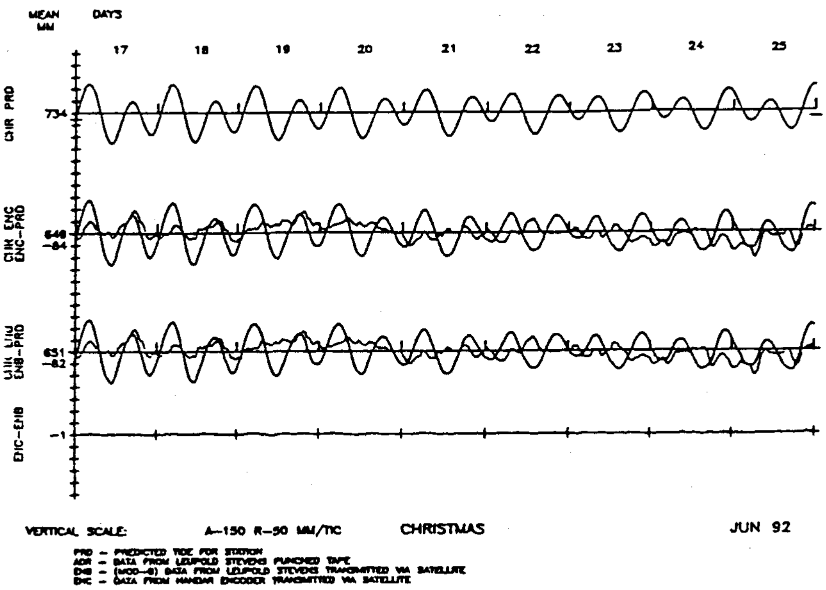

Figure 5. Nine-day time section showing data, residuals, and differences for near-real time data transmitted by the Handar DCP via satellite and received at UH.

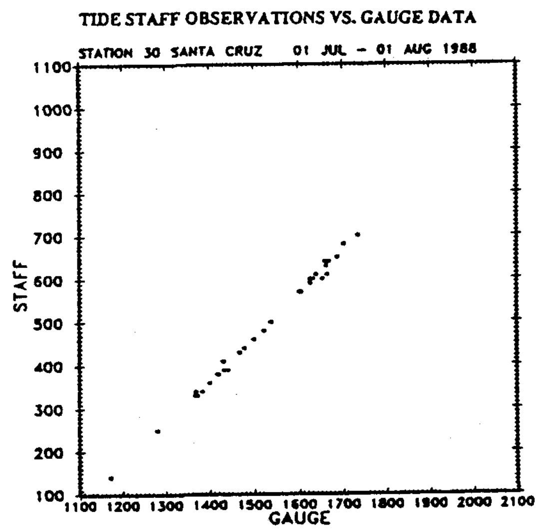

Figure 6. Scatter diagram for assessing the quality of the calibration information.

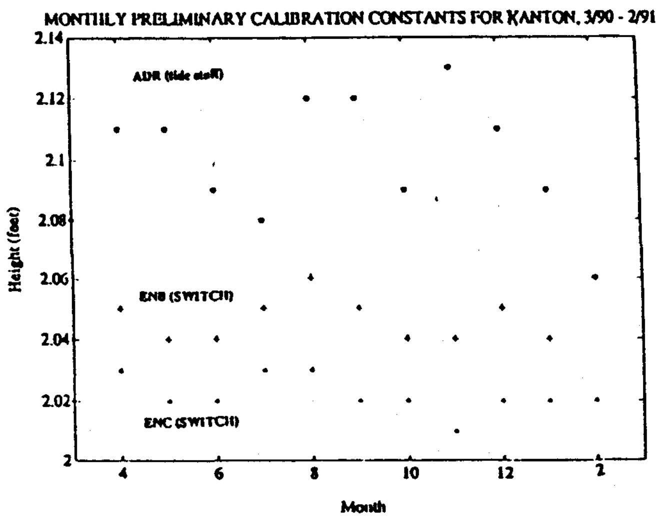

Figure 7. Assessment of the stability of the preliminary calibration constants for each channel using the tide staff observations and the reference level switch. The standard deviation in obtaining each preliminary constant is about 0.1 ft. for the tide staff readings and 0.01 ft. for the switch.

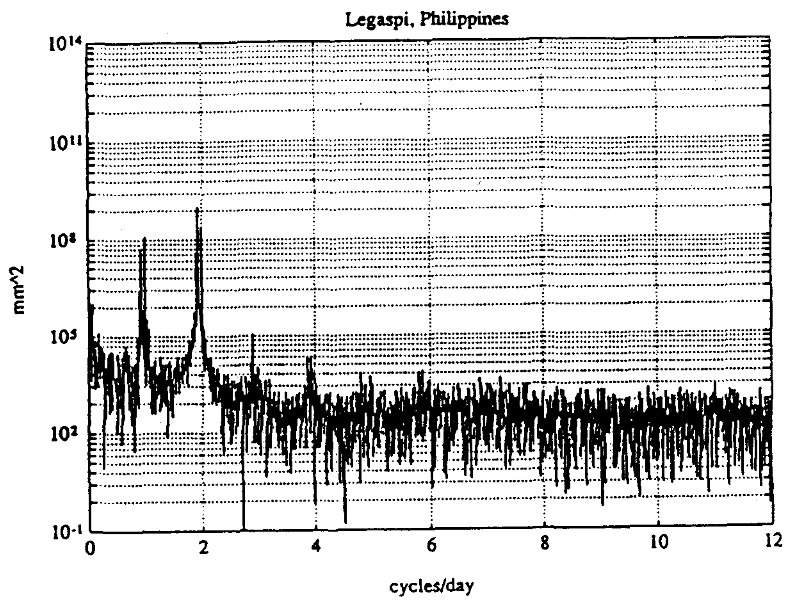

Figure 8a. Tidal spectrum with a weak high-frequency components.

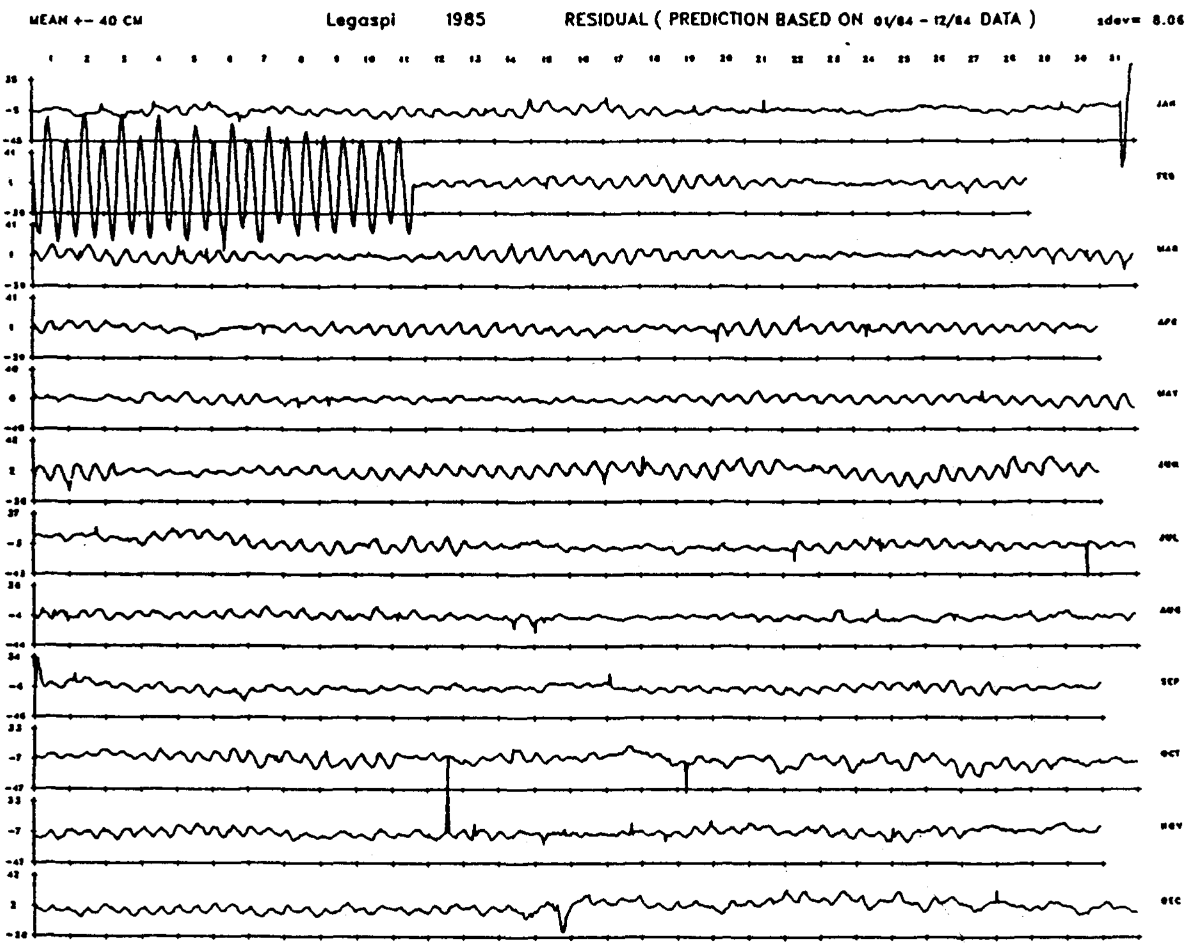

Figure 8b. Residuals of the hourly data showing a timing offset of exactly one hour in early February and many data spikes. The data are from an A.OTT float and well analog gauge that have been spot sampled on the hour. The timing shift and spikes were correctable.

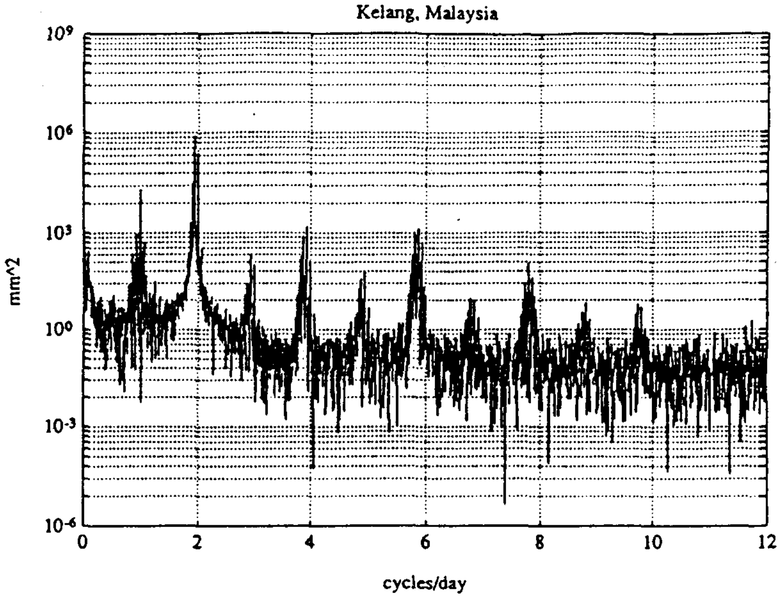

Figure 9a. Tidal spectrum with significant shallow water components.

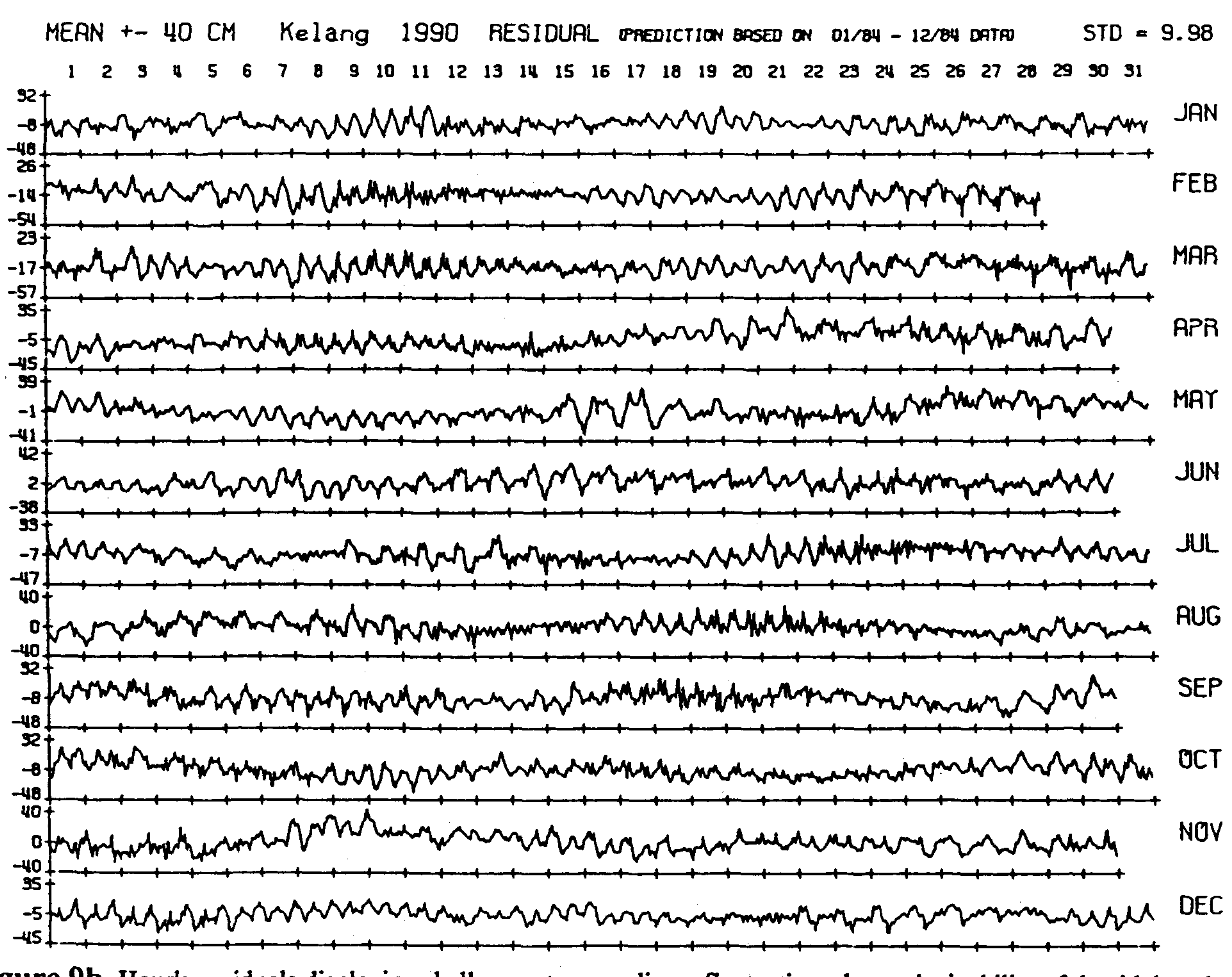

Figure 9b. Hourly residuals displaying shallow water, non-linear fluctuations due to the inability of the tidal analysis to resolve these higher frequency tidal components. These high-quality data are from a digital float and well gauge that samples every 10-seconds with 50-second averages, which in turn are decimated to hourly with a five-point filter.

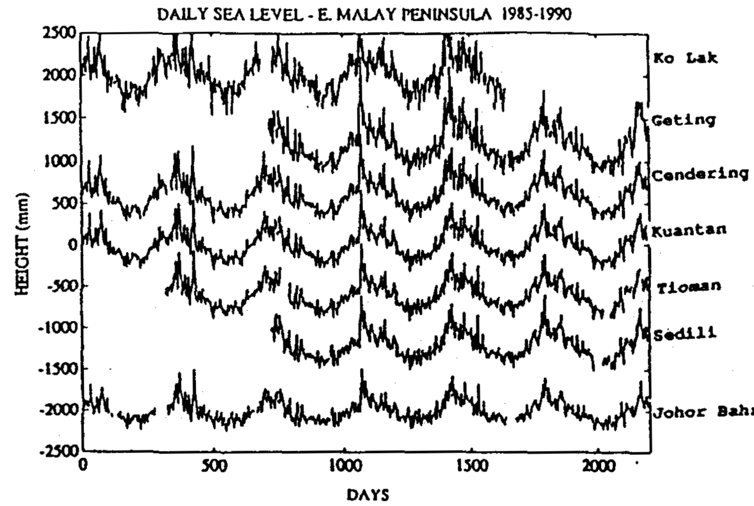

Figure 10. For regional stations, overlays of daily data plots are useful for examination of the stability of the reference level. In this case, the sea level is highly coherent and no obvious reference level shifts are present.

