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MANUAL ON SEA LEVEL MEASUREMENT AND INTERPRETATION

Volume II - Emerging Technologies

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CONTENTS

1. INTRODUCTION

In 1985 the Intergovernmental Oceanographic Commission (IOC) published its Manual on Sea Level Measurement and Interpretation (Manuals and Guides No. 14 UNESCO). This new publication is complementary to the previous version, extending and updating the material on measurements. Several detailed reviews of interpretation of sea level data have been published since 1985, e.g. IPCC 1990.

The introduction to the 1985 Manual recognised the importance of climate change as an influence on sea levels, but failed to anticipate the dramatic increase in both scientific and popular interest in sea level as a result of the anticipated "greenhouse" global climate warming. In their report (1990) the Intergovernmental Panel on Climate Change (IPCC) predicted sea level rises of 18cms by 2030 and of 66cms by 2100 (These have since been revised slightly downwards - see Wigley and Raper, 1992). The IPCC also showed that changing sea level could be of great economic and social significance for coastal areas. These conclusions were reinforced by the Second World Climate Conference (Jager and Ferguson 1990). In response to the concern about climate change, the World Meteorological Organisation has established a Global Climate Observing System (GCOS) to be developed by the joint efforts of World Meteorological Organisation (WMO), IOC, International Council of Scientific Unions (ICSU) and United Nations Environment Programmes (UNEP). The oceanographic component of this will be provided by the Global Ocean Observing System (GOOS) under the auspices of the IOC in collaboration with WMO, ICSU and UNEP. This was confirmed at the 16th session of the IOC Assembly (resolution XVI-8). The IOC Global Sea Level Observing System (GLOSS) will be an important component of the total Global Ocean Observing System (IOC, 1990 GLOSS Implementation Plan).

The response to these demands by the sea level measuring community has been rapid and substantial. In many countries there have been significant developments in the methods of measuring sea level and in the fixing of tide gauge benchmark in geocentric coordinates. Satellites are now measuring sea level by altimetry on a routine basis and it is increasingly necessary to integrate these with the ground-based longer term sea level measurements. The GLOSS basic network of some 300 stations has been consolidated, with many countries establishing national GLOSS committees for coordinating across agencies. The major oceanographic programmes Tropical Ocean Global Atmosphere (TOGA) programme and World Ocean Circulation Experiment (WOCE) have given a new impetus to obtaining accurate and widely distributed measurements.

At its second meeting in Miami (October 1990) the IOC Group of Experts on GLOSS recognised these developments. Within the GLOSS programme, workshops have been held on measurements of sea level in hazardous regions (IOC reports 1988 and 1991). The Group of Experts considered that the time was right for a revised manual which would contain the essence of the developments in a form accessible to people working on sea level measurement and analysis. The draft Manual - II was reviewed by the IOC Group of Experts on GLOSS (October 1993). This second volume has been prepared under the editorship of David Blackman of the Proudman Oceanographic Laboratory, Bidston Observatory, UK. The IOC is grateful to him and to the other authors from the GLOSS Group of Experts for their contributions.

D.T. Pugh Chairman IOC GLOSS Group of Experts

REFERENCES

Intergovernmental Oceanographic Commission (IOC). 1990. Global Sea Level Observing System (GLOSS) implementation plan. Intergovernmental Oceanographic Commission, Technical Series, No. 35, 90pp.

Intergovernmental Oceanographic Commission (IOC). 1988. Workshop on sea-level measurements in hostile conditions, Bidston, UK, 28-31 March 1988. Summary report and submitted papers. Intergovernmental Oceanographic Commission, Workshop Report, No. 54, 81pp.

Intergovernmental Oceanographic Commission (IOC). 1991. Workshop on sea-level measurements in Antarctica, Leningrad, USSR, 28-31 May 1990. Intergovernmental Oceanographic Commission, Workshop Report, No. 69, 8pp. and annexes and Workshop Report, No. 69 - Supplement "Submitted papers", 102pp.

Intergovernmental Oceanographic Commission (IOC). 1992. Joint IAPSO-IOC Workshop on sea-level measurements and quality control, Paris, 12-13 October 1992. Intergovernmental Oceanographic Commission, Workshop Report, No. 81, 166pp.

Jager, J. and Ferguson, H.L. 1990. Proceedings of the second World Climate Conference. Geneva, 29 Oct - 7 Nov 1990. In: Climate change: science, impacts and policy. Cambridge University Press. 578pp.

Wigley, T.M.L. and Raper, S.C.B., 1992. Indications for climate and sea level of revised IPCC scenarios. Nature, **357**, 293-300.

2. TIDE GAUGES

The most common type of tide gauge used worldwide remains the stilling well float gauge. However, other technologies, such as bubbler pressure gauges, are now used routinely in many countries. Acoustic techniques, which measuring the travel time of pulses reflected from the air/sea interface with automatic compensation for variations in sound velocity, also now have improved performance. A number of stepped sensor techniques have been attempted and new electronic and mechanical techniques have improved resolution, reliability and robustness (e.g. by Etrometa, see Appendix 1). Microwave and laser techniques, measuring the travel time of pulses reflected from the air/sea interface, have been used for wave measurements but are not yet sufficiently accurate for sea level measurements. In all types of system the long term stability in relating sea level measurements to a known land datum can be improved by the use of effective and regular datum control.

2.1 STILLING WELL GAUGES

On a global basis, probably the most common type of tide gauge consists of a stilling well containing a counterbalanced float. This technology was discussed extensively in Volume I of this Manual.

In this system the sea level is measured by determining the length of the float wire relative to a level fixed to the bench marks. The advantages of this system are that it is relatively simple to install and operate, and that it provides a very direct measurement of the sea level. The stilling well is not left completely open to the sea, but is vented via a small hole near the bottom of the well. This method of allowing water to enter the well provides a mechanical filtering of high frequency (notably surface gravity wave) variability. This venting method does, however, introduce some dynamical errors and other problems, but careful design and operation of these systems can partially deal with these effects (Shih & Baer 1991).

A "perfect" sea level gauge has not yet been achieved and all existing measurement techniques can suffer from errors or instabilities which need to be carefully understood and controlled when the highest accuracy measurements are needed.

2.2 DATUM PROBES

The function of a datum probe or switch is to identify the time when the sea level is at a known fixed level relative to the tide gauge datum. By relating this time to the tide gauge record any datum error or offset in the record can be identified. With a chart recorder a mark can be made automatically on the chart at the time the datum switch operates, indicating when the sea level rises or falls past the fixed switch level. At these times the recorded tidal level should be the level of the datum switch. If it is not then the tide gauge or recorder is in error and an offset can be applied to the record to compensate for this error. Where a data logging system is used the times of switching can be recorded in the data logger for subsequent interpolation of the recorded levels to the times of switching.

Ideally the datum switch should be mounted at about mid-tidal level outside a stilling well. However direct exposure to waves and swell make it impractical to deal with the large number of switchings and it is usually necessary to protect the switch within its own small stilling enclosure. Careful design of this enclosure should minimise any errors introduced, particularly if use is only made of sea level crossings in calm conditions giving rise to only single switchings. An acoustic type of switch has been found to be robust, reliable and to have small hysteresis (e.g. Bestobell Mobrey, Appendix 1).

2.3 ACOUSTIC TIDE GAUGES

A number of acoustic tide gauges have been developed which depend on measuring the travel time of acoustic pulses reflected vertically from the air/sea interface. This type of measurement can be made in the open with the acoustic transducer mounted vertically above the sea surface, but in certain conditions the reflected signals may be lost. To ensure continuous, reliable operation the acoustic pulses are generally contained within a vertical tube or well which can provide some degree of surface stilling. Averaging of a number of measurements will also have a stilling effect and give improved accuracy.

To accurately convert the time of travel of the acoustic pulses to sea level requires a knowledge of the velocity of sound between the acoustic transducer and the sea surface. The velocity of sound can vary significantly with changes in temperature and humidity (about 0.17%/°C) and some form of compensation is necessary for accurate sea level measurements. The simplest method is to continuously measure the air temperature at a point in the air column and use this to calculate the sound velocity to be used. To account for temperature gradients in the air column temperature sensors may be required at a number of different levels.

A more accurate method of compensation is by use of an acoustic reflector at a fixed level in the air column. By relating the reflection from the sea surface to that from the fixed reflector, direct compensation for variations in sound velocity between the acoustic transducer and the fixed reflector can be achieved. However this still does not account for any variations in sound velocity between the fixed reflector and the sea surface. To achieve full compensation would require a number of fixed reflectors covering the full tidal range.