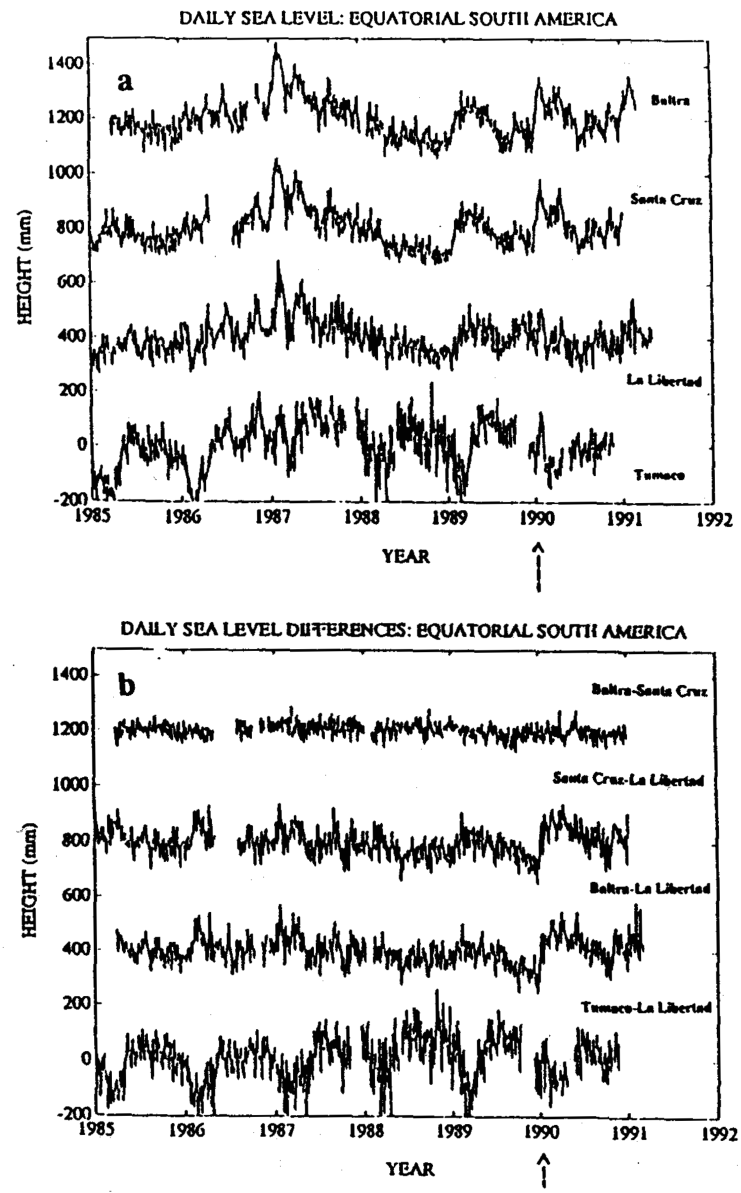

Figure 11a and b. In early January 1990, a Kelvin wave is seen in the daily sea level values at Baltra and Santa Cruz in the Galapagos and at Tumaco, Colombia, but is not evident at La Libertad, Ecuador (top plot, note arrow). The differences (below) between La Libertad and the Galapagos stations show a sharp jump. The original data rolls and tide staff readings for January 1990 of La Libertad must be investigated to resolve if a reference level shift has occurred.

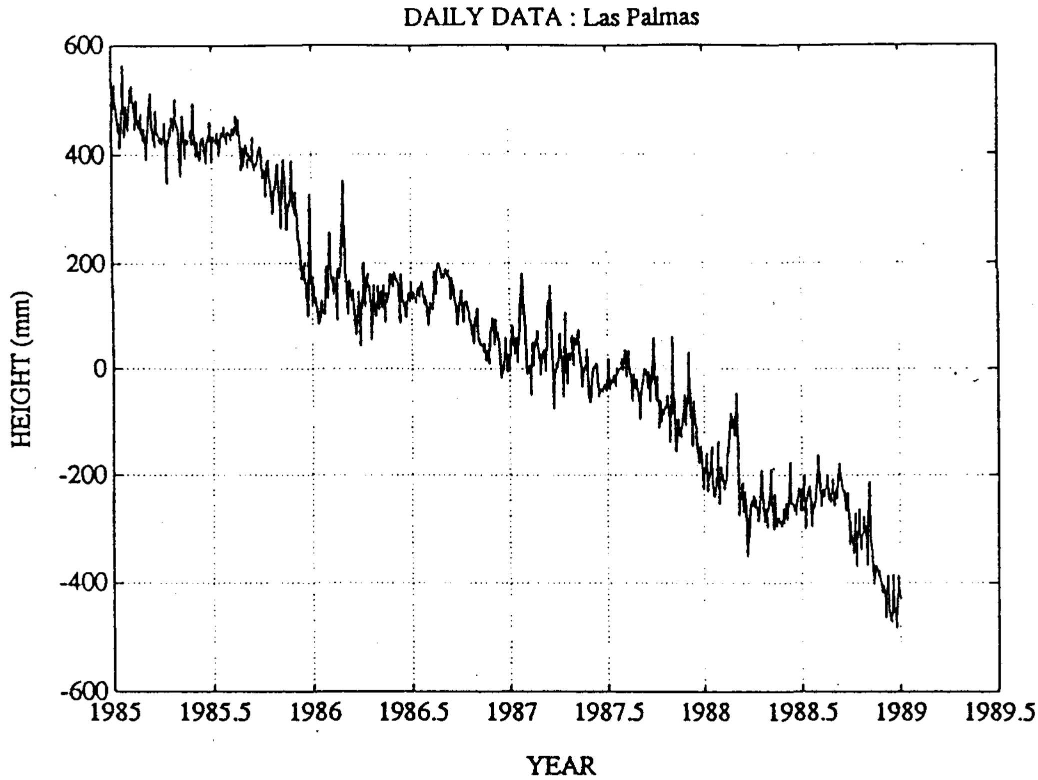

Figure 12a. Daily data with a downward trend of about 21 cm/year. The cause of the trend is presently unknown.

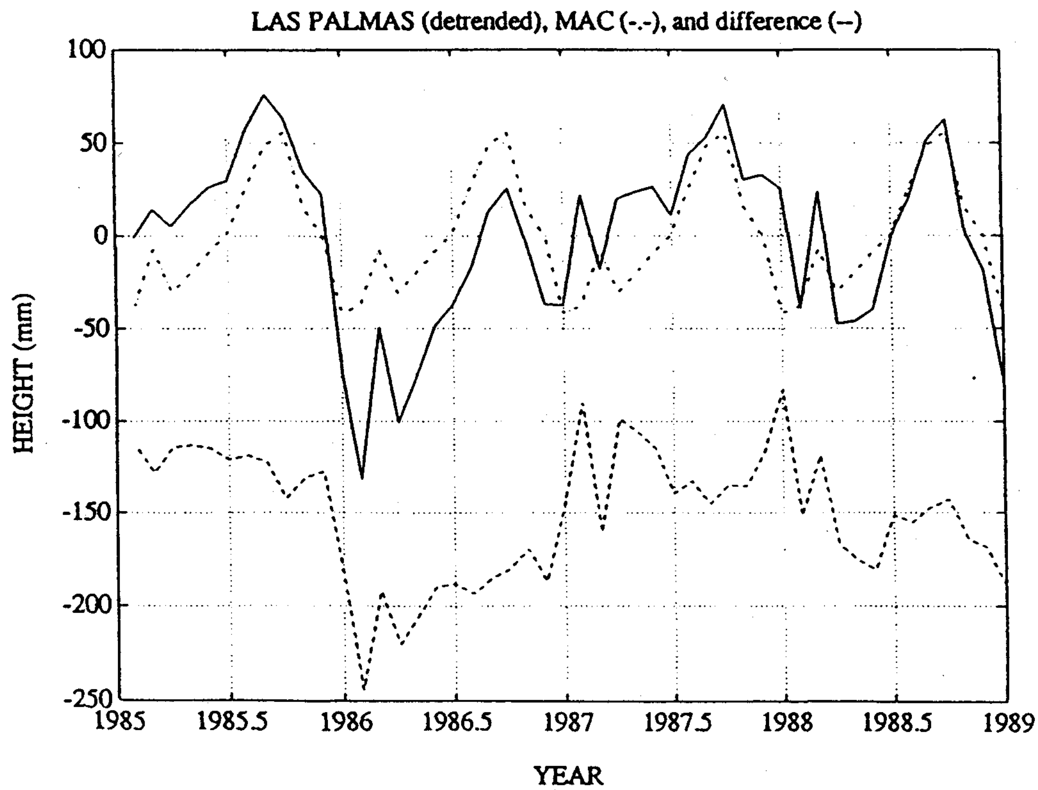

Figure 12b. Monthly data with trend removed (solid line) superimposed with the Mean Annual Cycle (MAC) above and detrended monthly data minus the MAC (below). With the trend removed, the data appear reasonable.

WOCE SEA LEVEL DATA PROCESSING AND QUALITY CONTROL

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The British Oceanographic Data Centre (BODC) has been given joint responsibility of Sea Level Data Assembly Centre (DAC) for the World Ocean Circulation Experiment (WOCE) together with the University of Hawaii. BODC's role is to assemble, distribute and supply sea level data to the full extent of quality control possible covering all the 100 or so gauges in the network. WOCE requires that the elevations should be accurate to 1 cm, the timing to 2 minutes and the atmospheric pressure measurements to 1 mbar. Quality control includes checking for reasonable values, tidal analysis to remove tidal variation to enable screening of residuals as a diagnostic for datum shifts and timing errors. Unusual signals are checked against adjacent stations.

BODC has gained much expertise in the field of data processing and banking over the last 15 years. Thus in some ways we have approached the task of WOCE Sea Level DAC from a different angle from those who operate a sea level network and process the resulting data. BODC has a sophisticated system for handling and archiving many types of oceanographic data. If we had set up a system for sea level data alone our approach may have been different with other aspects of the work being emphasised. Our starting point in data banking has been to assume that some quality control has already been carried out on the data and we have concentrated on checking apparently simple items. An example would be ensuring that latitude and longitude are correct (and not inland!) and checking that the format remains consistent throughout the data series or group of series. In our experience this does not always happen. This is especially true when dealing with historical data, for example it is quite possible that the unit of measurement may change from, say, metres to centimetres part way through a data series! In the past, operating a data banking service for a variety of data types, resources were not available to fully analyze all of the data that were to be banked. In any case, as noted above, this should not be necessary as the scientist working on the data should have done this. More recently however, BODC has had a much greater involvement in the early stages of data processing for a variety of oceanographic data.

One departure from this earlier mode of operation came with BODC's involvement with the Mediterranean Alpine Experiment (MEDALPEX). BODC was the RNODC (Responsible National Oceanographic Data Centre) for sea level data for this experiment which took place in 1981-82. Sea level data were requested from seven Mediterranean countries and passed through the normal data banking procedures. In addition to this the data were tidally analyzed and low pass filtered. Obviously to quality control the data this thoroughly was highly desirable, and allowed problems to be solved which might otherwise have gone unnoticed. Although we approached the task from a data management perspective, where our expertise lay, scientific support was always available at the Proudman Oceanographic Laboratory (POL) from sea level scientists and data processors who between them had a vast amount of experience. Once the data set had been compiled and quality controlled a report and magnetic tape containing the data set was produced.

This then is the background to BODC's involvement with WOCE sea level data. As it happens BODC is currently rewriting the sea level data processing software at POL, which hopefully will mean that, as far as possible, all sea level data coming in to the laboratory will be processed with the one software package. So operating a WOCE Sea Level DAC has meant an extension of our data banking work to include such tasks as tidal analysis as a matter of routine, in order to provide thorough quality control of the data.

Our first task as DAC was to set up a data tracking system, which we could continually update and data arrive and are passed through the various stages of processing. This also doubles as a data catalogue to scientists requesting data.

When data arrive at the DAC on magnetic media they are checked for readability, hopefully within 15 days of receipt and the data supplier will be informed of any problems and, if necessary, will be requested to resubmit the data.

Backup copies are made of the incoming data and they are transferred to BODC's internal format to allow checking and quality control of the data. Some software is written for each new format received, to interface with the main checking software. This has produced quite a lot of work in the early stages of the DAC operation; hopefully data suppliers will, in most cases, send subsequent years of data in the same format as the first submission. The data undergoes many checks at this stage to ensure that the format is consistent throughout the data and that the parameters and their units are properly defined. Most data are received in units of metres/centimetres/millimetres but some data are received in millibars where, for example, pressure recorders have been used.

Whilst working out the procedures to be adopted for data quality control and assessment due consideration was given to previous experience of sea level data banking for UK coastal and bottom pressure gauge data, the Mediterranean Alpine Experiment (MEDALPEX) sea level data set, the data processing system at POL and on the methods in use at the TOGA Sea Level Data Center in Hawaii. We have chosen to write our own software, partly because we already had a powerful software package for the rapid display of data, and also because of the speed of processing available on the workstations for repeated tidal analysis.

There are three main components to the data quality control:

i) flagging obvious wrong values
ii) correcting timing drifts
iii) maintaining reference level stability

Quality control is carried out with the aid of high speed graphics workstations, initially utilising the existing BODC data screening software, with some enhancements. Most significantly this means that data are tidally analyzed prior to being loaded into the data screening package. In the future we will be able to analyze the data from within the software package. The sea level data values are checked for spikes and physically unreasonable values. Most often the data are supplied as hourly values, but there is no restriction on this. The residuals produced from tidal analysis are screened to check for datum shifts, timing problems and other errors. The predictions used in the tidal analysis can also be displayed.

The screening software allows the sea level data values to be displayed as a stacked monthly plot or as a simple time series (i.e. parameters plotted against a single time axis). In this latter presentation all the parameters measured can be displayed, or a subset can be chosen. It is possible to overlay parameters which is very useful for the raw data and the predictions. It may also be useful to position atmospheric pressure near to the residuals. It is possible to 'zoom in', 'zoom out' and rapidly pan through the data. The scale of each parameter on the screen can also be set to a suitable value for that data. Thus the sea level data and predictions can be at the same scale while the residuals are at a larger scale. Adjacent stations can be compared to check out unusual signals. This can be done by grouping the series together prior to using the package. The data series can then be viewed together, one plotted over the other as required. In addition, any other parameters, for example, atmospheric pressure or sea surface temperature, can also be displayed and examined.

For WOCE, it is expected that the sea level and accompanying data will be supplied annually and, more importantly, that each submission will comprise at least 1 year of data from each site. If data of shorter duration are received they are quality controlled when a year of data is available, unless, of course, the tide gauge is expected to be non-operational for a long period. There are several reasons for this approach, the most important being that it is easier to detect and correct datum shifts using a longer time series and the effort required to check 1 year of data is similar to that required for 1 month of data.

Tidal analysis is performed on a year of good data. The Doodson type of harmonic analysis, which has been in use for many years at POL, is used. The harmonic constituents produced by the tidal analysis of one year's data can be used to predict the tides for other years. We will also maintain a database of harmonic constituents. Constituents can then be compared with those obtained from previous years of data and also with values in the IHB or POL constituents data bank.

Problems with the time channel will show up on the residuals obtained through the tidal analysis. The TOGA Data Centre corrects for timing errors of exact increments of 1 hour by shifting the data. BODC will do this after discussion with the data supplier. The software needed for this task is not part of the currently available package, but is under development.

Reference levels should have been corrected by the data supplier, but checks will be made using the residuals and also by calculating daily values from a simple 25 hour average. These can then be plotted out to monitor the stability of the reference level. Comparisons can again be made between nearby stations. Where shifts in the datum level are suspected, these will be referred back to the originator and appropriate adjustments made to the data. If shifts in the datum level cannot be resolved, they will be documented and this information stored with the data.

Tide gauge records will be split into separate files if the reference levels on either side of a shift are not linked by levelling to the same benchmarks. BODC will follow the TOGA Sea Level Centre practice of distinguishing between such stations by alphabetically placing letters behind the station name (i.e. Eniwetok-A, Eniwetok-B).

Where possible gaps in the data will have been filled from redundant sensors. However this is not always possible and the TOGA Data Center has developed methods for filling gaps in the data of 24 hours or less. This has not been the approach BODC has taken in the past, since the philosophy adopted has been not to alter any data values unless instructed to do so by the data originator. This approach will continue, at least in the immediate future. Hence gaps in the data will be flagged as null data and will be documented. However if data arrive via the TOGA Center already gap filled, these values will be retained but flagged as interpolated, if the appropriate information is provided. Spikes in the data record will be flagged as suspect values.

A quality assessment will be carried out on the data which will include a completeness index, indicating the percentage of days with data for each year, and a some measure of quality. This will indicate the proportion of available data that do not contain questionable fluctuations in the residuals. Each case must be carefully checked to determine whether the fluctuation is a natural event, an indication of mechanical problems with the tide gauge, or the result of unreliable predicted tides. All such features will be noted in the documentation stored with the data.

The qualifying information accompanying the data are also checked. This includes assembling datum information; the local datum should be recoverable through a set of permanent and auxiliary benchmarks. Details of the datum and its method of determination (including GPS surveys) is also required. Plain language documentation is compiled to accompany the data. This includes benchmark and levelling information, peculiar characteristics of the tide gauge site (for example, complex local geography, seiching, silting up of the harbour, river mouths) and listings of gaps in the data record. Any problems not resolved with data originators are also documented. Table 1 shows the sort of accompanying information which is needed to accompany the data so that scientists other than the data suppliers can use them with confidence.

Table 1: Information required to accompany the data

Each data series should include entries for the following:

- Country and organisation responsible for data collection and processing
- Originator's identifier for the series (e.g. site name and year)
- Geographical location (latitude and longitude)
- Dates and times of the start and end of the data series

Sufficient plain language documentation should accompany the data so as to ensure that they are adequately qualified and may therefore be used with confidence by a secondary user.

- Instrument
  - a) Instrument description, manufacturer, model, principle of measurement, method of recording - refer to publication or briefly describe
  - b) Instrument modifications and their effect on the data
  - c) Method and times of calibration, to include calibration factors
  - d) Frequency of cleaning, control of biological fouling
  - e) Operational history
  - f) Pertinent instrument characteristics; for example, for a conventional stilling well, information should include well diameter, orifice depth below mean water level and orifice height above sea bed; for a bubbler gauge - tube length, tube diameter, orifice diameter, density value used to convert to elevation, acceleration due to gravity and the formula used to compensate for tube length.

- Site
  - a) Brief description of location of tide gauge
  - b) Description of tide gauge benchmarks
  - c) Datum relationships
  - d) Datum history

- Data sampling/processing

  Brief description of processing procedures used to obtain final data values including:
  - a) Sampling scheme e.g. continuous recording, instantaneous, averaged
  - b) Interval between samples and duration of individual samples (raw data)
  - c) Number of raw data samples
  - d) Nominal interval of processed data
  - e) Gaps in the data record
  - f) Timing and/or datum corrections applied
  - g) De-spiking/smoothing/interpolating methods and editing procedures

Report any additional item or event that may have affected the data, or have a bearing on the subsequent use of the data.

The WOCE Sea Level DAC has been in operation for almost two years and to some extent we are still developing and improving our procedures. In addition we still have some work to complete in our software development, for example, the calculation of daily, monthly and annual mean values of sea level. For this we will standardise on the method used by the TOGA Sea Level Center. In the future other higher level products may be produced, but our initial priority is to build up a high quality data bank of sea level data.

SEA-LEVEL DATA PROCESSING IN JAPAN

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1. ORGANISATIONS

In Japan, Sea-level observations are mainly carried out by three organizations, Geographical Survey Institute (GSI), Japan Meteorological Agency (JMA) and Hydrographic Department of Maritime Safety Agency (HD-MSA). Their observation purposes are different, but the results are valid for each other. For smoothly exchange of their data, Coastal Movements Data Center was set up within GSI, as shown in figure 1. Monthly mean sea level (NS~) values observed by Agencies are sent to CMDC and compiled promptly in order to detect crustal movement for earthquake forecasting. Almost permanent tide stations of Japan are checked for their reliabilities such as datum control, and registered in CMDC. Therefore monthly MSL values and the essential information of tide stations are archived and served by CMDC as well as individual agencies. In 1991, 115 stations are registered in CMDC.

Figure 1 : Japanese organizations concerned to sea level observations.

	--- Geographical Survey Institute (GSI)
Coastal Movements Data Center (Within GSI)	
	--- Japan Meteorological Agency (JMA)
	--- Hydrographic Department of Maritime Safety Agency (HD-MSA)
	--- Earthquake Research Institute of Tokyo University
	--- others

2. DATA PROCESSING

Float type tide gauges installed on the stilling well are used in the almost permanent stations of Japan. Pressure gauges are used only in the temporary or hostile stations. Following is the case of float type gauge.

Traditional sea-level data processing of our HD is as follows;

a) Check the time and height references of the record.
b) Smooth tidal curve to diminish fluctuations shorter than 4 hours period.
c) Read hourly values, and times and heights of High and Low Waters.
d) Calculate the daily means (24 hours) and the monthly means.

Additionally, the reading errors are checked using a quadratic function fitting program.

Recently, automatic tide gauge systems are used in many stations. In this system, sea-level is sampled every 15 or 30 seconds using shaft. encoder, which measures the rotation of gauge shaft following the up-down movement of float and converts analogue to digital values. Sampled data is smoothed using low-pass filter to cut the high frequent fluctuations shorter than 2 hours. Smoothed data is checked by eye and re-sampled to hourly values. Remains are same as traditional processing.

3. DATUM CONTROL

Observation Datum is checked one or two times a month by comparing the actual water height which is measured from the contact point to the water surface, and the reading in the record. Continuity of the observation datum to the contact point is maintained. The heights from the contact point to tide gauge bench mark (TGBM), and to the geographical surveying bench mark (GSBM) network which is connected to the national datum T.P. (Tokyo Peil), are surveyed about every 5 years.

Recently, GSI starts the project to fix their TGBM in the geocentric coordinate using VLBI and GPS.

4. PUBLICATION

Coastal Movement Data Center publishes monthly and annual MS~, values in the following;

Annual report :	Monthly mean sea level with Monthly mean atmospheric pressure Monthly mean sea water temperature
Every 5 years :	"TABLES AND GRAPHS OF ANNUAL MEAN SEA LEVEL, ALONG THE JAPANESE COAST"

Each organization publishes daily MSL values as the annual report of the tidal observation every year as follows;

Geographical Survey Institute

Tidal Records: Yearly

Japan Meteorological Agency

1) Prompt Report of Sea-level observation* : Monthly

2) Tide Observations : Yearly

* which includes monthly MSLs and extreme values such as in the cases of storm surge or tsunami.

Hydrographic Department **

Data Report of Hydrographic Observations, series of Tide: Yearly

** Sea Level Data of the Syowa Station is published as a part of "Japan Ant.arctic Research Expedition (JARE) Data Report" (Oceanography series) from the National Institute of Polar Research : Yearly

Japan Oceanographic Data Center which is established within the HD, collects and compiles the hourly sea-level data in non-real time base, which are utilized for oceanographic researches.

PROCEDURES FOR THE QUALITY CONTROL OF OBSERVED SEA LEVEL AT THE AUSTRALIAN NATIONAL TIDAL FACILITY (NTF)

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1. INTRODUCTION

In this brief report, the intention is to consider three aspects of data quality control practised at the NTF:

a) The system provided to maintain the data, after its acquisition, free from degradation in a secure data bank.

b) The procedures applied to incoming data from local authorities which use low-key float-operated or equivalent tide gauges.

c) The procedures applied to incoming data from SEAFRAME stations in co-ordinated standard networks such as the Australian Baseline Array.

2. DATA BANK SECURITY

Although modern technology has brought welcome innovations, not least the ability to communicate data by telemetry via satellite or modem in real-time, and even to reprogram the field equipment in a similar manner, it is nevertheless necessary to consider associated hazards. When responsibility is accepted for the collation, processing and archiving of data of a strategic nature, which may hold the key to major environmental processes, of which climate change is perhaps the most significant, it is also implied that the parallel responsibility exists to maintain the quality of the data over long periods of order twenty years and more. The same evolution of technology which provides the power of the systems unfortunately also allows exposure to risk from social and cultural noise or at worst erosion resulting from illegal intrusion or careless practice.

At the NTF much attention has been given to these matters leading to the structure of the computational and communication system which is illustrated in Figure 1. The building in which the Facility is housed is linked to the adjacent University Campus by a microwave link and thence to the outside world. Within the building a first low level security element exists in the form of a PABX Gateway Card which identifies the building and a second card which then identifies the NTF tenancy. Within the Facility there exists a structure providing increasing security through three Local Area Networks (LANs), with the strategic data bank receiving maximum protection and virtual isolation in LAN 3.

LAN 1 represents a basic level of security and is served by a number of P.C.s where general miscellaneous work is conducted including administration, report production and word processing behind the protection of the NTF Gateway. Further security is achieved through the monitoring of user practices.

LAN 2 represents the area for Research and Development. Here resides the standard product software, time series analysis and activities associated with product development:

Modelling
Program Development
Publications
Instrument Calibration and tests
Archive of station history and performance
Mirror copy of the Data Bank
Electronic Mail
Administrative Archives and Management

The nature of these tasks inevitably requires a measure of external intercourse and the migration of software. Software used here is developed, or if of a proprietary nature, is recomplied in this environment. Arrangements are also in hand to provide a quarantine service for software where the above procedures are not relevant.

This sub-network is protected by the FIREWALL principle, a combined hardware/software dedicated host which resides between the internal network and the external world. Viewed from outside, the host renders the internal network invisible and by this means provides a high level of security. From inside, the FIREWALL is completely transparent.

LAN 3 is the residence of the Operational System and Data Base supporting Data Acquisition, Data Banking, Data Processing and Analysis with its own computer power on hand. To all intents and purposes this is a stand-alone system, normally isolated from the other networks except when an internal demand for communication arises and then only through hygienic media under policed conditions.

Other than this integrated hierarchy of sub-networks, the basic data archive and essential software are stored on rewritable optical disks and duplicated on the DSS DAT tape micro cassettes. The former have a capacity of 600 megabytes and the latter in excess of a gigabyte. The material is subjected to a rigid backup routine and copies are stored in two different areas of the University Campus.

3. PORT AUTHORITY DATA

The Facility aims to access data from the coastlines of Australasia wherever material of acceptable quality can be found and especially where there is a prospect of long term observation. There are a number of unfortunate implications, notably:

* No control over instrumentation or field procedures although the national committee, The Permanent Committee on Tides and Mean Sea Level, has assisted by preparing a booklet on recommended operating procedures (PSMSL, 1984).

* Considerable diversity in instrumental types exists:- digital, punched paper tape, drum chart, strip chart, etc.

* Data is only available in arrears, and typically 18 months in arrears, so that there is little opportunity to react to malfunctions.

* Local interest is non-scientific and associated with coarse resolution.

* Growth in the Public Service agencies of the philosophy of cost recovery places a monetary value on tidal data and militates against the principles of national and digital data banks in the public domain.

The NTF continues to receive data from 60 or more such stations of which approximately half are of analogue type. Most of these are processed annually to update the basis of tidal predictions for Australian ports. Rigorous quality control procedures are not generally applicable but procedures which are applied fall into three categories:

The experience gained in processing and archiving each data set is summarised on a standard format, Figure 2, which includes some feedback and advice to the local operators. Unfortunately the time lag in this exercise limits the effectiveness of the procedure but an attempt is made to interest the operator in the value of his or her attention, and encouragement is given to maintain recommended standards. In particular the operator is requested to keep check sheets where time and height discrepancies of the record are recorded at frequent intervals. Such discrepancies are incorporated in the data processing phase.

Given the shortcomings described above, greater reliance is placed upon analytical and statistical procedures. In a routine fashion an harmonic tidal analysis is performed on the new data and the results are compared with earlier versions directly, and through the computation of tidal times and heights for an independent observed time series say over one month. More reliance is placed upon a study of the residuals (Observed elevations minus computed elevations) of the dependant data set and again these are considered in various ways, for example:

In their own right since a pseudo-harmonic signal which occurs from time to time in a residual series may well indicate time errors, while discontinuities might herald a datum shift. Data processing staff become quite expert in such identifications whereupon, with reference again to the original record, errors can be adjusted. Special attention is given to the regional coherency of the residual signal noting that the Australian coastline is noted for the progression of coastally-trapped long waves. If a particular residual time series simply displays apparently random excursions from a zero value extending up to 1 m or more and with pseudo-periods of five and more days, there is no evidence to assist in the diagnosis of the cause. The explanation could be that the tide gauge or its operator has a poor control of datum which is then allowed to drift in a significant fashion. Alternatively this behaviour might well represent the presence of real signals. The answer is to formulate a work plan which proceeds in time on a regional basis so that the residual series at each port can be compared and contrasted with its neighbours both spatially and temporarily. A pattern in time and space is obviously the argument for the presence of a real signal as opposed to instrumental or operator malfunction.

Figure 3 shows residual time series from seven Australian stations plotted for a period of one month. The coastal distance from Geraldton to Williamstown is in excess of 3,500 Kms and over this range regional support is given for the reality of non-tidal signals. Other features such as the negative "spike" on the second day at Esperance, are seen to be noise and long sequences of such a treatment provide a basis for the recognition of station specific signatures such as the 8 hour shelf resonance which occurs at Thevenard.

* Rare opportunities arise where the station instrumentation provides some duplication of information, which can be used for verification. Figure 4 illustrates one such example of a station in Thailand for which the non-tidal residuals are plotted over a period of 6 months from two radically different sensors at the same site; one, a Leupold and Stevens A71 float-operated gauge is compared with the output of a bottom-mounted vented pressure gauge, an ENDECO 1029. The quality of agreement is mutually confirmative.

There are special problems in the case of historic data in Australia which arise from imperfections in its infrastructure combined with the logistic problems associated with the size of the continent. Nevertheless geodetic survey is now expanding rapidly, spurred by the new technologies which compensate for the tyranny of distance. Local tide gauge surveys and tide

gauge calibrations are inevitably rare events and in consequence the monitoring of tide gauge datum proves to be very difficult. The recommended practice for mean sea level to adopt strict references (Revised Local Reference, RLR) to a specific benchmark at a specific epoch has been impossible to achieve. In consequence the attempts to produce long homogeneous time series suitable for studies of sea level trends or the statistics of extreme events have had to rely upon theoretical and statistical procedures applied to the time series in order to identify and remove datum shifts. This has been achieved for some 85 locations on the Australian coastline and the resultant data sets are probably as homogeneous as any other sea level time series, but absolute datum cannot be identified or quoted.

4. DATA FROM THE SEAFRAME ARRAYS

Although the basic principles, already outlined, can be applied to the SEAFRAME systems, these represent a revolution in quality control in their self-diagnosis abilities, in their automatic provision of statistical assessment, in their real-time telemetry allowing rapid response to malfunction and more, but especially in their reliability. The quality control provisions are therefore more powerful, nevertheless, as is common with new systems some years must pass during which experience will be gained. In consequence the procedures at the NTF must be regarded as in an evolutionary mode.

The procedures outlined in the following notes constitute a package nearing completion but with the provision for continual development in response to experience.