2.3.1 ACOUSTIC GAUGES WITH SOUNDING TUBES

The National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS) - (USA), has been involved in a multi-year implementation of a Next Generation Water Level Measurement System (NGWLMS) within the US national tide gauge network and at selected global sites. At the present time (October 1992), 110 of the 189 stations of the national network have these new systems, as do 22 NOAA Global Sea Level sites around the world (Gill et al., 1992). The new systems are being operated alongside the present analogue-to-digital (ADR) gauges at all stations for a minimum period of one year to provide datum ties to and data continuity with the historical time series. Dual systems will be maintained at a few stations for several years to provide long term comparison information. The same technology gauges have also been deployed in several other countries (e.g. Australia, see Lennon et al., 1992).

The NGWLMS tide gauge uses an Aquatrak water level sensor (Dartex Inc.) with a Sutron data processing and transmission system. The Aquatrak sensor sends a shock wave of

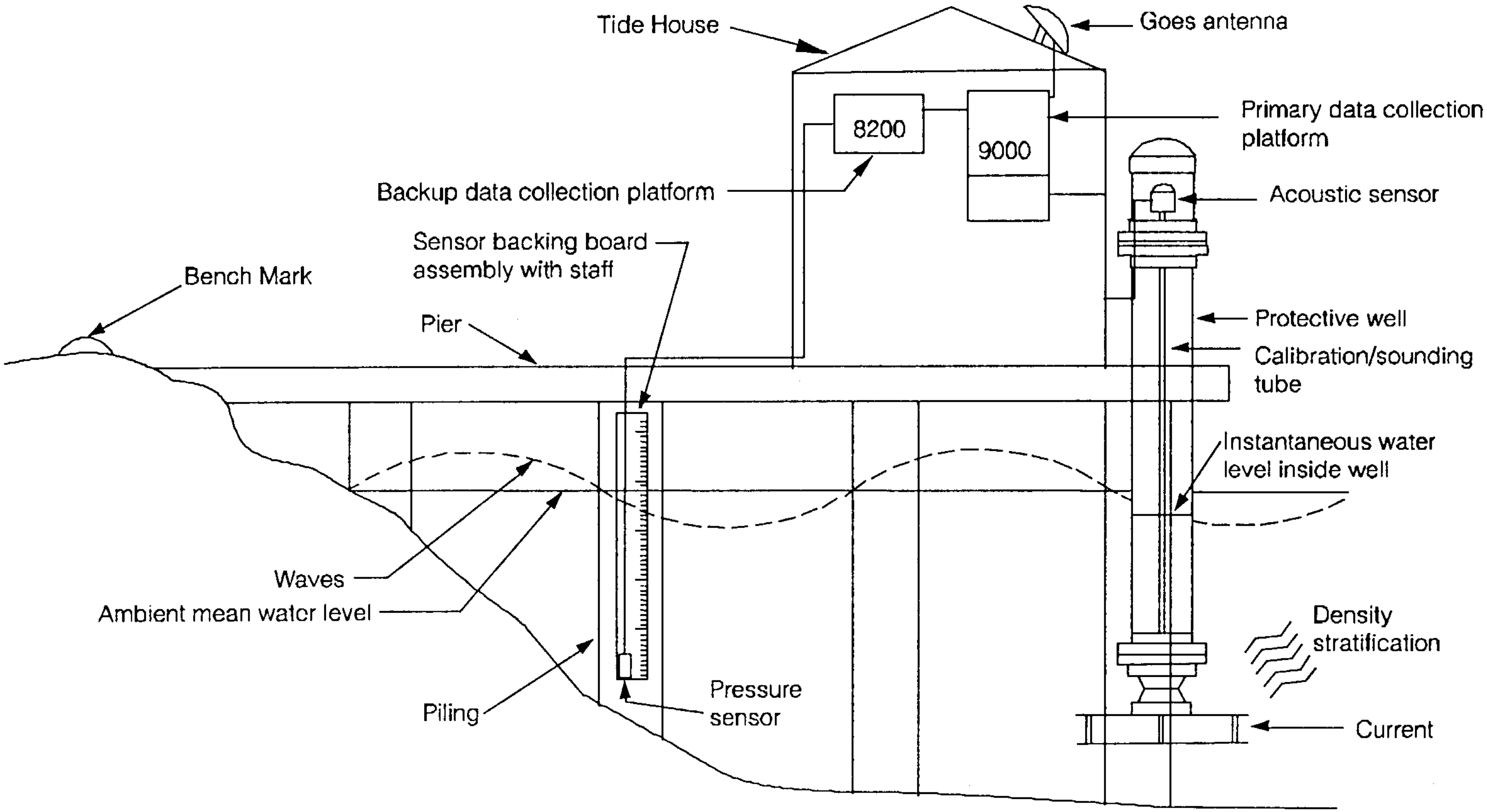


Figure 2.1

Next Generation Water Level measurement System acoustic energy down a 1/2-inch diameter PVC sounding tube and measures the travel time for the reflected signals from a calibration reference point and from the water surface. Two temperature sensors give an indication of temperature gradients down the tube. The calibration reference allows the controller to adjust the measurements for variations in sound velocity due to changes in temperature and humidity. The sensor controller performs the necessary calculations to determine the distance to the water surface. The sounding tube is mounted inside a 6-inch diameter PVC protective well which has a symmetrical 2-inch diameter double cone orifice. The protective well is more open to the local dynamics than the traditional stilling well and does not filter much of the wind waves and chop. In areas of high velocity tidal currents and high energy sea swell and waves, parallel plates are mounted below the orifice to reduce the pull down effects (Shih and Baer, 1991). Figure 2.1 is a schematic of a typical NGWLMS installation. To obtain the best accuracy the acoustic sensor is calibrated by reference to a stainless steel tube of certified length, and the zero offset is determined.

The NGWLMS also has the capability of handling up to 11 different ancillary oceanographic and meteorological sensors. The field units are programmed to take measurements at 6-minute intervals with each measurement consisting of 181 one-second interval water level samples centred on each tenth of an hour. Software rejects outliers etc. and measurements have typically 0.01 foot resolution. Data are transmitted via telephone or satellite connections.

Papers by Gill and Mero (1990a, 1990b) and Gill et al. (1992) describe the acoustic sensor calibration methods and temperature gradient induced errors, while Gill et al. (1992), Lennon et al. (1992) and Vassie et al. (1992) present comparisons between NGWLMS and conventional (stilling well or bubbler) systems in the USA, Australia and the UK. For example, US comparisons (Gill et al., 1992) between NGWLMS and ADR data have shown small differences, on the order of millimetres, for the various tidal and datum parameters, which 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 closely in order to ensure no long term bias. Much work remains to be done on the long term intercomparisons between technologies.

2.3.2 ACOUSTIC GAUGES WITHOUT SOUNDING TUBES

An instrument manufactured by MORS Environment uses a 41.5 KHz transducer with a beam width of 5° which can be operated in an existing stilling well or in the open. A temperature sensor in the air column is used to compensate for variations in the velocity of sound, and the measurement range is between 0.6 and 15 metres.

A similar instrument by Sonar Research and Development has been developed which operates at 50 KHz with a beamwidth of 4°. It can be operated in the open or in a plastic tube of about 25cm diameter. Compensation for variation in the velocity of sound is achieved by use of a bar reflector mounted 75cm from the acoustic transducer. An accuracy of 0.05% is claimed over a range of 15 metres.

For both these systems, datum control needs to be verified externally e.g. by long periodic tide pole checks.

2.4 PRESSURE SENSORS

The principle of all pressure systems is to measure the hydrostatic pressure of the water column at a fixed point and convert that pressure into a level.

2.4.1 PNEUMATIC BUBBLER SYSTEMS

In a pneumatic bubbler system air is passed at a metered rate through a small bore tube to a pressure point fixed below the lowest expected tide level (Figure 2.2). Provided that the air flow rate is low and the air supply tube is not too long the pressure of the air in the system will equal the hydrostatic pressure plus atmospheric pressure. A pressure recording instrument connected into the air supply tube will now record changes in water level as changes in pressure.

The measured pressure P_m is related to the water level above the pressure point outlet by the hydrostatic relationship :-

$$P_m = Dgh + P_a$$

where
P_m = measured pressure
D = water density
g = gravitational acceleration
h = water head above the pressure point outlet
P_a = atmospheric pressure

If the pressure P_m is measured using a differential transducer then the pressure is

$$P_m = Dgh$$

It is necessary therefore to know the site water density and gravitational constant for the accurate conversion of pressure to height.

(i) Pressure Point

The pressure point normally takes the form of a short vertical cylinder with a closed top face and open at the bottom. The metered air enters through a fitting in the top of the pressure point and escapes through a small bleed hole 4mm diameter drilled 5cm from the open end of the cylinder.

The pressure point should be fixed rigidly to a stable structure with the closed end uppermost, horizontal and with the open end not less than 0.5 metres from the sea bed, ideally about two metres below LAT.