A) Daily validation

Prior to normal office hours when telephone modem connections are less troubled by traffic and when line charges are at a minimum, the appropriate computer workstation interrogates each SEAFRAME station on the network and receives a brief report on the condition of the system. The daily observed values are downloaded at this time. In the event of failure to connect there is a wait time imposed of 1.5 minutes when a second interrogation is initiated. If the second attempt also fails then this station is relegated to the bottom of the list and the procedure is repeated at the end of the normal schedule. Table 1 gives an example of the simple output which is available to the array operators from start of business and in this as in most cases a reassuring interrogation schedule is provided. Here the differences in the number of bytes is explained by the different number of sensors on board and the report deals with the last complete day in GMT available at the time of the schedule.

B) Weekly Procedures

Although the daily procedures are very helpful in providing assurance that the SEAFRAME stations are continuing in operation, without major malfunction, and with a clear indication of the size of the time series held on station, the quality of the data is unassessed at this stage. In this context it is also necessary to bear in mind that the SEAFRAME stations are set up to meet much tighter specifications then their forbears so that quality control is much more important. In the current schedule operated at the NTF, data is subjected to quality control on a weekly basis. In so doing advantage is taken of automatic features of the instrumentation in order to produce a quick check upon the data gathered. At the present time, the checks undertaken are of a simple nature and are based upon an identification of the observed range, the mean value and its standard deviations, and in this way are designed to provide a comprehensive check against the occurrence of gross error with a minimum of operator attention.

An example of the Weekly Data Verification Report is given as Table 2A and a glossary of the items listed is provided in Table 2B.

C) Improvements in Train

It is now planned to introduce more rigorous checks in this weekly reporting procedure as follows:

Now that a sizeable observed record is available from most of the new stations, the intention is that harmonic tidal constituents will be held on the interrogating workstation so that the Primary Water Level may be checked against the computed astronomical tide, after adjustment for the static barometric pressure effect, using the simultaneously observed barometric pressure from the File F.

Currently the B sensor is simply stored and is available for use should there be a problem with the Primary Water Level Sensor. It is now planned to provide a more realistic interpretation of sea level from the pressure record using water temperature from the record of File E, and to combine this with a regional estimate of open ocean salinity, noting that by definition, all the Baseline Stations have open ocean exposure, in order to provide a realistic value of water density which is likely to have a significant seasonal variation.

When laboratory calibrations have progressed to the stage where the influence of vertical temperature profiles on the Aquatrak system is known with better precision, a new file will be created to hold "corrected" primary data using the upper and lower temperatures of the File A.

D) Monthly and Longer Period Checks

As in the case of the Port Authority Data, great reliance is placed upon graphical presentation (Figure 5) as the most efficient and comprehensive of checking procedures. Note that:

* the plots of filtered residuals represent an inverse image of barometric pressures with a high degree of agreement.

* the primary sensor + 0.96 * secondary sensor plots almost as a straight line and, given the proposed treatment for density and the application of a common datum this situation will be improved.

* the perturbing meteorological parameters are ready to hand as are the enclosed air temperatures which will affect the speed of the acoustic pulse.

Perhaps the most powerful check of all remains, as in earlier cases, as the graphical representation of the non-tidal residuals and, for the same region as depicted in Figure 3, these are plotted in Figure 6 for the SEAFRAME gauges. Apart from Broome, which is still unsupported by high quality tidal harmonic constants, the individual signatures of the stations become readily recognisable as the sea level responds to the high energy of the Southern Ocean as in Hillarys, Esperance and Portland, or to the local resonances at Thevenard and Port Stanvac and, of course the progressive coastally-trapped long waves.

E) Characteristics of Standard Deviations

As indicated elsewhere (Lennon et al, 1992) there remains a great deal to be learned before it can be claimed that the performance of the Aquatrak sensor is known and understood in its application to high resolution sea level measurement. Meanwhile the possible tests to be made are numerous. It is intended to conclude this study by reference to one incomplete testing procedure, of many, which shows potential in this respect. In the Figure 7 series, the standard deviation of the samples which make up each 6 minute primary water level measurement is plotted against sea level. The exercise provides greater insight into the performance of the Aquatrak system, so that certain comments can be made:

Laboratory tests and experience elsewhere had suggested that very minor irregularities in the inner tube, down which the Aquatrak pulses are fired, could provide noise and premature "returns". Consequently there was some anxiety over the performance of the system at locations where the tidal range is large. The Baseline stations with the largest tidal range are in fact Broome and Darwin. Figure 7 suggests that these cases are adequately treated by the SEAFRAME system. The plots are well-ordered in a compact distribution with few outliers and with small standard deviations despite the fact that at mid-tide level, considering the tidal range, the sea level must be changing quite significantly within the 3 minute sampling period. Presumably this is the signature of calm tropical conditions.

The inference can be made that the tidal range is not a significant factor in producing large standard deviations, note for example the position of Portland and Esperance. What seems to be the governing feature is exposure to wave conditions in a high energy ocean.

The anomalous plots for Rosslyn Bay represent the most startling result from this exercise, and in this context the following comments can be made:

* There is a clear gradient with the standard deviations increasing sharply with distance from the Aquatrak.

* There is a suggestion of a serious calibration problem.

* Reference to the residual series, not present here, revealed a connection in a strong diurnal spike with a preference to occur near midday. This cannot be explained by an Aquatrak fault or by any association with tidal range or by a simple error in laboratory calibration. The cause seemed to be associated with atmospheric effects. It so happens that there is concern over the site works at this station where, because of concern over small boat traffic, the tubular structure is fitted with a metal shroud as a protective device. It appears that an undesirable effect of this shroud is to perturb the temperature at the top of the acoustic travel path above the "Cal. hole", which therefore can no longer be assumed to represent the total acoustic flight path to the water surface. This single diagnosis is sufficient to justify the procedure of careful examination of the behaviour of the standard deviations against other variables, notably the relationship between standard deviation and the tidal elevation.

There remain several puzzling features in the treatment of the standard deviations and these remain under study, not least being the anomalous characteristics of the plots for Port Stanvac which, at this stage, seem to be attributed to an inherent software problem in the instrument.

5. CONCLUSIONS

At the NTF a start has been made in designing procedures to test the validity, precision and accuracy of the sea level observations before consignment to the strategic data bank. This procedure is in a state of development which clearly will continue in the foreseeable future, especially in the case of the newly-commissioned SEAFRAME stations as their complex performance characteristics are slowly revealed. In those matters which concern GLOSS, and especially in studies associated with Climate Change and Sea Level Trends, or Satellite Altimetry, the specifications are so rigorous, and the task of meeting them so onerous, that every attempt must be made to be assured that the sea level observations are sound, free from bias and clearly enroute towards the concept of Absolute Sea Level. The comments here represent a first attempt to meet these responsibilities.

REFERENCES

Lennon,G.W., Woodland, M.J. and Suskin, A.A.: Acoustic sea level measurements in Australia, IAPSO/GLOSS Meeting, IOC, Paris, October 1992.

Permanent Committee for Tides and Mean Sea Level: Recommended operating procedures for tide gauges on the national network. National Mapping Council of Australia, Special Publication No. 9, NMP/001.6, 1984.

FIGURE CAPTIONS

LIST OF TABLES

VIEWED FROM OUTSIDE

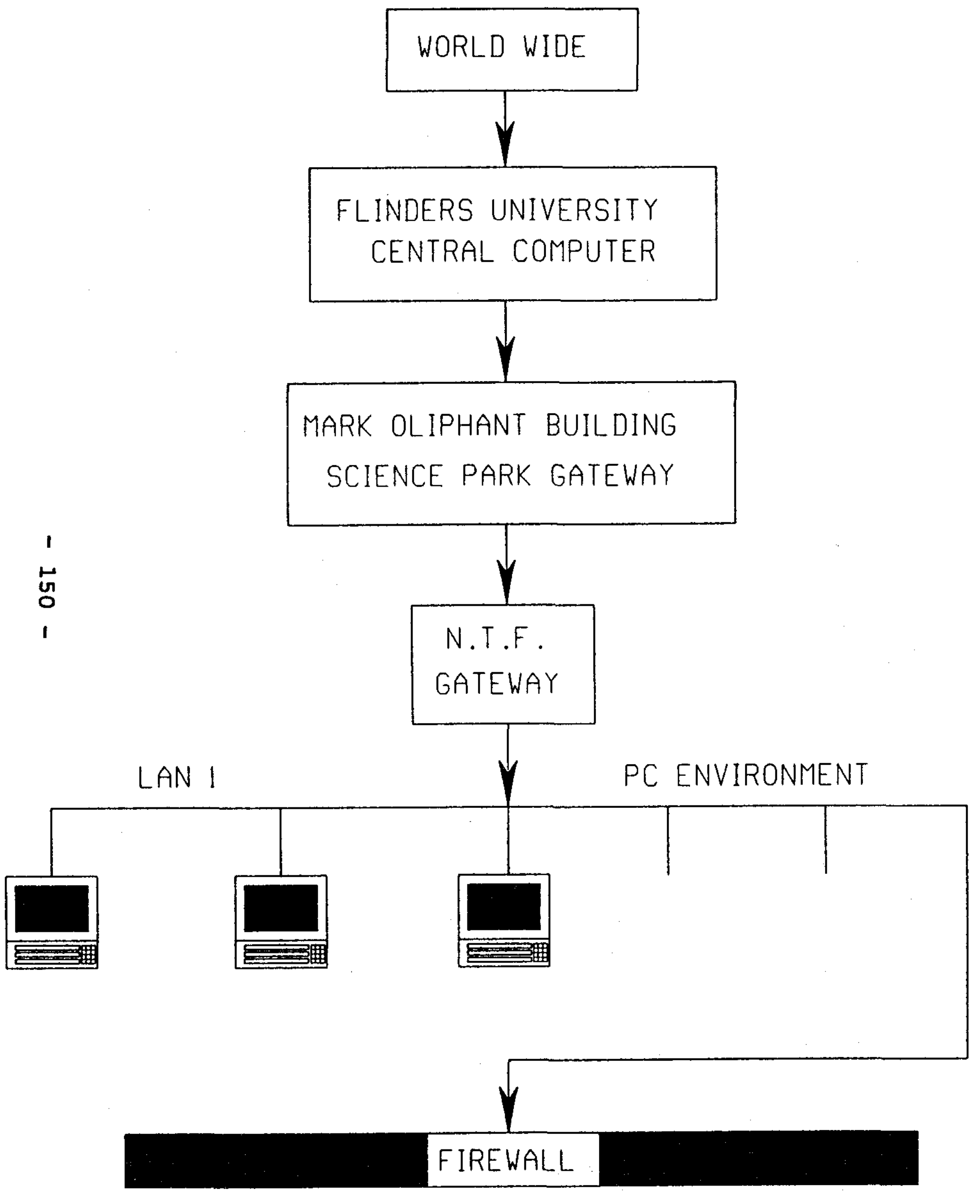

Figure 1A

AS VIEWED BY PROJECT STAFF

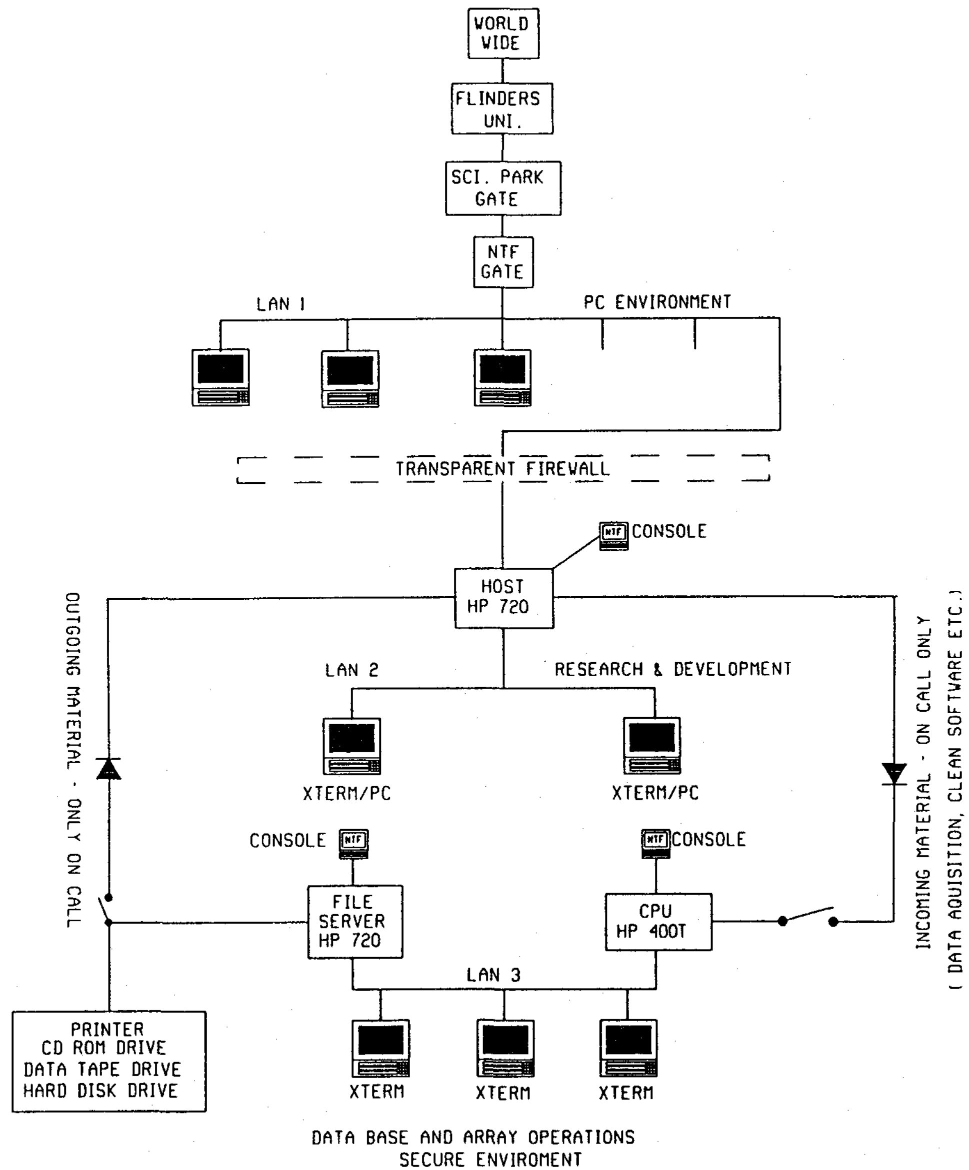

Figure 1B

PERMANENT COMMITTEE ON TIDES AND MEAN SEA LEVEL

SEA LEVEL DATA QUALITY

STATION: ____________ SUPPLIED BY: ____________

PERIOD OF DATA: ____________ DIGITISED BY: ____________

1. CHART TYPE: STRIP ☐ DRUM ☐ 2. RECORD TYPE: COPY ☐ ORIG. ☐

3. RECORD QUALITY: EX. ☐ GOOD ☐ FAIR ☐ POOR ☐

4. SCALE: HEIGHT 1m = ______ cms. 1hr = ______ cms.

5. CONTINUITY (GAPS): FREQUENCY: ____________ DURATION: ____________

6. FREQUENCY OF TIME AND HEIGHT CHECKS: ____________

7. METHOD OF TIME AND HEIGHT CHECKS: ____________

8. NOTATION OF CHECK DATA: GRAPH ☐ SEPARATE ☐

9. MAGNITUDE OF ERROR OBSERVED: TIME: ____________

HEIGHT: ____________

10. OPERATOR RESPONSE TO ERROR: NOTE ☐ ADJUST ☐ NONE ☐

11. ADEQUATE INFORMATION ON DATUM SUPPLIED: YES ☐ NO ☐

12. INDICATION OF INDEPENDENT CHECK BY WELL FLUSHING OR WELL SOUNDING: YES ☐ NO ☐

13. COMMENT: ____________

Figure 2

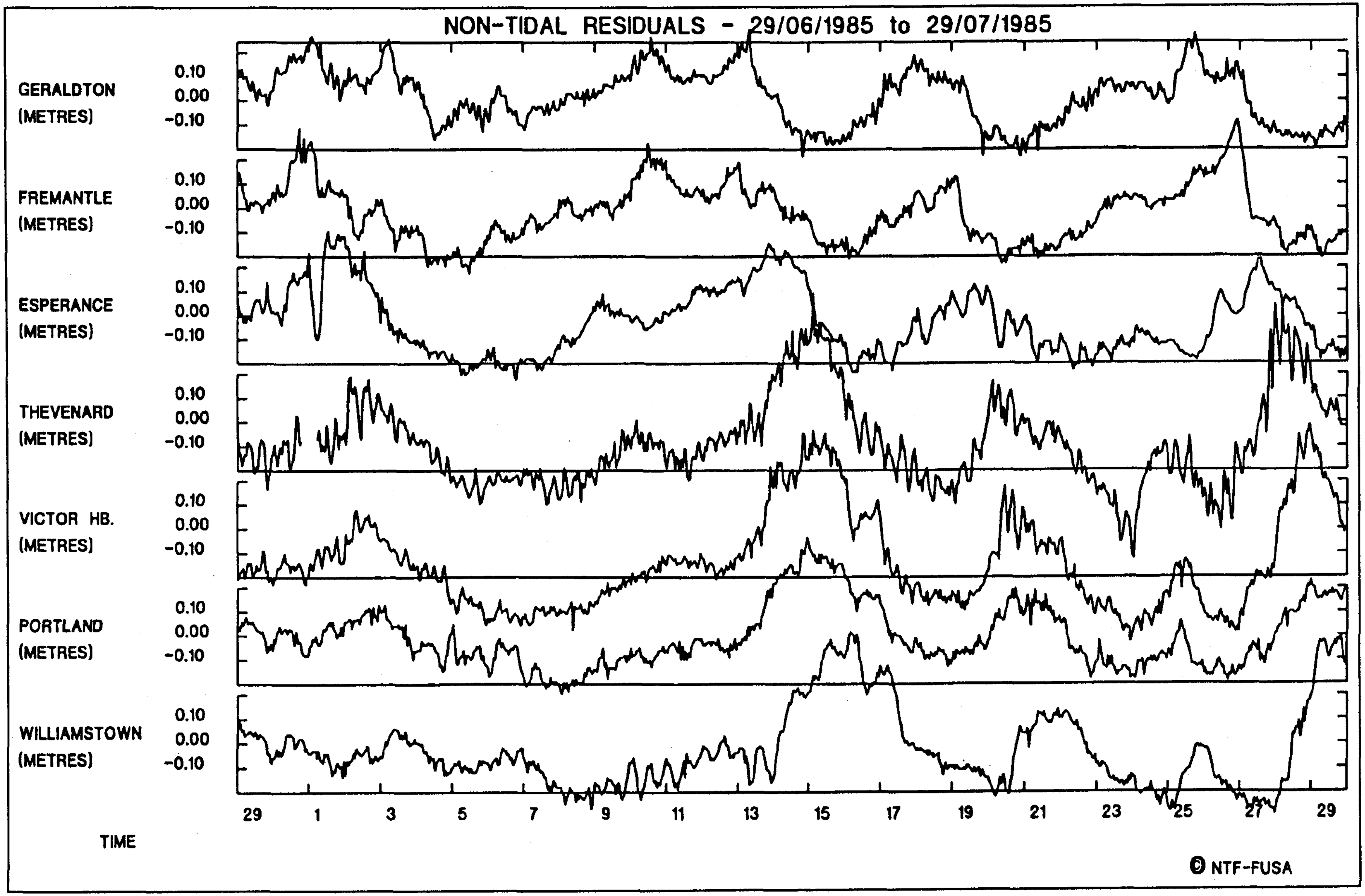
NON-TIDAL RESIDUALS - 29/06/1985 to 29/07/1985
GERALDTON (METRES)
FREMANTLE (METRES)
ESPERANCE (METRES)
THEVENARD (METRES)
VICTOR HB. (METRES)
PORTLAND (METRES)
WILLIAMSTOWN (METRES)
0.10
0.00
-0.10
29 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29
TIME
© NTF-FUSA