The diameter of the pressure point is dependant on the length of the air supply tube beyond the flow control valve. As a general guide the volume of the pressure point above the bleed hole should be at least equal to the volume of the air supply line.

The pressure point should be constructed of such materials to be able to resist corrosion, cracking and attack from marine organisms. It is advisable to sleeve the bleed hole with copper which will help prevent marine growth at this vital point.

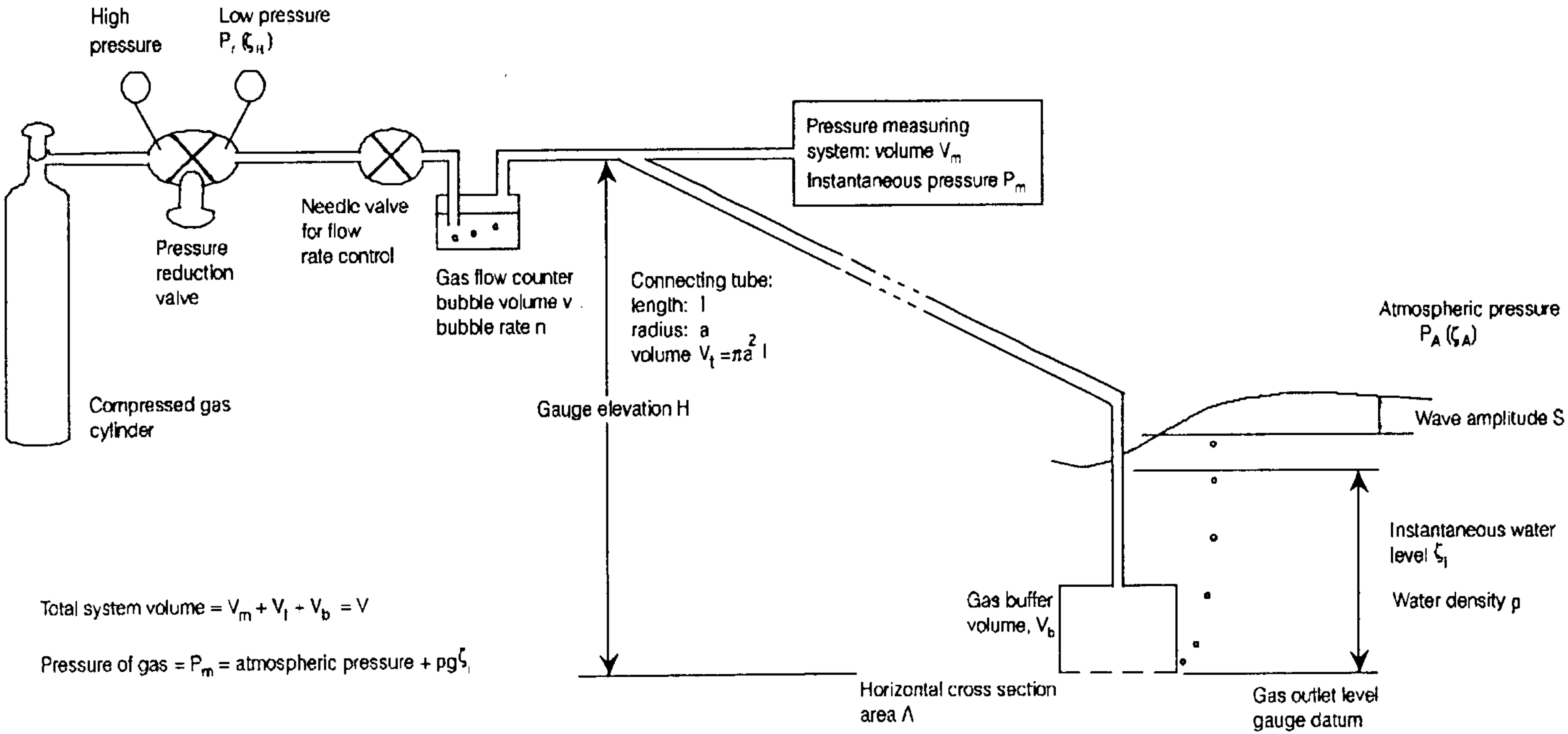


Figure 2.2

Schematic diagram of the pneumatic tide gauge and its principal system parameters

(ii) Air Supply Tube

The tube supplying air to the pressure point should be of a corrosion free non-kinking material. Nylon tube within a protective sheath should be used. Tubing with an outside diameter of 6mm and a bore of 4mm is recommended for systems with tube length up to 200 metres.

As the air enters the pressure point it becomes compressed and pushes the water down until it reaches the bleed hole where it escapes and bubbles up to the surface.

The tubing should be protected where necessary by laying it in conduit, sheathing or metal casing. It should be securely fixed to withstand the most severe weather conditions. Where tubing is laid along piers, quays or wharfs it must be positioned so as to avoid abrasive scuffing from vessels and mooring lines.

(iii) Pneumatic Controls

The pneumatic control panel should be designed to provide :-

a) Air to the pressure point metered at a constant and controllable rate.

b) The ability to purge the system with air at a very high flow rate.

c) Protection against over pressurisation for the controls and instruments.

The diagram (Figure 2.3) shows a typical circuit for a pneumatic control panel incorporating these features.

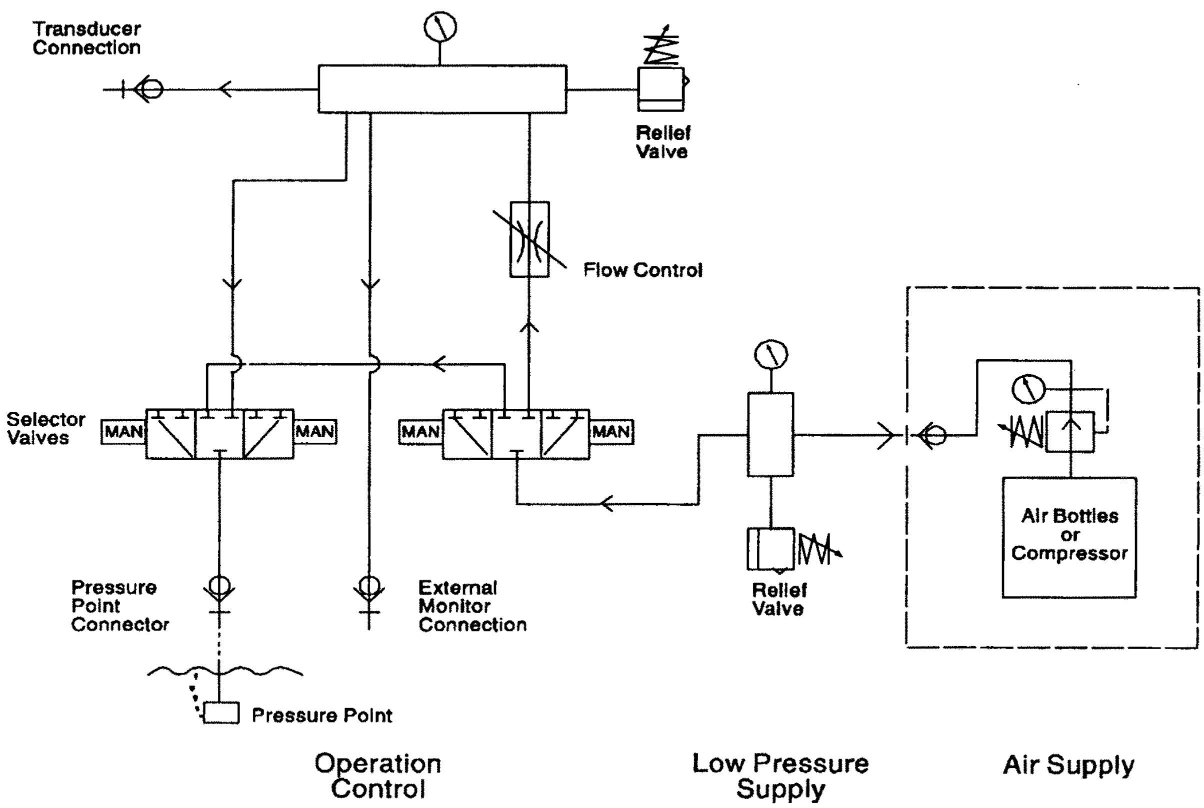


Figure 2.3

Schematic diagram of control equipment

The air supply may be derived from high pressure air bottles or a compressor. Where a compressor is used the air receiver should be large enough to provide a supply for five days in the event of compressor breakdown or failure of the electricity supply.

The air must be passed through moisture and particle filters before being regulated to supply a constant pressure of between 3 to 4 bars. A pressure gauge should be fitted to the unit to indicate this pressure. A relief valve is required to prevent the pressure downstream of this regulator exceeding 5 bars.