Figure 3

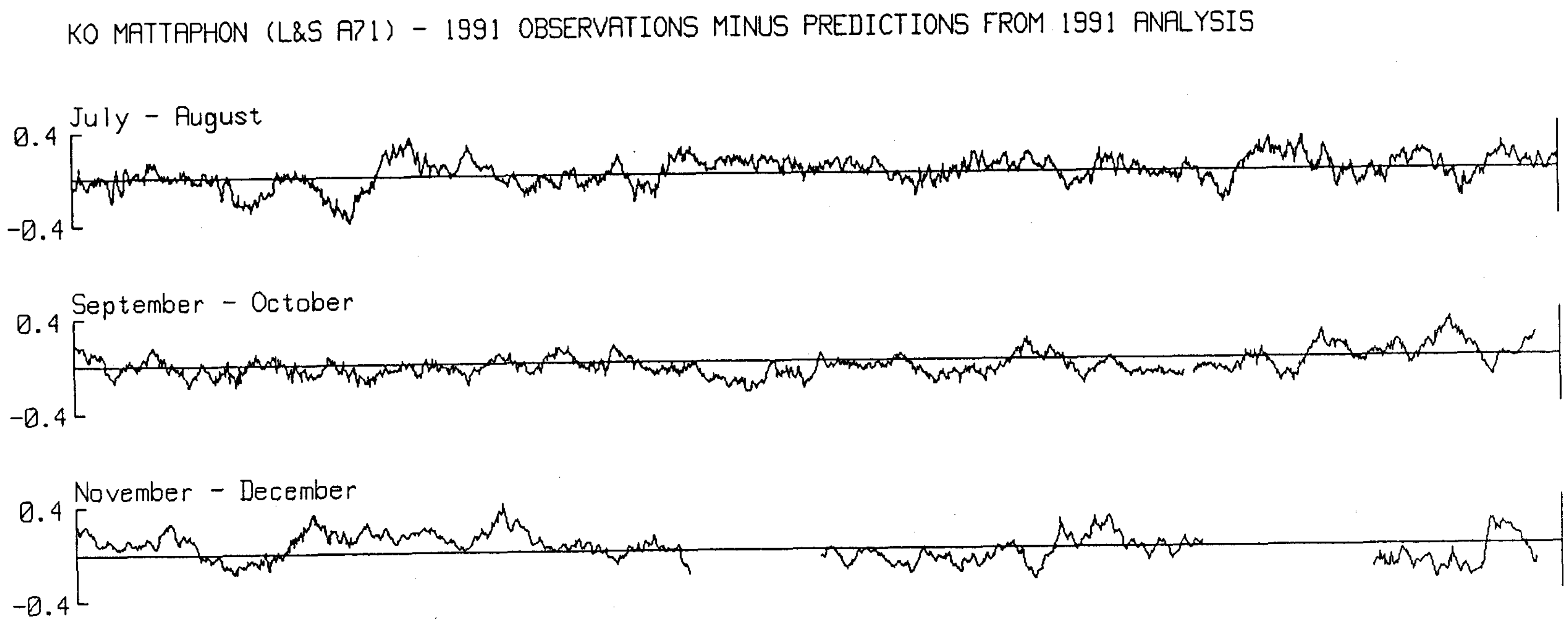

Figure 4A

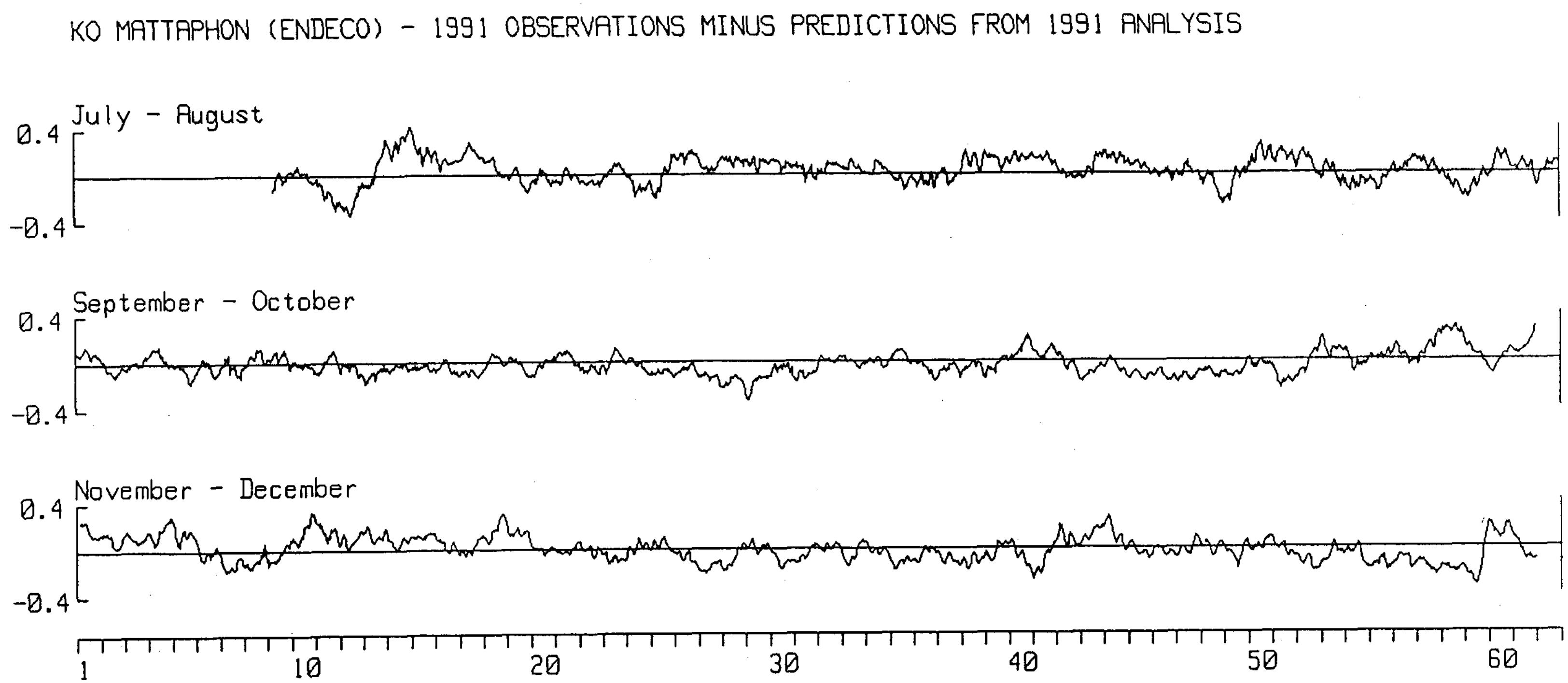

Figure 4B

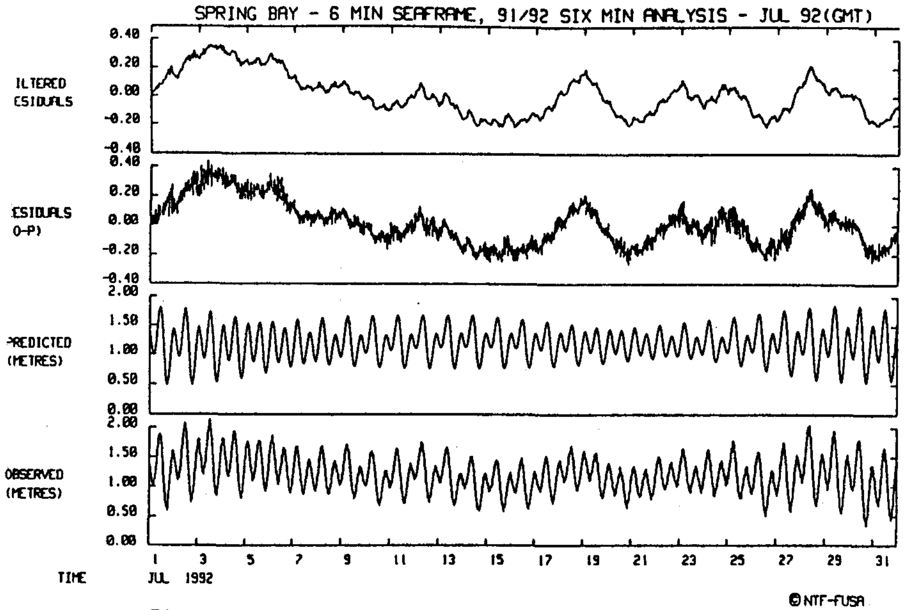

Figure 5A

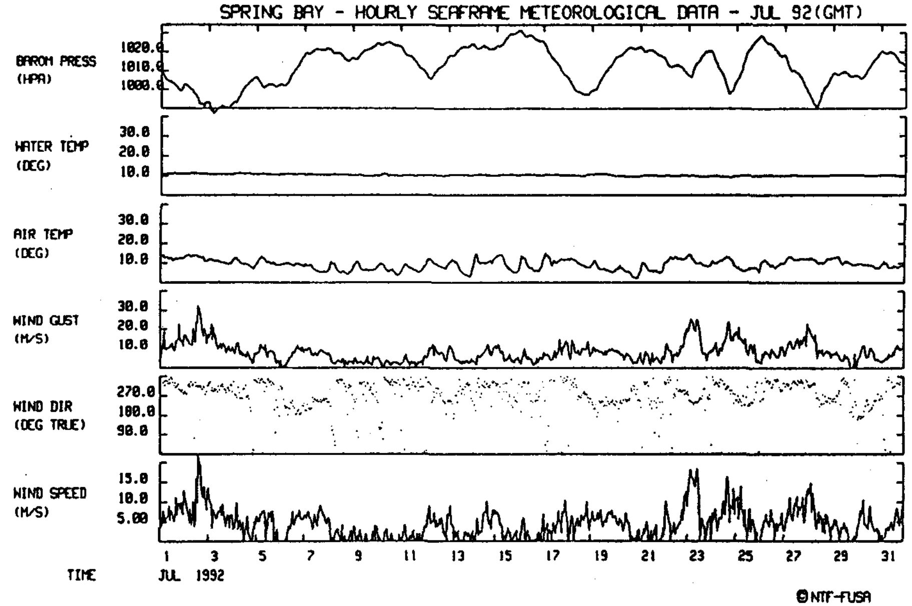

Figure 5B

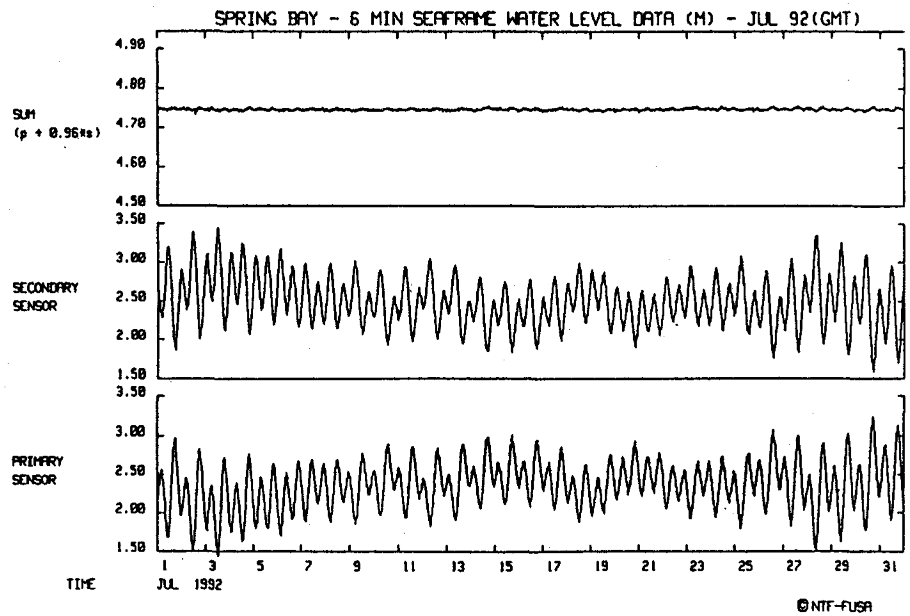

Figure 5C

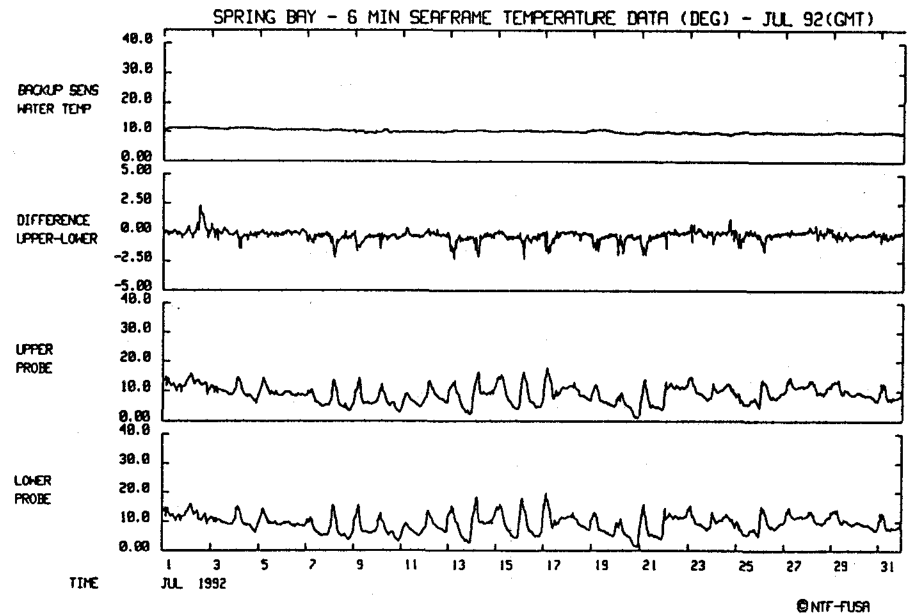

Figure 5D

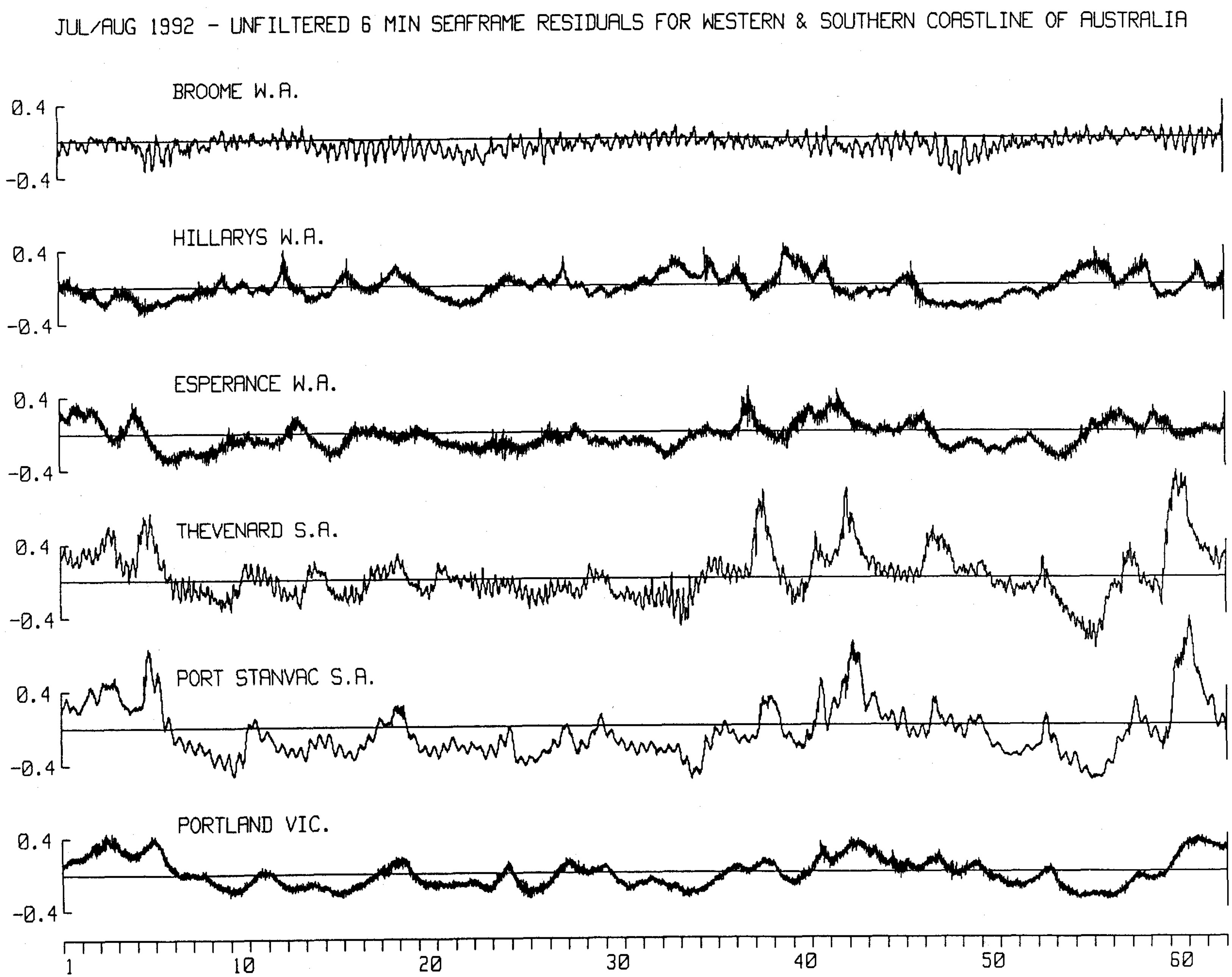
JUL/AUG 1992 - UNFILTERED 6 MIN SEAFRAME RESIDUALS FOR WESTERN & SOUTHERN COASTLINE OF AUSTRALIA
BROOME W.A.
HILLARYS W.A.
ESPERANCE W.A.
THEVENARD S.A.
PORT STANVAC S.A.
PORTLAND VIC.
0.4
-0.4
1
10
20
30
40
50
60