A flow control valve and indicator operating from the supply pressure is required to meter air to the pressure point. The flow rate required is dependant on the tidal range and the volume of the system but must be sufficient to maintain a flow of bubbles from the pressure point on the fastest rising tide.

Tappings for the tidal recording instruments are taken from a point on the supply to the pressure point downstream of the flow control valve. A pressure gauge should be incorporated to indicate this downstream pressure. A relief valve must be incorporated to protect the instruments from overpressurising.

A purging system is required to enable an unrestricted air flow to pass from the supply to the pressure point. During purging the instrument must be isolated from the supply.

It is essential that all pneumatic valves, connectors and fittings used in the construction of the pneumatic panel are of the highest quality since any leakage in the system downstream of the flow control valve will produce an error in the indicated system pressure. Leakage elsewhere in the system will increase the volume of air consumed which can be critical when the air is supplied from high pressure air cylinders.

(iv) Design Criteria for Pneumatic Bubbler Systems

Care must be exercised in the design of pneumatic systems in order to minimise errors in measurement. Where sources of error cannot be eliminated their effect must be known so that corrections can be applied to the measured pressures. The major criteria are listed below together with equations from which the magnitude of measuring errors can be deduced.

(v) Minimum Gas Flow Rate

Gas must be passed into the bubbler system at a rate that is sufficient to maintain the system pressure equal to the water pressure at the pressure point at the fastest rising tide, so that the bleed hole emits bubbles at all times.

$$f > \frac{V}{10} R_{max} \text{ (ml/sec)}$$

where f = gas flow rate

V = total volume of system (ml)

R_{max} = max rate of rise in water level (m/sec)

(vi) Static Pressure Head

For all designs the measuring point will be at higher elevation than the pressure point outlet. Consequently the pressure of the gas in the system will differ at the two points in accordance with the difference in elevation and the gas pressure :-

$$P_m = (\rho - P_{oa} (\frac{H}{\gamma_A} + 1))\ gh$$

where P_m = measured pressure

ρ = water density

P_{oa} = air density at atmospheric pressure

H = elevation of measuring point above pressure point outlet

γ_A = water level equivalent of atmospheric pressure

h = depth of water above pressure point outlet

g = gravitational acceleration

(vii) Dynamic Pressure Gradient

When gas is passed through a tube a pressure gradient along the tube will result due to the gas viscosity, the magnitude of the pressure drop being dependent on tube dimensions and gas flow rate in the following relationship :-

$$\Delta P = \frac{8\eta l}{\Pi a^2} (f - \frac{\Delta P_m}{P_m} (V_m + \frac{\Pi a^2 l}{2}))$$

where ΔP = pressure drop

η = gas viscosity at system temperature

l = length of tube

a = radius of tube

f = gas flow rate

ΔP_m = incremental change in Pm in unit time

P_m = instantaneous pressure at measuring device

V_m = volume of measuring device

In most designs of pressure transducer V_m is very small and can be ignored; the relation then becomes :-

$$\Delta P = \frac{8\eta l}{\Pi a^2} (f - \frac{\Delta P_m}{2P_m} \Pi a^2 l)$$

2.4.2 DIRECT READING SYSTEMS

The sea level may be measured by fixing a waterproof pressure transducer below the lowest expected tide level (Figure 2.4) with the power/signal cable connected to an on-shore data logging unit. If a vented power/signal cable is used a differential transducer may be fitted with the reference side of the transducer vented to atmosphere providing continuous correction for changes in atmospheric pressure.

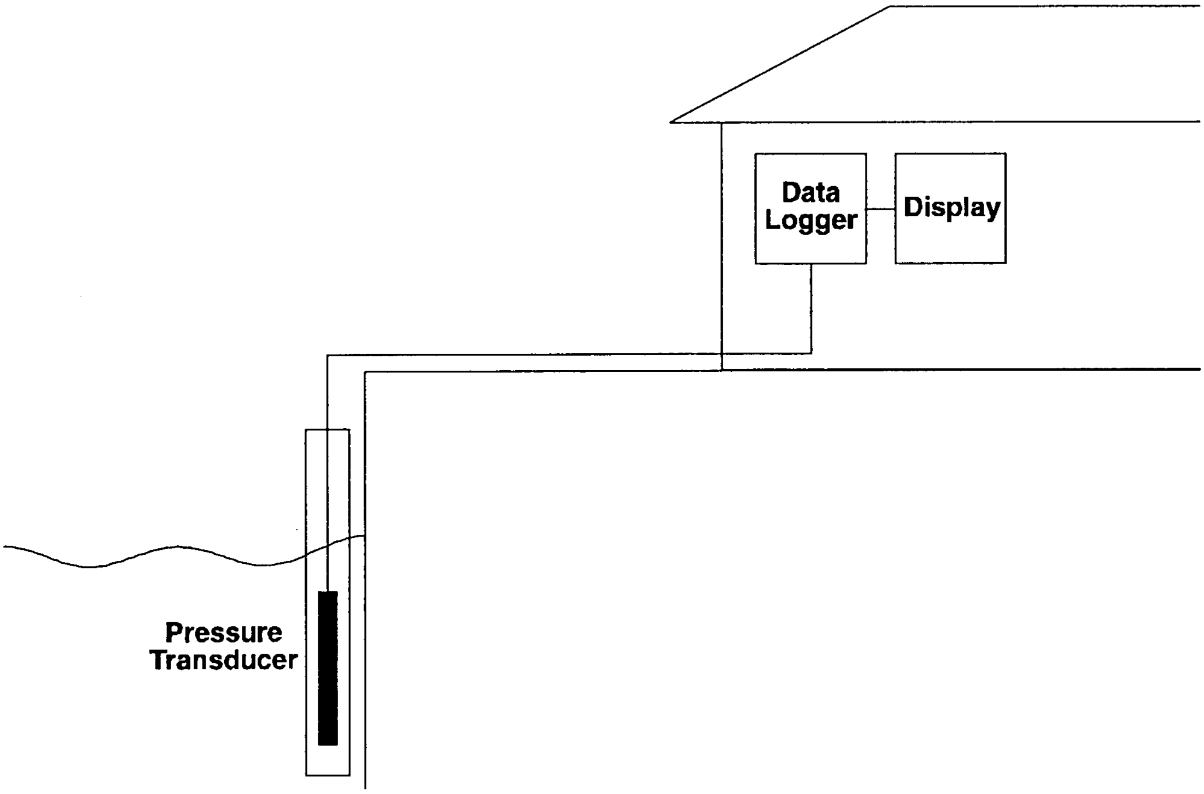


Figure 2.4

The majority of these pressure sensors use strain gauge or ceramic technology. Changes in water pressure causes changes in resistance or capacitance in the pressure element. The signal is amplified and may be displayed and stored in shore based data logging equipment.

The maintenance and calibration of these transducers is more demanding than pneumatic bubbler systems as the transducer is fixed underwater where it is susceptible to temperature variation and fouling (see section 2.5 for possible datum control methods).

(i) Temperature Effects

All pressure transducers are sensitive to temperature variations and this must be borne in mind when purchasing instruments. The expected range of temperatures to be experienced at the site should not produce an error greater than 0.01% of the full working range. If this is not possible then it is recommended that the transducer temperature is monitored for later correction of the recorded data or the transducer is housed in a constant temperature enclosure.

(ii) Pressure Systems Datum

The datum of a pneumatic system is the elevation of the pressure point bleed hole. The datum of a transducer mounted underwater is the sensor diaphragm or pressure cell.

2.4.3 HOSTILE CONDITIONS

All systems must be built and installed to withstand the severest weather conditions with protection against damage from vessels and flotsam.

(i) Effect of Waves

Surface waves will produce a rapid cyclic change in pressure in a bubbler system. The error so produced is dependent on wave amplitude in the following relation

$$E = \frac{V}{A}\,\frac{S}{P_o}$$

where

E = error

V = total system volume

A = horizontal cross sectional area of pressure point

S = pressure amplitude of short period wave

P_o = water head pressure at outlet below trough of a wave

In general the average error will not exceed 0.05% of the wave amplitude.

(ii) Effect of Currents

Areas of strong currents should be avoided when siting bubbler measuring systems. The presence of a pressure point in the tidal current will distort the velocity field, so that the pressure sensed cannot be interpreted simply as the undisturbed hydrostatic pressure. Depending on whether the bleed hole faces into or away from the current the measured pressure will be greater or less than the hydrostatic pressure. If a pressure point has to be fixed in strong currents it should be positioned so that the bleed hole is tangential to the main current flow to minimise the error.

(iii) Density Variations

Since the water levels measured by pressure systems are a function of the water pressure at the pressure point outlet, variations in the water density can lead to errors in both bubbler and direct reading systems. Such density variations are most pronounced at sites situated close to or on river estuaries. If an estuarine site must be used, specific gravity measurements should be taken and corrections applied.

2.5 PRECISE DATUM CONTROL FOR PRESSURE TIDE GAUGES

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, 1990a) 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.

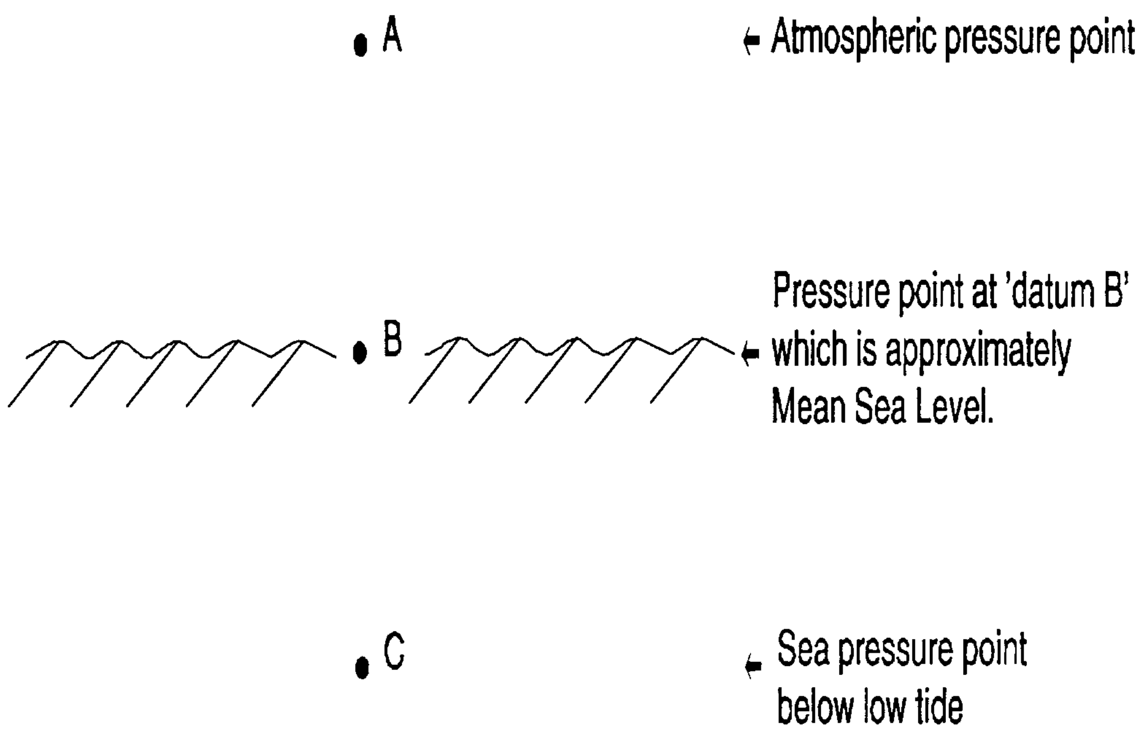
The stilling well method probably produces usable results, as long as comparisons are performed over several complete tidal cycles to remove the effect of any lag in the well. However, a stilling well will not always be present and it will have its own systematic error sources (Lennon, 1971). A tide 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 (Committee on Tide Gauges, 1986).

Pressure tide gauges already comprise a major subset of those in the Global Sea Level Observing System (GLOSS) 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 the Proudman Oceanographic Laboratory (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.

2.5.1 A BRIEF DESCRIPTION OF THE METHOD

A schematic pressure gauge setup is shown in Figure 2.5 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., 1993). 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).



(a) an 'A gauge' which measures atmospheric pressure;

(b) a 'C gauge' which measures sea pressure;

(c) a 'B gauge' placed at approximately mean sea level.

Figure 2.5

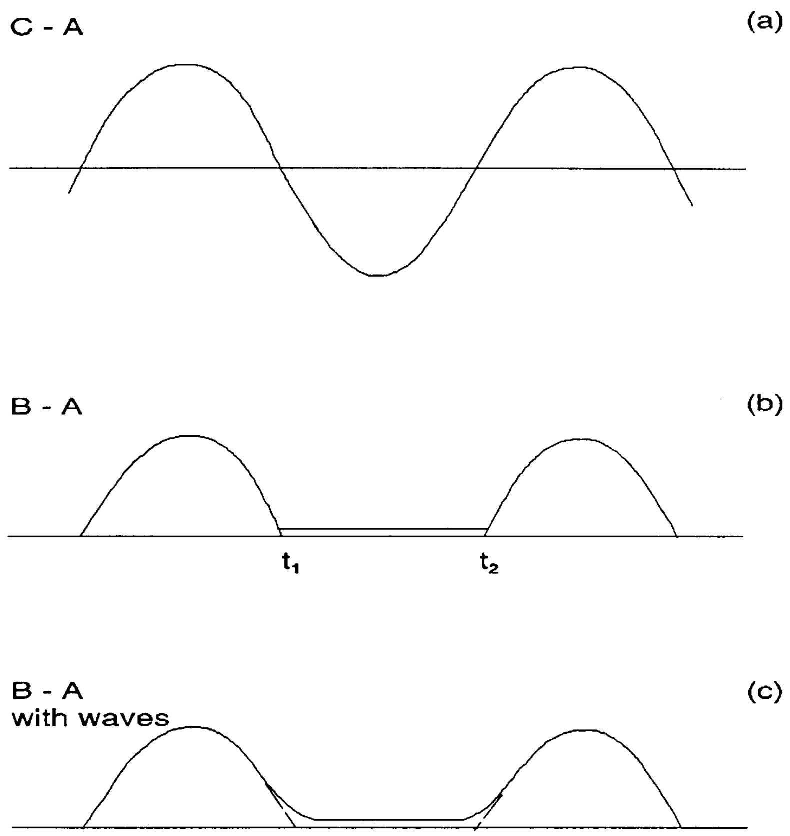
Schematic illustration of a pressure gauge setup containing three pressure transducers

In the present experiment, another pressure gauge 'B' is placed at 'datum B' (Figure 2.5) 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 millibars (i.e. to within a few centimetres), it is known *where* it is measuring it to millimetric precision.

Figure 2.6(a) shows schematically the C-A record while Figure 2.6(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 2.6(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 2.6(a) on to 2.6(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 2.6(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 2.6(c) can still be matched with 2.6(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



(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.

Figure 2.6

Schematic illustrations of time series comparisons 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 2.6(b) on to that of Figure 2.6(a), they can be continuously adjusted for by constant constraint of C-A to the B datum imposed by the least squares adjustment.

2.5.2 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 Permanent Service for Mean Sea Level (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. It is intended that these will be operating at least two sites in the second half of 1992. 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.

REFERENCES

Banaszek, A.D., 1985. Procedures and problems associated with the calibration and use of pressure sensors for sea level measurements. In, Advances in underwater technology and offshore engineering, **4**, 103-127. (London: Graham and Trotman).

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

Committee on Tide Gauges. 1986. Tide Gauge Requirements. Ministry of Agriculture Fisheries and Food.

Gill, S.K. and Mero, T.N. 1990a. Next generation water level measurement system : implementation into the NOAA National Water Level Observation Network.pp.133-146 in, Towards an integrated system for measuring long term changes in global sea level, (ed. H.F. Eden). (Report of a workshop held Woods Hole Oceanographic Institution, May 1990). Washington, DC.: Joint Oceanographic Institutions Inc. (JOI). 178pp. & appendix.

Gill, S.K. and Mero, T.N. 1990b. Preliminary comparisons of NOAA's new and old water level measurement system. pp 172-180 in Oceans '90, New York: IEEE, 604pp.

Gill, S.K., Mero, T.N. and Parker, B.B. 1992. NOAA operational experience with acoustic sea level measurement. pp.13-25 in, IOC Workshop Report No. 81, Joint IAPSO-IOC workshop on sea level measurements and quality control. Intergovernmental Oceanographic Commission, Paris.

Intergovernmental Oceanographic Commission (IOC). 1985. Manual on sea level measurement and interpretation. Intergovernmental Oceanographic Commission, Manuals and Guides, No. 14, 83pp.

Intergovernmental Oceanographic Commission (IOC). 1988 Workshop on sea-level measurements in hostile conditions, Bidston, UK, 28-31 March 1988. Summary report and submitted papers. Intergovernmental Oceanographic Commission, Workshop Report No. 54, 81pp.

Intergovernmental Oceanographic Commission (IOC). 1990. Global Sea Level Observing System (GLOSS) implementation plan. Intergovernmental Oceanographic Commission, Technical Series, No. 35, 90pp.

Lennon, G.W. 1971. Sea level instrumentation, its limitations and the optimisation of the performance of conventional gauges in Great Britain. International Hydrographic Review, **48**(2), 129-147.