Figure 6

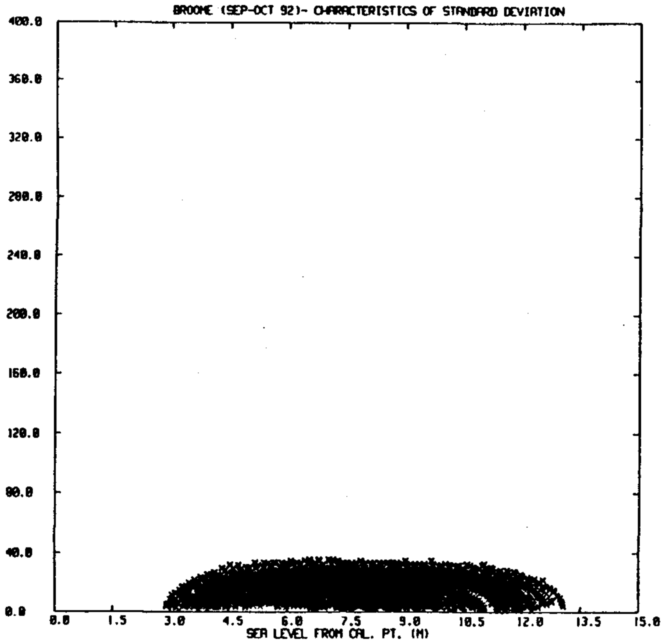

Figure 7A

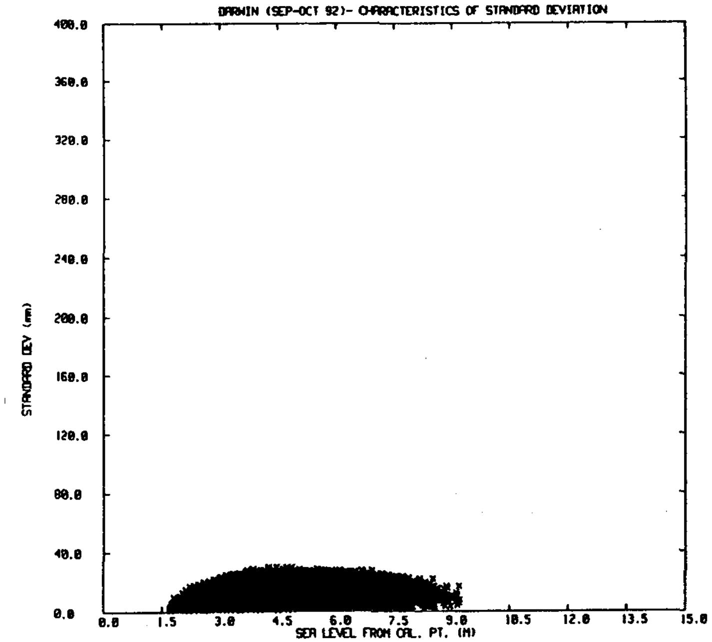

Figure 7B

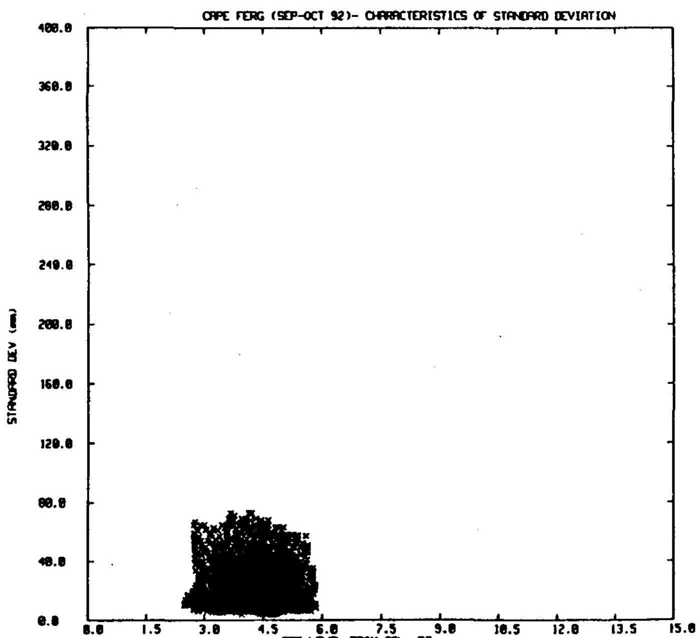

Figure 7C

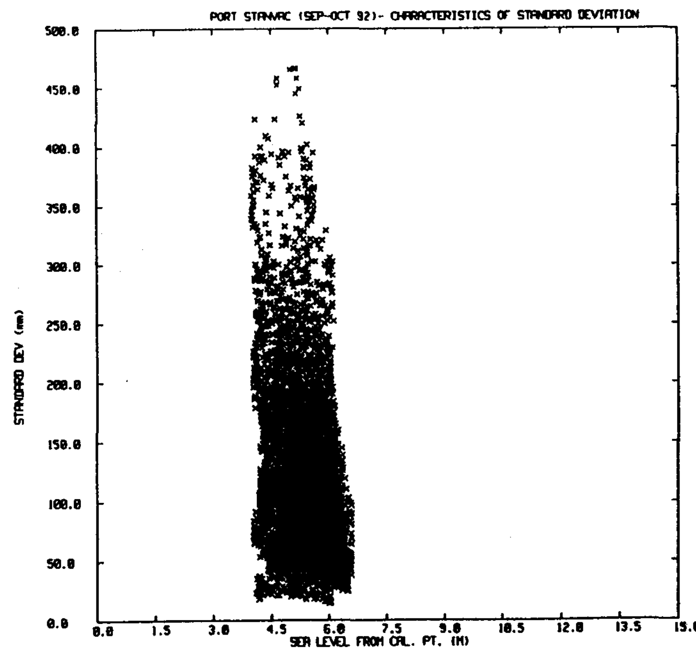

Figure 7D

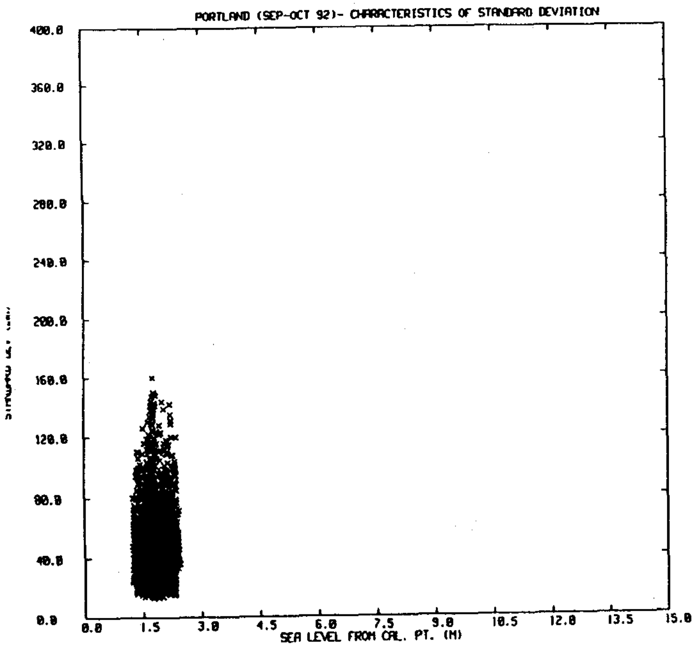

Figure 7E

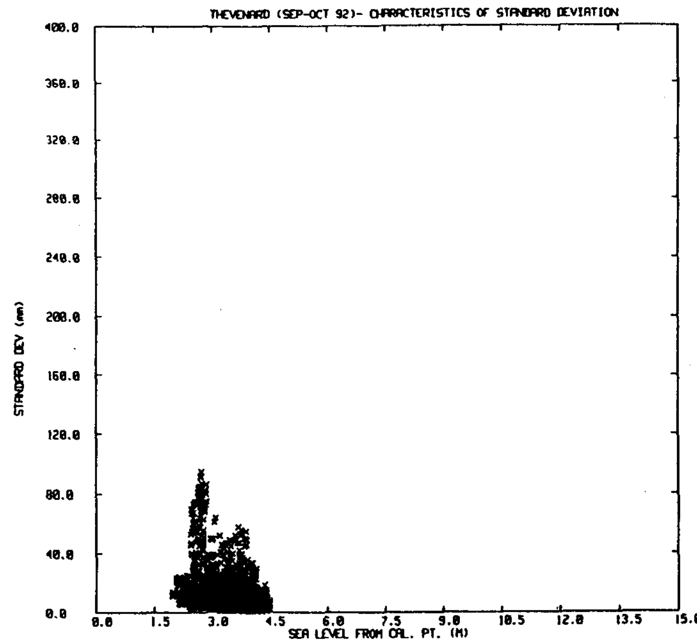

Figure 7F

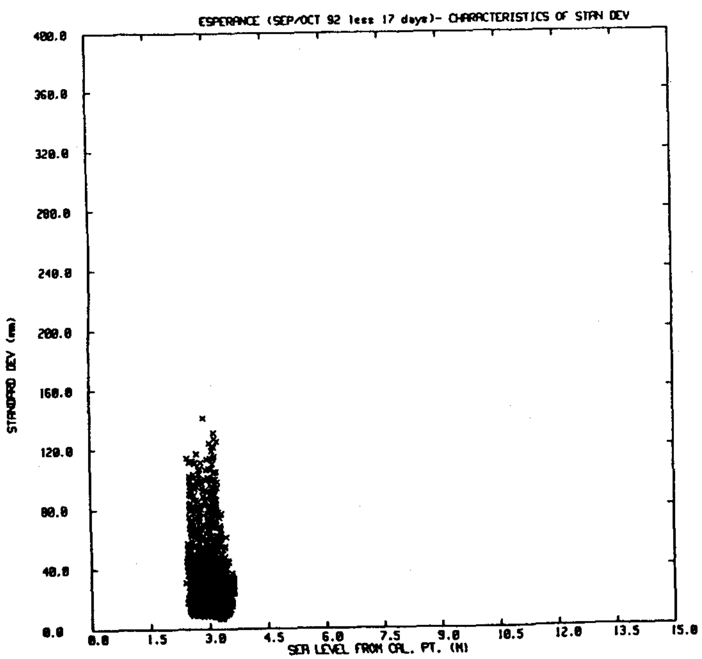

Figure 7G

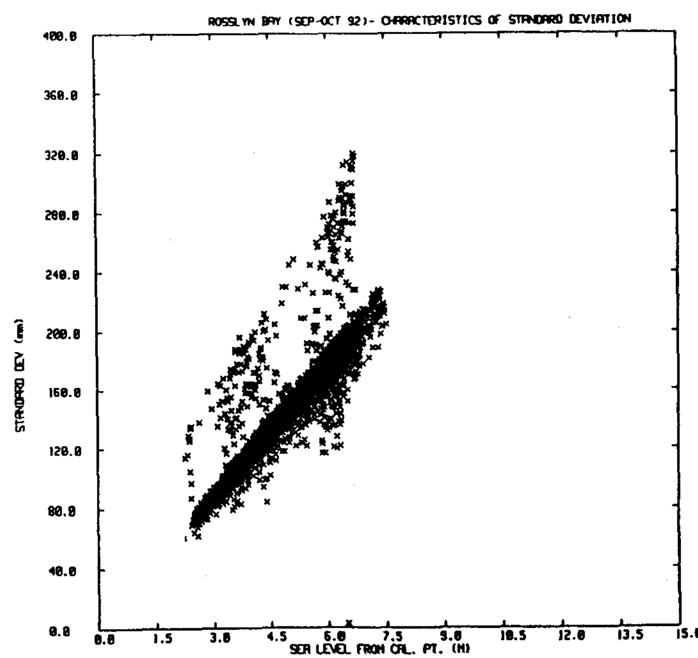

Figure 7H

NATIONAL TIDAL FACILITY
DAILY DATA ACQUISITION REPORT

Date : 06/11/91

ST	LOCATION	START TIME (CST)	TIME TAKEN	END TIME (CST)	DIAL NUM	MESSAGE	FIRST LINE (GMT)	LAST LINE (GMT)	BINARY(Bytes)
1	Burnie	07:00:08 AM	hr 2 min 47.5 sec	07:02:58 AM	1	SUCCESS	921104, 000000, "0"	921104, 235543, "A"	8960
2	Broome	07:03:04 AM	hr 4 min 27.0 sec	07:07:34 AM	1	SUCCESS	921104, 000000, "0"	921104, 235827, "S"	14592
3	C Ferguson	07:07:41 AM	hr 3 min 22.5 sec	07:11:06 AM	1	SUCCESS	921104, 000000, "0"	921104, 235833, "S"	9216
4	Darwin	07:11:12 AM	hr 4 min 24.0 sec	07:15:38 AM	1	SUCCESS	921104, 000000, "0"	921104, 235756, "B"	15104
5	Esperance	07:15:45 AM	hr 3 min 22.1 sec	07:19:10 AM	1	SUCCESS	921104, 000000, "0"	921104, 235834, "S"	8960
6	Hillarys	07:19:16 AM	hr 4 min 47.2 sec	07:24:05 AM	1	SUCCESS	921104, 000000, "0"	921104, 235859, "B"	14976
7	Pt Kembla	07:24:12 AM	hr 3 min 20.0 sec	07:27:35 AM	1	SUCCESS	921104, 000000, "0"	921104, 235834, "S"	9216
8	Portland	07:27:41 AM	hr 4 min 09.5 sec	07:31:53 AM	1	SUCCESS	921104, 000000, "0"	921104, 235833, "S"	8960
9	Rosslyn Bay	07:31:59 AM	hr 3 min 54.3 sec	07:35:56 AM	1	SUCCESS	921104, 000000, "0"	921104, 235542, "A"	8960
10	SpringBay	07:36:02 AM	hr 4 min 23.1 sec	07:40:28 AM	1	SUCCESS	921104, 000000, "0"	921104, 235756, "B"	14848
11	Thevenard	07:40:35 AM	hr 3 min 20.0 sec	07:43:57 AM	1	SUCCESS	921104, 000000, "0"	921104, 235834, "S"	8960
12	Cocos Is	07:44:03 AM	hr 6 min 31.4 sec	07:50:37 AM	1	SUCCESS	921104, 000000, "0"	921104, 235831, "S"	15104

DATA ACQUISITION Started at 07:00:07 AM & Ended at 07:50:44 AM (CST)

Table 1

NATIONAL TIDAL FACILITY
WEEKLY DATA VERIFICATION REPORT

Source File : dn.dmp Directory : /users/aust/data_in/bn
Data Period : 921026 to 921101 Date Printed : 02-Nov-92, 08:00:03 AM (CST)

FILE	UNITS	MIN	MAX	READ	MEAN	STDEV
File : A				Primary Sensor		
raw__A	m	1.721	9.147	1680	5.286	1.941
stdevA	m	0.001	0.028	1680	0.012	0.007
outlrA	-	0	7	1680	0.023	-
utempA	°C	24.800	34.100	1680	28.982	1.754
ltempA	°C	23.700	33.600	1680	28.245	1.746
dtempA	°C	-1.000	2.700	1680	0.737	0.437
File : raw__A				Adjusted A to CD		
levelA	m	0.075	7.501	1680	3.936	1.941
File : resA				Residual		
resd_A	m	-0.049	0.210	1680	0.071	0.049
File : B				Backup Sensor		
raw__B	m	1.428	9.273	1680	5.503	2.050
stdevB	m	0.003	0.030	1680	0.013	0.007
outlrB	-	0	4	1680	0.163	-
wtempB	°C	28.800	30.200	1680	29.341	0.245
Batt_B	Volts	12.600	13.500	1680	12.938	0.350
File : sumAB				SumAB = A+B*0.96		
Sum_AB	m	10.47	10.54	1680	10.51	0.01
File : C				Speed/Direction/Gust		
speedC	m/s	0.00	8.00	168	2.64	1.77
dirt_C	°True	1.00	359.00	168	177.73	121.80
gust_C	m/s	0.00	16.30	168	5.41	2.39
File : D				Air Temperature		
airtpD	°C	23.4	30.5	168	27.76	1.542
File : E				Water Temperature		
wtempE	°C	29.1	30.3	168	29.76	0.254
File : F				Barometric Pressure		
barmF	Hpa	1007.1	1013.4	168	1010.00	1.375
File : S				System Status		
Batt_S	Volts	13.900	14.100	168	13.970	0.047
Chrg_S	Volts	27.800	28.900	168	28.287	0.236

Table 2A

Column Headings :-	
UNITS	Self-Explanatory
MIN	Minimum value in reporting period - in this case from October 26th to November 1st in GMT
MAX	Maximum value in reporting period
READ	No. of values logged in reporting period (6 min values for sensors A & B, 60 min values for C to S)
MEAN	Self-Explanatory
STDEV	Standard Deviation of sensor over total time series
Row Identification	
Sensor A	Primary Water Level, Aquatrak
raw A	Untreated 6 min data
stdev A	Each 6 min value is the mean of 181 one second samples. This is the standard deviation of the 181 values
outlr A	Indicates outliers which differ from the mean by 3 standard deviations
utemp & ltemp A	Indicate upper and lower temperatures in the protective well
dtemp A	Indicates the temperature difference between upper & lower temperatures
Sensor B	Is a bottom-mounted pressure sensor. Other row indicators are as for Sensor A
wtemp B	Water temperature from a thermister set about 1 meter below C.D. (Chart Datum)
Batt B	Refers to the backup logger battery
sum AB	Refers to the addition of raw values from sensors A & B. A measured downwards from the Aquatrak. The B pressure sensor, vented to the atmosphere, effectively measures the height of the water column above. Since they are of opposite sign the sum would be approximately zero if properly related to the same datum. At this raw stage there is no datum set. The sum should remain approximately fixed - see STDEV
speed C	Wind speed generally mounted 10m above sea surface
dirt C	Wind direction
gust C	Maximum gust in recorded period
airtp D	Air Temperature
wtemp D	Water Temperature at a level
barm F	Barometric Pressure
batt S	Main Battery
Chrg S	Battery Charger Condition

Table 2B

QUALITY CONTROL IN THE ACQUISITION AND PROCESSING OF WATER LEVEL DATA

S.K. Gill and B.B. Parker

Ocean and Lake Levels Division, Office of Ocean and Earth Sciences, National Ocean Service, NOAA Rockville, MD 20852 U.S.A.

1. INTRODUCTION

Quality control in data processing, field procedures, instrumentation, and other aspects of water level measurement have been a major focus of the National Ocean Service (NOS) since systematic measurements began in the mid 1800's. NOS operates the U.S. National Water Level Observation Network (NWLON), which presently consists of 189 long-term continuously operating water level stations in the U.S. coastal ocean, the Great Lakes, and ocean island possessions and territories. NOS also operates 22 additional sites around the world as part of the NOAA Global Sea Level Network. Thousands of other stations have been installed for finite periods for particular purposes such as charting, marine boundaries, dredging, or special navigational needs.

The datum continuity requirements of nautical charting, marine boundary disputes, and most recently sea level rise research, the data continuity and now real-time requirements of navigation, and the sheer quantity of data acquired each year, have all demanded careful development of and adherence to documented detailed Standard Operating Procedures (SOPs). These SOPs cover all activities from installation and maintenance in the field to data processing and analysis in headquarters, and include a documented operational data quality assurance program.

NOS is presently operating two water level measurement systems, and aspects of both systems will be briefly described with respect to quality control. The analog-to-digital recorder (ADR) float system has been used for two decades in the U.S. After a sufficient overlap period (at least one year at all locations), it will be phased out and replaced by the Next Generation Water Level Measurement System (NGWLMS), which includes not only the new acoustic gauge discussed in an earlier paper, but also a new Data Processing and Analysis Subsystem (DPAS). DPAS is a fully-integrated system involving a high performance relational database used in a client-server architecture and a network of workstations. DPAS covers all activities from field activities through analysis products and will automate many operations done manually with the ADR system. The NGWLMS has many improvements over the ADR system with respect to quality assurance.

2. FIELD OPERATIONS

Quality control begins in the field. NOS water level gauges have always been operated using extensive on-site care and monitoring using trained local tide observers. NOS has field parties on both coasts of the U.S. (at Norfolk, Virginia, and at Seattle, Washington) that are tasked with annual preventive maintenance and levelling, with providing emergency corrective maintenance to the gauges, and with maintaining gauge repair shops. In some instances contracted field personnel have maintained stations under strict government inspection. Documented preventive and corrective maintenance procedures have been developed and implemented for each gauge system. The NGWLMS acoustic sensors undergo periodic replacement and calibration checks.

A critical aspect of data quality with respect to the use of sea level data in climate and global change studies is the maintenance of station datums. Second-order Class I levels (nominal accuracy in elevation difference between points = 3mm * $\sqrt{d}$, where d = distance between the points in km) are run on a yearly basis from the tide staff, Electric Tape Gauge (ETG), or acoustic sensor levelling point to a network of permanent bench marks to monitor the vertical stability of the tide station and its support structure (e.g. a pier) relative to land. Over time some of the bench marks themselves may be destroyed or become unstable and are replaced. Adequate spacing and numbers of bench marks are maintained at each location to ensure datum continuity. These procedures ensure data continuity in two ways: (1) if a measurement system is destroyed during a storm a new one can be easily reinstalled to collect data relative to station datum because the bench marks are used to preserve the station datum, and (2) the data can be precisely adjusted if a supporting structure or bench mark are found to be unstable over time.

3. DATA MONITORING

The ability to closely monitor the data and the instrumentation in order to quickly identify and correct problems before a significant amount of data is lost or corrupted is a key part of quality control. With the ADR systems some obvious instrument problems can be detected by the tide observer during his daily visits, but generally detection of errors in the data are delayed up to a month, i.e. until the tide roll is received and checked at headquarters. The NGWLMS, however, allows near-real-time examination of data and instrumentation quality control parameters, since data are received via GOES every three hours.

For the ADR systems, operational contact is maintained with the local tide observers to ensure proper gauge operation and prompt notification of maintenance needs. The observers call field maintenance personnel when problems are detected and are sometimes trained to perform minor repairs themselves at remote stations. The observers send in weekly and monthly reports to headquarters. The data are sent to headquarters on a monthly basis so that it can be reviewed for validity and corrective maintenance requirements. Feedback is given to the observers and field parties for proper action. Further feedback is provided as the data are processed and analyzed and the output products are reviewed.

The NGWLMS system operation does not use a local tide observer. Data are transmitted via satellite every three hours from each station to the GOES satellite downlink. Four times each day the data are transferred to the data processing and analysis system and undergo automated quality control checks. The satellite messages also contain parameters associated with the status of the hardware components and provide information on the health of the field unit. Summary reports of the quality control checks and field unit status checks are reviewed on a daily basis so that any corrective maintenance processes can be initiated. For NGWLMS stations equipped with telephone, the data can be monitored using automatic and manually initiated telephone calls.

4. USE OF BACKUP MEASUREMENT SYSTEMS AND ALTERNATIVE MEANS OF DATA RETRIEVAL

The configuration of each water level station includes an independent backup water level measurement system that can be used to fill gaps should the primary gauge malfunction. The backup to the ADR float driven gauges are gas-purged "bubbler" pressure gauges with the sensors installed separately from the ADR stilling wells and with separate data recording systems. The NGWLMS field units are configured also with a separate backup pressure sensor using a completely separate data logger.

The NGWLMS system improves chances of data recovery since the primary mode of data collection into the data base is a transmission every three hours via the GOES satellite downlink. Most field units will eventually have telephone lines installed, so that the major secondary mode of data collection will be via automatic telephone call to the station by DPAS. The third method of data retrieval in case of satellite and telephone failure is on-site manual collection with a laptop computer or data logger. Each field unit stores at least 30 days of the most recent data. Data are then transferred using data diskettes.

5. DATA PROCESSING

Water level data have been routinely processed on a monthly basis using a combination of autonomous and non-autonomous procedures with the amount of autonomous processing depending on the type of gauge. NOS is presently in a transition period from not only old technology water level measurement systems, but from older and unlinked computer systems, hard copy data bases (for the older data sets), and varying digital data formats to a new NGWLMS Data Processing and Analysis Subsystem (DPAS). DPAS is a fully integrated, state-of-the art computer system that will perform the following NGWLMS functions: data acquisition, data processing, analysis and quality control, database management, field requirements assessment, logistics control, administrative tracking, and data dissemination. Basic design work has been completed and some software implementation has been completed and is being used. The scheduled completion date is the end of 1993.

The nucleus of DPAS is Sybase, a high performance relational data base management system (DBMS). Sybase is used in a client-server architecture with a VAX computer acting as a database server. Other VAX computers are being networked to the database server to provide network services. Application software, consisting of both commercial and custom written software, are run on workstations which are 386 and 486-based Personal Computers (PC's) running under the OS/2 operating system. System design is modular so that specific modules can be updated and improved as needed. DPAS automates many functions that are now manual processes. Routine data processing and quality control tasks are automated and routine data analyses and ad-hoc analyses are performed with relative ease. The extensive data archive, including most of the historical time series information (which are being digitized) will be directly and readily available through DPAS to internal and external users.

Independent of gauge or computer system, the data processing includes key verification steps which must be completed by senior oceanographers before the data go forward towards archival and dissemination. Data edits and changes are checked and audited. Data quality is quantified for each month of data and data quality parameters are monitored on a station-by-station and on a network-wide basis using a data base management system. This allows for fact-based decisions with regard to operation of the NWLON and the Global Sea Level Network.

Operational data processing and quality control steps vary slightly depending on the gauge system. However, once loaded into the computer data base, these steps are controlled by computer algorithms; analyst handling of outputs and diagnostics are controlled by the standard operating procedures.

The marigrams from the analog and ADR gauges are visually scanned for malfunctions and data problems prior to translation onto computer. At this time, the tide observer readings and the gauge operation are further checked through statistical analysis of the staff/ETG-to-gauge differences.

Once the fundamental 6-minute interval data are loaded into the computer database, they undergo tolerance checks with historical parameters for flat spots, "third difference" continuity (rate of change), and maximum/minimum expected values. Problem areas (both in elevation and time) are compared to predicted data or with nearby stations for assessment.

Standard output products, which include hourly heights, times and heights of high and low waters, and monthly mean datums, are reviewed for consistency both internally, using diagnostics from computer algorithms, and externally by statistical and graphical comparison to simultaneous data from nearby stations or from predicted tides.

6. INDEPENDENT REVIEW

Operational data quality assurance includes two important steps that call for independent checks of the data and derived products prior to final acceptance of the data as part of the historical record.