Lennon, G.W., Woodland, M.J. and Suskin, A.A. 1992. Acoustic sea level measurements in Australia. pp.26-39 in, IOC Workshop Report No.81, Joint IAPSO-IOC workshop on sea level measurements and quality control. Intergovernmental Oceanographic Commission, Paris.

Noye, B.J. 1974a. Tide-well systems I: some non-linear effects of the conventional tide well. Journal of Marine Research, **32**(2), 129-135.

Noye, B.J. 1974b. Tide-well systems II: the frequency response of a linear tide-well system. Journal of Marine Research, **32**(2), 155-181.

Noye, B.J. 1974c. Tide-well systems III: improved interpretation of tide-well records. Journal of Marine Research, **32**(2), 193-194.

Pugh, D.T. 1972. The physics of pneumatic tide gauges. International Hydrographic Review, **49**(2), 71-97.

Pugh, D.T. 1987. Tides, surges and mean sea-level: a handbook for engineers and scientists. Chichester: John Wiley and Sons, 472pp.

Shih, H.H. and Baer, L. 1991. Some errors in tide measurement caused by dynamic environment. In Tidal Hydrodynamics (editor Bruce B. Parker) pp 641-671.

Smith, D.E., Spencer, R., Vassie, J.M. and Woodworth, P.L. 1991. Precise datum control for pressure sea level records. POL Internal Document.

Spencer, R., Foden, P.R., McGarry, C., Harrison, A.J., Vassie, J.M., Baker, T.F., Smithson, M.J., Harangozo, S.A., and Woodworth, P.L. 1993. The ACCLAIM programme in the South Atlantic and Southern Oceans. International Hydrographic Review, **70**, 7-21.

Vassie, J.M., Woodworth, P.L., Smith, D.E. and Spencer, R. 1992. Comparison of NGWLMS, bubbler and float gauges at Holyhead. pp 40-51 in, IOC Workshop Report No.81, Joint IAPSO-IOC workshop on sea level measurements and quality control. Intergovernmental Oceanographic Commission, Paris.

3. DATA TRANSMISSION

3.1 DATA LINKS FOR TIDE GAUGES

Sea level data measured and recorded at a tide gauge installation is frequently required for use at some other location. The method of data transmission used depends very much on the time response required, and the distance involved. Time scales can vary from almost instantaneous information to a one year record or longer, and the distance scales from a few hundred metres to thousands of kilometres.

For long time scales it is possible to physically transfer the tide gauge record over any distance, but for shorter time scales it may be necessary to transfer the data in the form of electrical signals. This can be done by telephone line, either dedicated or through the public switched telephone network (PSTN), by direct radio link, by satellite link, or by a combination of these.

For example, if instantaneous data is required then a dedicated telephone line, or direct radio link is needed. The PSTN can be used as a very near real time link, and the slight risk of an unobtainable line can usually be accommodated in many applications.

All data links from tide gauge installations require the measurement taken to be converted to an electrical form which can be processed to provide a digital measurement in millimetres above a Chart Datum. For example, in a float operated gauge, the float wire pulley shaft can be used to drive a shaft encoder or potentiometer to give an electrical signal with a linear relation to sea level. The scaling of this signal can be set by the gearing ratio used and the datum can be set by adjustment of the gear meshing. In a pressure operated tide gauge the pressure transducer used may have a non-linear electrical output which has to be conditioned electronically to give a suitable linear output related to Chart Datum. The parameters used in this conditioning have to be derived from laboratory calibration of the pressure transducer characteristics, and the value of sea water density used.

Apart from the case where an instantaneous measurement is required, the transducer output should be integrated over the period between data samples in order to filter out any shorter term variations in sea level. A suitable sampling period for tidal and longer period sea level variations is fifteen minutes. These fifteen minute averaged values should be time tagged and stored in a solid state buffer memory. The memory should be large enough to store all of the data measured during the longest anticipated period between interrogations.

Complex equipments of this type use microprocessors to control and implement the processes and calculations required. This allows the system to be quite flexible and to accommodate a number of different sensors and interrogation requirements. Information about the status and condition of the equipment can be transmitted along with the sea level measurements, so that faults can be quickly rectified to minimise loss of data. The time at which the sea level reaches a fixed datum switch can also be recorded and transmitted so that the gauge datum can be checked during each tidal cycle.

Less complex, purpose built equipments have been used for particular applications. One example is the system used by the UK Storm Tide Warning Service (STWS) at Bracknell to obtain real time data from a number of the permanent tide gauge installations on the East

Coast of the United Kingdom. In this system the output from potentiometers on float gauges is continuously digitised and transmitted along dedicated telephone lines to Bracknell where records are made and compared with predictions on chart recorders. The system can also transmit and record a signal when the sea level makes contact with a datum probe (Bestobell) at a known vertical position.

A number of systems have been designed for use by Water Authorities to allow an instantaneous measurement to be transmitted using the PSTN. Some of these systems are interrogated manually and others use special decoding and recording equipment which can also be used with automatic dialling facilities. Other systems have been developed using radio links to obtain and record data at a central station, either on demand or on a continuous basis.

For the United Kingdom national network of permanent tide gauge installations a centralised data recording and monitoring system called DATARING has been developed using the PSTN (Rae 1988). This system uses a microprocessor at each installation to process and control data from a number of different sensors and inputs. The processed data are stored in a buffer memory awaiting interrogation. At the main control station a desk top computer controls the automatic dialling of each tide gauge installation at regular intervals, and also the checking and transfer of the data in each buffer memory into the computer memory. The clocks at each installation are automatically checked and corrected by reference to a master clock, and information about the operation of the equipment at each site is flagged so that corrective action can be quickly taken if necessary. Data are transferred to a main computer where further check procedures are carried out on the data before it is processed and stored by the British Oceanographic Data Centre (BODC) in preparation for tidal analysis. Other users such as the Storm Tide Warning Service and the Water Authorities can access any of the tide gauge sites independently through the PSTN using a small computer and telephone modem.

Within the framework of the IGOSS sea-level programme in the Pacific (ISLP-Pac) the Specialised Oceanographic Centre (SOC) for ISLP-Pac (Honolulu, USA) collects sea-level data in near real time via cable, telex, telephone and satellite from 92 Pacific sea level stations.

3.2 SATELLITE DATA LINKS

Data from very remote or inaccessible tide gauge installations or from widespread national or international tide gauge networks can be transmitted by geostationary or orbiting satellite systems. A number of suitable satellite systems are available for use, including ARGOS, GOES (METEOSAT, GMS), and INMARSAT, each having different characteristics.

The ARGOS system operates worldwide using two NOAA sun-synchronous low polar orbiting satellites with a period of 101 minutes. A platform transmitter terminal (PTT) has a data capacity of 256 bits per satellite pass and, depending on location there may be a delay of up to several hours before data is available to users through the French Space Agency (CNES) Toulouse Space Centre. The number of accessible satellite passes to be expected is latitude dependent, varying from about 7 per day at the equator to 28 per day at the poles.

GOES-E (USA), GOES-W (USA), METEOSAT (Europe), and GMS (Japan) are equatorial geostationary satellites which together offer compatible worldwide coverage, except for latitudes greater than about 75°. Each data collection platform (DCP) is allocated fixed two minute time slots during which 649 bytes of data can be transmitted to a satellite. Up to one time slot per hour can be allocated to each DCP, so that if necessary data could be available to users within about one hour of measurement.

INMARSAT Standard-C also uses equatorial geostationary satellites to give worldwide coverage except for latitudes greater than about 75°. This system allows two way data communication in near real-time at a rate of 600 bits per second, with a data message up to 256 Kbytes.

As part of the World Ocean Climate Experiment (WOCE) a number of sea level stations have been established on islands in the South Atlantic, at Ascension, St. Helena, Tristan da Cunha, Falklands and Signy. At each station sea pressure (Paroscientific, Digiquartz), sea temperature and barometric pressure are continuously recorded and in addition hourly averaged values of these parameters are transmitted twice per day through the METEOSAT system using an Applied Satellite Technology transmitter. These data are retransmitted from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) receiving centre on the Global Telecommunications System (GTS) to the UK Meteorological Office. From there they are retransmitted by telex to a computer at the Proudman Oceanographic Laboratory (POL) where they are processed prior to input to the British Oceanographic Data Centre (Palin and Rae 1987).

Many of the sea level stations installed on the Pacific and Atlantic coasts of the USA and on islands in the Pacific Ocean transmit data to the GOES-E and GOES-W satellites. These data are received at the National Environmental Satellite and Data Information Service (NESDIS) facility at Wallops Island, Virginia, from where they are retransmitted to the NESDIS Central Data Distribution Facility (CDDF) at Camp Springs, Maryland. Appropriate data are then routed to the Tropical Ocean Global Atmosphere (TOGA) Sea Level Centre and the Pacific Tsunami Warning Centre (PTWC) in Hawaii, and to the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) at Rockville, Maryland. Data can normally be available within a few minutes of being received from a DCP.

Satellite transmitting sea level gauges which are part of the Pacific Island network (Wyrtki et al., 1988) use Handar Multiple Access Data Acquisition Modules. Input to these units is normally derived from two independent stilling well and float gauges (Fisher and Porter, Leupold and Stevens) or from a float gauge and a sea pressure transducer (Robinson-Halpern, Honeywell). Installations which are part of the NOS Next Generation Water Level Measurement System (NGWLMS, Mero and Stoney 1988) use Sutron 9000 Remote Terminal Units. The primary sea level sensor used is an Aquatrak Model 3000 air acoustic water level sensor (Bartex), with a back-up sea pressure transducer (Druck).

Data transmission through ARGOS, METEOSAT and GOES satellites may now be arranged through Collecte Localisation Satellites (CLS). Addresses of the suppliers of the equipment and services referred to are given in Appendix 1.

REFERENCES

Mero, T.N. and Stoney, W.M. 1988. A description of the National Ocean Service Next Generation Water Level Measurement System. Proceedings of the Third Biennial National Ocean Service International Hydrographic Conference, Baltimore, Maryland; April 12-15, 1988.

Palin, R.I.R. and Rae, J.B. 1987. Data transmission and acquisition systems for shore-based sea-level measurements. pp 1-6 in, 5th International Conference on Electronics for Ocean Technology, Heriot-Watt University, Edinburgh, 24-26 March 1987. London: Institution of Electronic and Radio Engineers. 223pp. (Institution of Electronic and Radio Engineers Publication No. 72).

Rae, J.B. 1988. Centralised data collection and monitoring systems for coastal tide gauge measurements. pp 19-25 in, Tidal measurement and instrumentation. Papers presented at the Hydrographic Society Seminar, April 1987, London, (ed. J.A. Kitching). Dagenham, Essex: Hydrographic Society. 35pp. (Hydrographic Society Special Publication No. 19).

Wyrtki, K., Caldwell, P., Constantine, K., Kilonsky, B.J., Mitchum, G.T., Mizamoto, B., Murphy, T. and Nakahara, S., 1988. The Pacific Island Sea Level Network. University of Hawaii, JIMAR 88-0137, Data Report 002, 71pp.

4. LEVELLING

4.1 GEODETIC FIXING OF TIDE GAUGES

The first Manual on Sea Level Measurements and Interpretation (pages 21 to 29) describes how sea level measurements are related to a nearby bench mark called the tide gauge bench mark (TGBM). This should be a round headed bolt either in bedrock or a substantial structure such as a quay wall. The first manual also describes how the TGBM should be regularly connected by spirit levelling to a local network of bench marks extending over one or two kilometres to check the stability of the TGBM. This ensures that the relative sea level measured by the tide gauge is not only relative to the TGBM but is also representative of the surrounding area. The manual also states that the bench marks should be connected to the national levelling network so that their elevations are given with respect to the national levelling datum point.

First order geodetic spirit levelling is accurate to 1 or 2mm over distances of a few kilometres and therefore annual relevellings are very suitable for detecting any vertical movements of the TGBM with respect to the local benchmarks. However, spirit levelling over very long distances has been found to be influenced by significant systematic errors. The long distance connections to the national datum point, therefore, only give a *nominal* height for the tide gauge and are not normally useful for determining the crustal movements at the tide gauge, which are usually only a few millimetres per year. Due to these systematic errors, national relevellings or readjustments of previous levellings can give spurious apparent changes in the height of the TGBM. This is the reason that the PSMSL requires mean sea level data defined with respect to the TGBM rather than with respect to the national datum point.

Over the past few years, advances in modern geodetic techniques have given new methods for geodetic fixing of tide gauge bench marks. These are the techniques of space geodesy and absolute gravity. The space geodesy measurements can be used to geocentrically fix the TGBM and therefore the mean sea level at the tide gauge will be defined in a global geocentric reference frame. This will therefore give an absolute mean sea level, rather than mean sea level relative to each local TGBM. The sea level is then defined in the same geocentric reference frame that is used for satellite altimetry and can therefore be directly compared with the altimetric sea levels.

Repeated space geodesy measurements at the tide gauge, (for example, annually for a decade or so), will enable the vertical crustal movement to be determined and removed from the mean sea level trend to give the true sea level trend due to climatic influences. Measuring changes of gravity near the tide gauge using an absolute gravimeter allows a completely independent determination of the vertical crustal movements. Figure 4.1 shows a schematic diagram of a tide gauge system to measure absolute sea levels.

An international working group was set up by the International Association for the Physical Sciences of the Ocean under its Commission on Mean Sea Level and Tides to recommend a strategy for the geodetic fixing of tide gauge bench marks (Carter et al., 1989). The following sections briefly describe the methods that are now recommended. The reader is referred to Carter et al., 1989 for further details. Table 4.1 summarises the accuracies required for the various measurements.

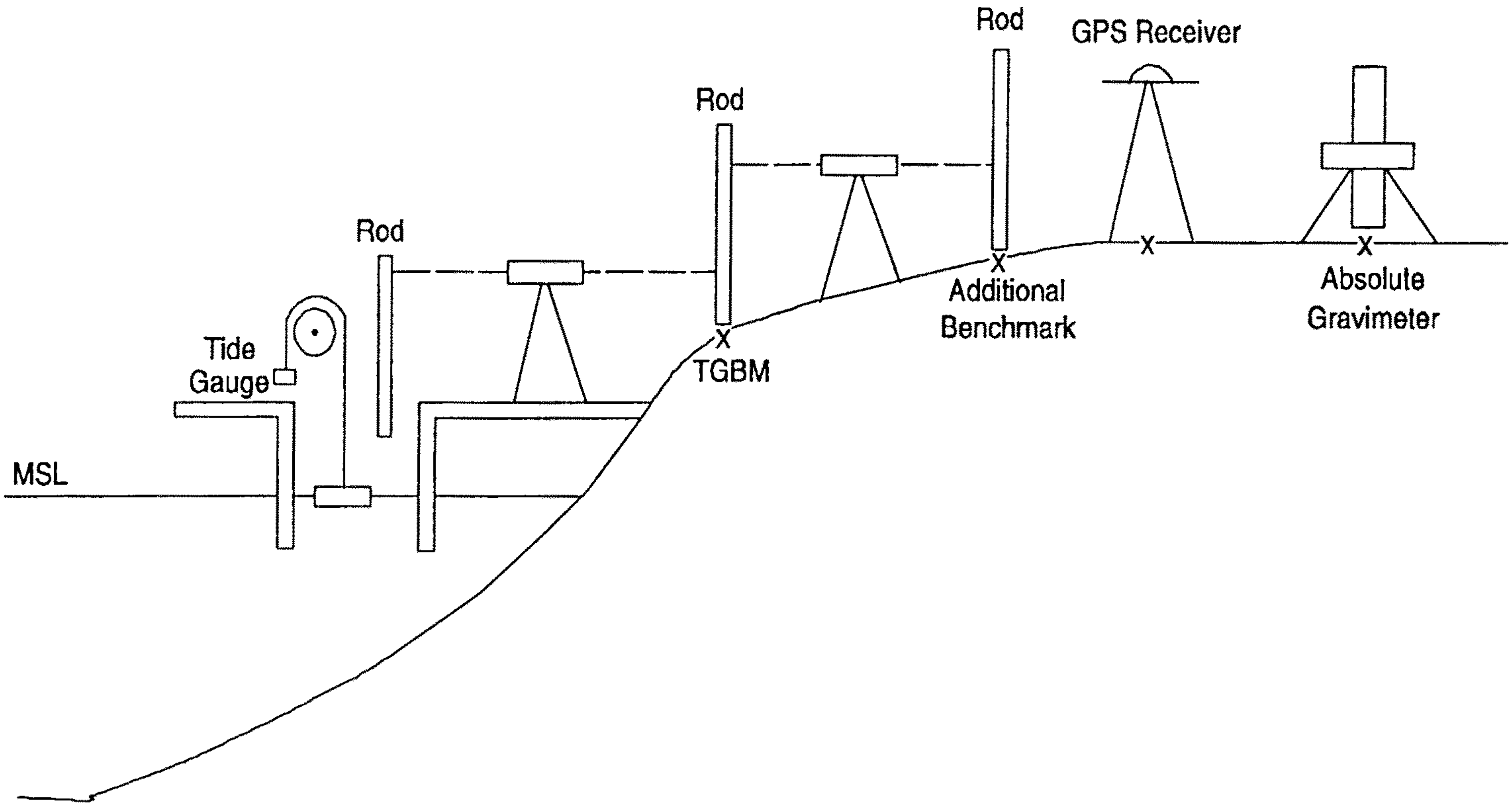


Figure 4.1

Schematic of tide gauge to measure absolute sea level

Technique Required	Accuracy
(1) Local network of bench marks for relative sea levels (primary levelling or GPS)	0 to 1km : < 1mm 1km to 10km : < 1cm
(2) GPS from TGBM to SLR/VLBI reference frame	< 1cm
(3) Absolute gravity at SLR/VLBI sites and near tide gauges	< 2μgal