First, on a calendar year basis, year-end reviews of the data and output products are made to ensure consistency and validity over a year time period. The review for each station is performed by an oceanographer not directly responsible for the routine processing of the data from that station. Data are reviewed for internal consistency as well as for consistency with nearby stations in the NWLON. Anomalous data are scrutinized, the cause of the anomalies determined, and adjustments made if necessary.

Second, an independent check of the data are made by a senior oceanographer not directly involved with the data processing or the year-end review process. The monthly means and yearly means are again checked; however, this time in the context of verifying the differential levelling ties and the vertical stability of the bench marks, tide staffs/electric-tape-gauges, and pier structures. The record is reviewed for possible required adjustment over the long term. This second check cannot be done unless levelling has been done both before and after the data were obtained. The data are also checked at that time for consistency with the historical record and for consistency with nearby stations so that data continuity problems do not occur.

ANNEX II

LIST OF PARTICIPANTS

I. INVITED EXPERTS

Mr. P.C. **CALDWELL (Rapporteur)**
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No.	Title	Languages
1	CCOP-IOC, 1974, Metallogenesis, Hydrocarbons and Tectonic Patterns in Eastern Asia (Report of the IDOE Workshop on); Bangkok, Thailand, 24-29 September 1973 UNDP (CCOP), 138 pp.	E (out of stock)
2	CICAR Ichthyoplankton Workshop, Mexico City, 16-27 July 1974 (UNESCO Technical Paper in Marine Sciences, No. 20).	E (out of stock) S (out of stock)
3	Report of the IOC/GFCM/ICSEM International Workshop on Marine Pollution in the Mediterranean; Monte Carlo, 9-14 September 1974.	E, F E (out of stock)
4	Report of the Workshop on the Phenomenon known as 'El Niño'; Guayaquil, Ecuador, 4-12 December 1974.	E (out of stock) S (out of stock)
5	IDOE International Workshop on Marine Geology and Geophysics of the Caribbean Region and its Resources; Kingston, Jamaica, 17-22 February 1975.	E (out of stock) S
6	Report of the CCOP/SOPAC-IOC IDOE International Workshop on Geology, Mineral Resources and Geophysics of the South Pacific; Suva, Fiji, 1-6 September 1975.	E
7	Report of the Scientific Workshop to Initiate Planning for a Co-operative Investigation in the North and Central Western Indian Ocean, organized within the IDOE under the sponsorship of IOC/FAO (IOFC)/UNESCO/EAC; Nairobi, Kenya, 25 March-2 April 1976.	E, F, S, R
8	Joint IOC/FAO (IPFC)/UNEP International Workshop on Marine Pollution in East Asian Waters; Penang, 7-3 April 1976.	E (out of stock)
9	IOC/CMG/SCOR Second International Workshop on Marine Geoscience; Mauritius, 9-13 August 1976.	E, F, S, R
10	IOC/WMO Second Workshop on Marine Pollution (Petroleum) Monitoring; Monaco, 14-18 June 1976.	E, F E (out of stock) R
11	Report of the IOC/FAO/UNEP International Workshop on Marine Pollution in the Caribbean and Adjacent Regions; Port of Spain, Trinidad, 13-17 December 1976.	E, S (out of stock)
11 Suppl.	Collected contributions of invited lecturers and authors to the IOC/FAO/UNEP International Workshop on Marine Pollution in the Caribbean and Adjacent Regions; Port of Spain, Trinidad, 13-17 December 1976.	E (out of stock), S
12	Report of the IOCARIBE Interdisciplinary Workshop on Scientific Programmes in Support of Fisheries Projects; Fort-de-France, Martinique, 28 November-2 December 1977.	E, F, S
13	Report of the IOCARIBE Workshop on Environmental Geology of the Caribbean Coastal Area; Port of Spain, Trinidad, 16-18 January 1978.	E, S
14	IOC/FAO/WHO/UNEP International Workshop on Marine Pollution in the Gulf of Guinea and Adjacent Areas; Abidjan, Côte d'Ivoire, 2-9 May 1978.	E, F
15	CPPS/FAO/IOC/UNEP International Workshop on Marine Pollution in the South-East Pacific; Santiago de Chile, 6-10 November 1978.	E (out of stock)
16	Workshop on the Western Pacific, Tokyo, 19-20 February 1979.	E, F, R
17	Joint IOC/WMO Workshop on Oceanographic Products and the IGOSS Data Processing and Services System (IDPSS); Moscow, 9-11 April 1979.	E
17 Suppl.	Papers submitted to the Joint IOC/WMO Seminar on Oceanographic Products and the IGOSS Data Processing and Services System; Moscow, 2-6 April 1979.	E
18	IOC/UNESCO Workshop on Syllabus for Training Marine Technicians; Miami, 22-26 May 1978 (UNESCO reports in marine sciences, No. 4 published by the Division of Marine Sciences, UNESCO).	E (out of stock), F, S (out of stock), R
19	IOC Workshop on Marine Science Syllabus for Secondary Schools; Llantwit Major, Wales, U.K., 5-9 June 1978 (UNESCO reports in marine sciences, No. 5, published by the Division of Marine Sciences, UNESCO).	E (out of stock), E, S, R, Ar
20	Second CCOP-IOC Workshop on IDOE Studies of East Asia Tectonics and Resources; Bandung, Indonesia, 17-21 October 1978.	E
21	Second IDOE Symposium on Turbulence in the Ocean; Liège, Belgium, 7-18 May 1979.	E, F, S, R
22	Third IOC/WMO Workshop on Marine Pollution Monitoring; New Delhi, 11-15 February 1980.	E, F, S, R
23	WESTPAC Workshop on the Marine Geology and Geophysics of the North-West Pacific; Tokyo, 27-31 March 1980.	E, R
24	WESTPAC Workshop on Coastal Transport of Pollutants; Tokyo, 27-31 March 1980.	E (out of stock)
25	Workshop on the Intercalibration of Sampling Procedures of the IOC/ WMO UNEP Pilot Project on Monitoring Background Levels of Selected Pollutants in Open-Ocean Waters; Bermuda, 11-26 January 1980.	E (superseded by IOC Technical Series No. 22)
26	IOC Workshop on Coastal Area Management in the Caribbean Region; Mexico City, 24 September-5 October 1979.	E, S
27	CCOP/SOPAC-IOC Second International Workshop on Geology, Mineral Resources and Geophysics of the South Pacific; Nouméa, New Caledonia, 9-15 October 1980.	E
28	FAO/IOC Workshop on the effects of environmental variation on the survival of larval pelagic fishes. Lima, 20 April-5 May 1980.	E
29	WESTPAC Workshop on Marine Biological Methodology; Tokyo, 9-14 February 1981.	E
30	International Workshop on Marine Pollution in the South-West Atlantic; Montevideo, 10-14 November 1980.	E (out of stock) S
31	Third International Workshop on Marine Geoscience; Heidelberg, 19-24 July 1982.	E, F, S
32	UNU/IOC/UNESCO Workshop on International Co-operation in the Development of Marine Science and the Transfer of Technology in the context of the New Ocean Regime; Paris, 27 September-1 October 1982.	E, F, S
32 Suppl.	Papers submitted to the UNU/IOC/UNESCO Workshop on International Co-operation in the Development of Marine Science and the Transfer of Technology in the Context of the New Ocean Regime; Paris, 27 September-1 October 1982.	E
33	Workshop on the IREP Component of the IOC Programme on Ocean Science in Relation to Living Resources (OSLR); Halifax, 26-30 September 1963.	E
34	IOC Workshop on Regional Co-operation in Marine Science in the Central Eastern Atlantic (Western Africa); Tenerife, 12-17 December 1963.	E, F, S
35	CCOP/SOPAC-IOC-UNU Workshop on Basic Geo-scientific Marine Research Required for Assessment of Minerals and Hydrocarbons in the South Pacific; Suva, Fiji, 3-7 October 1983.	E
36	IOC/FAO Workshop on the Improved Uses of Research Vessels; Lisbon, 28 May-2 June 1984.	E
36 Suppl.	Papers submitted to the IOC/FAO Workshop on the Improved Uses of Research Vessels; Lisbon, 28 May-2 June 1984.	E
37	IOC/UNESCO Workshop on Regional Co-operation in Marine Science in the Central Indian Ocean and Adjacent Seas and Gulfs; Colombo, 8-13 July 1985.	E
38	IOC/ROPME/UNEP Symposium on Fate and Fluxes of Oil Pollutants in the Kuwait Action Plan Region; Basrah, Iraq, 8-12 January 1984.	E
39	CCOP (SOPAC)-IOC-IFREMER-ORSTOM Workshop on the Uses of Submersibles and Remotely Operated Vehicles in the South Pacific; Suva, Fiji, 24-29 September 1985.	E
40	IOC Workshop on the Technical Aspects of Tsunami Analysis, Prediction and Communications; Sidney, B.C., Canada, 29-31 July 1985.	E
40 Suppl.	IOC Workshop on the Technical Aspects of Tsunami Analysis, Prediction and Communications, *Submitted Papers;* Sidney, B.C., Canada, 29-31 July 1985.	E
41	First Workshop of Participants in the Joint FAO/IOC/WHO/IAEA/UNEP Project on Monitoring of Pollution in the Marine Environment of the West and Central African Region (WACAF/2); Dakar, Senegal, 28 October-1 November 1985.	E
43	IOC Workshop on the Results of MEDALPEX and Future Oceanographic Programmes in the Western Mediterranean; Venice, Italy, 23-25 October 1985.	E
44	IOC-FAO Workshop on Recruitment in Tropical Coastal Demersal Communities; Ciudad del Carmen, Campeche, Mexico, 21-25 April 1986.	E (out of stock) S
44 Suppl.	IOC-FAO Workshop on Recruitment in Tropical Coastal Demersal Communities, *Submitted Papers;* Ciudad del Carmen, Campeche, Mexico, 21-25 April 1986.	E
45	IOCARIBE Workshop on Physical Oceanography and Climate; Cartagena, Colombia, 19-22 August 1986.	E
46	Reunión de Trabajo para Desarrollo del Programa "Ciencia Oceánica en Relación a los Recursos No Vivos en la Región del Atlántico Sud-occidental"; Porto Alegre, Brazil, 7-11 de abril de 1986.	S
47	IOC Symposium on Marine Science in the Western Pacific: The Indo-Pacific Convergence; Townsville, 1-6 December 1966.	E
48	IOCARIBE Mini-Symposium for the Regional Development of the IOC-UN (OETB) Programme on 'Ocean Science in Relation to Non-Living Resources (OSNLR)'; Havana, Cuba, 4-7 December 1986.	E, S
49	AGU-IOC-WMO-CPPS Chapman Conference: An International Symposium on 'El Niño'; Guayaquil, Ecuador, 27-31 October 1986.	E
50	CCALR-IOC Scientific Seminar on Antarctic Ocean Variability and its Influence on Marine Living Resources, particularly Krill (organized in collaboration with SCAR and SCOR); Paris, France, 2-6 June 1987.	E
51	CCOP/SOPAC-IOC Workshop on Coastal Processes in the South Pacific Island Nations; Lae, Papua-New Guinea, 1-8 October 1987.	E

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No.	Title	Languages
52	SCOR-IOC-UNESCO Symposium on Vertical Motion in the Equatorial Upper Ocean and its Effects upon Living Resources and the Atmosphere; Paris, 6-10 May 1985.	E
53	IOC Workshop on the Biological Effects of Pollutants; Oslo, 11-29 August 1986.	E
54	Workshop on Sea-Level Measurements in Hostile Conditions; Bidston, UK, 28-31 March 1988	E
55	IBCCA Workshop on Data Sources and Compilation, Boulder, Colorado, 18-19 July 1988.	E
56	IOC-FAO Workshop on Recruitment of Penaeid Prawns in the Indo-West Pacific Region (PREP); Cleveland, Australia, 24-30 July 1988.	E
57	IOC Workshop on International Co-operation in the Study of Red Tides and Ocean Blooms; Takamatsu, Japan, 16-17 November 1987.	E
58	International Workshop on the Technical Aspects of the Tsunami Warning System; Novosibirsk, USSR, 4-5 August 1989.	E
58 Suppl.	Second International Workshop on the Technical Aspects of Tsunami Warning Systems, Tsunami Analysis, Preparedness, Observation and Instrumentation. *Submitted Papers*; Novosibirsk, USSR, 4-5 August 1989.	E
59	IOC-UNEP Regional Workshop to Review Priorities for Marine Pollution Monitoring Research, Control and Abatement in the Wider Caribbean; San José, Costa Rica, 24-30 August 1989.	E, F, S
60	IOC Workshop to Define IOCARIBE-TRODERP proposals; Caracas, Venezuela, 12-16 September 1989.	E
61	Second IOC Workshop on the Biological Effects of Pollutants; Bermuda, 10 September-2 October 1988.	E
62	Second Workshop of Participants in the Joint FAO-IOC-WHO-IAEA-UNEP Project on Monitoring of Pollution in the Marine Environment of the West and Central African Region; Accra, Ghana, 13-17 June 1988.	E
63	IOC/WESTPAC Workshop on Co-operative Study of the Continental Shelf Circulation in the Western Pacific; Bangkok, Thailand, 31 October-3 November 1989.	E
64	Second IOC-FAO Workshop on Recruitment of Penaeid Prawns in the Indo-West Pacific Region (PREP); Phuket, Thailand, 25-31 September 1989.	E
65	Second IOC Workshop on Sardine/Anchovy Recruitment Project (SARP) int he Southwest Atlantic; Montevideo, Uruguay, 21-23 August 1989.	E
66	IOC *ad hoc* Expert Consultation on Sardine/Anchovy Recruitment Programme; La Jolla, California, USA, 1989.	E
67	Interdisciplinary Seminar on Research Problems in the IOCARIBE Region; Caracas, Venezuela, 28 November-1 December 1989.	E (out of stock)
68	International Workshop on Marine Acoustics; Beijing, China, 26-30 March 1990.	E
69	IOC-SCAR Workshop on Sea-Level Measurements in the Antarctica; Leningrad, USSR, 28-31 May 1990.	E
69 Suppl.	IOC-SCAR Workshop on Sea-Level Measurements in the Antarctica; Leningrad, USSR, 28-31 May 1990.	E
70	IOC-SAREC-UNEP-FAO-IAEA-WHO Workshop on Regional Aspects of Marine Pollution; Mauritius, 29 October - 9 November 1990.	E
71	IOC-FAO Workshop on the Identification of Penaeid Prawn Larvae and Postlarvae; Cleveland, Australia, 23-28 September 1990.	E
72	IOC/WESTPAC Scientific Steering Group Meeting on Co-Operative Study of the Continental Shelf Circulation in the Western Pacific; Kuala Lumpur; Malaysia, 9-11 October 1990.	E
73	Expert Consultation for the IOC Programme on Coastal Ocean Advanced Science and Technology Study; Liège, Belgium, 11-13 May 1991.	E
74	IOC-UNEP Review Meeting on Oceanographic Processes of Transport and Distribution of Pollutants in the Sea. Zagreb, Yugoslavia, 15-18 May 1989.	E
75	IOC-SCOR Workshop on Global Ocean Ecosystem Dynamics; Solomons, Maryland, USA, 29 April-2 May 1991.	E
76	IOC/WESTPAC Scientific Symposium on Marine Science and Management of Marine Areas of the Western Pacific; Penang, Malaysia, 2-6 December 1991.	E
77	IOC-SAREC-KMFRI Regional Workshop on Causes and Consequences of Sea-Level Changes on the Western Indian Ocean Coasts and Islands; Mombasa, Kenya, 24-28 June 1991.	E
78	IOC-CEC-ICES-WMO-ICSU Ocean Climate Data Workshop Goddard Space Flight Center; Greenbelt, Maryland, USA, 18-21 February 1992.	E
79	IOC/WESTPAC Workshop on River Inputs of Nutrients to the Marine Environment in the WESTPAC Region; Penang, Malaysia, 26-29 November 1991.	E
80	IOC-SCOR Workshop on Programme Development for Harmful Algae Blooms; Newport, USA, 2-3 November 1991.	E