Table 4.1

Techniques required for geodetic fixing of Tide Gauge Bench Marks (TGBMs)

4.2 GLOBAL POSITIONING SYSTEM

The U.S. Department of Defense, over the last few years, has been launching satellites as part of a satellite based global navigation system called the Global Positioning System (GPS). When the constellation of satellites is complete in the early 1990's, it will consist of 21 satellites (and 3 spares) at an altitude of 20,000km (12 hour orbital period) arranged so that at any one time at least 4 satellites will be visible from any point on the Earth's surface. The satellites transmit coded modulations on two carrier frequencies (carrier wavelengths of 19 and 24 cm). With access to the codes, a user with a GPS satellite receiver can determine his real time position to an accuracy of the order of 10 metres. The key development that is now giving the accuracies required for crustal deformation work is to use the phases of the two carrier waves rather than the codes. By using pairs of dual frequency GPS receivers, relative vector positioning has been achieved at the centimetric level for baselines of up to 1000km in length. The reader is referred to the articles by Dixon (1991), Hager et al. (1991) and Bilham (1991) for a review of the advances in differential GPS measurements and the application to the measurement of crustal deformations.

The report of the working group (Carter et al., 1989) recommends that the global absolute sea level monitoring system should be based upon the primary satellite laser ranging (SLR) stations and Very Long Baseline Interferometry (VLBI) radio telescopes of the International Earth Rotation Service (IERS) Terrestrial Reference Frame. Many of the 30 to 40 station positions in this network are now known to within 2cm (Ray et al., 1991, Carter and Robertson, 1990). The addition of more stations and further improvements in accuracy are expected in the next few years. SLR observations have already been used to determine the vertical motion of stations to within 1 mm/year (Kolenciewicz et al., 1992).

The recommended procedure is to connect the TGBM to the nearest primary SLR or VLBI site using differential dual frequency GPS. If satellite visibility is restricted at the TGBM, then a new bench mark may have to be installed nearby for the GPS measurements and connected to the TGBM by primary spirit levelling (see Figure 4.1).

4.3 ABSOLUTE GRAVITY MEASUREMENTS

The report also recommends that absolute gravity measurements should be made at the SLR/VLBI stations and in the vicinity of the tide gauge. This will give an important, completely independent, check upon the vertical crustal movements at both the tide gauge and the IERS sites. At remote sites, such as on oceanic islands that are far removed from the VLBI/SLR stations, absolute gravity may be the only feasible method of determining the vertical crustal movement at the tide gauge.

For a review of the recent advances in absolute gravimetry, the reader is referred to Marson and Faller (1986) and Torge (1989). The principle of the absolute gravimeter is the measurement of the acceleration of a mass in free fall (or rise and fall) in a vacuum using a laser length standard and a rubidium frequency time standard. The mass is a retro-reflector which forms one arm of a Michelson laser interferometer. A lot of effort has been put into reducing or eliminating various sources of systematic error. A great deal of experience has been gained during the past few years using portable absolute gravimeters built by the Joint Institute of Laboratory Astrophysics (JILA), Boulder, Colorado (Torge et al., 1987, Peter et al., 1989, Lambert et al., 1989). The gravity value is obtained by making repeat drops over one or two days at each site and corrections are made for tides and atmospheric pressure variations. At good sites repeat visits show that a precision of about 2 μgals can be achieved. The absolute accuracy is harder to estimate but is believed to be about 6 μgals. After more developments to reduce the errors still further, a new portable absolute gravimeter is available commercially from the AXIS Instruments Company, Boulder, Colorado (superceded by Micro g). The specifications for this instrument are a precision of ± 1 μgal and an accuracy of ± 2 μgals.

The gravity gradient in free air, at the Earth's surface, is 3 μgal/cm. In practice, for crustal deformation work, since a large area of the Earth's surface is usually displaced simultaneously, the measured gravity change is of the order of 2 μgal/cm. Thus, it can be seen that absolute gravity and space geodetic techniques are both approaching the equivalent accuracy of 1cm that is required for measuring vertical crustal movements.

In order to avoid the higher microseismic noise for gravity measurements immediately adjacent to the coastline, the report recommends that the absolute gravity measurements should be made at sites 1 to 10km inland. The gravity site (which is normally in a building with reasonable temperature control) has also then to be connected to the TGBM by spirit levelling or GPS. Inland sites also enable a higher accuracy to be achieved for the calculation of the ocean tide loading and attraction correction to the gravity measurements. However, measurements for a few months with a well calibrated continuously recording relative gravimeter should enable corrections to be made to a few tenths of a microgal at any distance from the coastline (Baker et al., 1991).

REFERENCES

Baker, T.F., Edge, R.J. and Jeffries, G., 1991. Tidal gravity and ocean tide loading in Europe. Geophysical Journal International, **107**, 1-11.

Bilham, R., 1991. Earthquakes and sea level: space and terrestrial metrology on a changing planet. Reviews of Geophysics, **29**, 1-29.

Carter, W.E. and Robertson, D.S., 1990. Definition of a terrestrial reference frame using IRIS VLBI observations: approaching millimetre accuracy. In: C. Boucher and G.A.Wilkins (Editors). Symposium, 105: Earth rotation and coordinate reference frames. Springer-Verlag, New York. pp 115-122.

Carter, W.E., Aubrey, D.G., Baker, T.F., Boucher, C., Le Provost, C., Pugh, D.T., Peltier, W.R., Zumberge, M., Rapp, R.H., Schutz, R.E., Emery, K.O. and Enfield, D.B., 1989. Geodetic fixing of tide gauge bench marks. Woods Hole Oceanographic Institution Technical Report WHOI-89-31/CRC-89-5. Woods Hole Oceanographic Institution, Woods Hole, Mass. 02543, USA.

Dixon, T.H., 1991. An introduction to the Global Positioning System and some geological applications. Review of Geophysics, **29**, 249-276.

Hager, B.H., King. R.W. and Murray, M.H., 1991. Measurement of crustal deformation using the Global Positioning System. Annual Reviews of Earth and Planetary Sciences, **19**, 351-382.

Kolenkiewicz, R., Smith, D.E., Pavlis, E.C. and Torrence, M.H., 1992. Direct estimation of vertical variations of satellite laser tracking sites from SL8 LAGEOS analysis. Annales Geophysicae, **10**(1), 111.

Lambert, A., Liard, J.O., Courtier, N., Goodacre, A.K., McConnell, R.K. and Faller, J.E., 1989. Canadian absolute gravity programme: Applications in geodesy and geodynamics. EOS, **70**, 1447-1460.

Marson, I. and Faller, J.E., 1986. g - the acceleration of gravity: its measurement and its importance. Journal of Physics E: Scientific Instruments, **19**, 22-32.

Peter, G., Moose, R.E., Wessells, C.W., Faller, J.E. and Niebauer, T.M., 1989. High precision absolute gravity observations in the United States. Journal of Geophysical Research, **94**, 5659-5674.

Ray, J.R., Ma, C., Ryan, J.W., Clark, T.A., Eanes, R.J., Watkins, M.M., Schutz, B.E. and Tapley, B.D., 1991. Comparison of VLBI and SLR geocentric site coordinates. Geophysical Research Letters, **18**, 231-234.

Torge, W., 1989. Gravimetry. W. de Gruyter, Berlin, 465pp.

Torge, W., R`der, R.H., Schnhll, M., Wenzel, H.-G. and Faller, J.E., 1987. First results with the transportable absolute gravity meter JILAG-3. Bulletin Geodesique, **61**, 161-176.

5. DATA PROCESSING

In the 1985 IOC Manual, Section 4 on data reduction covered all aspects regarding the processing of chart/graphical records. A variety of typical problems were discussed and solutions suggested. Whilst some of these problems were specific to chart records (e.g. continuity) the majority could equally well apply to the processing of digital records.

5.1 PC BASED SOFTWARE

The aim of data processing software should be to ensure the scientific validity of the data. Three main aspects should be considered :

a) linking of the data to a reference level e.g. permanent benchmark

b) timing; identification of missing scans etc.

c) correction of spikes and filling of short gaps

Many organisations have developed their own processing software to validate incoming data in varied formats and media and are specific to their requirements. However two organisations have developed PC based software as a contribution to GLOSS and other programs with the aim of enabling participating countries to be able to process and validate their own records. Contact names and addresses are given in Appendix 2.

5.1.1 TOGA SOFTWARE

The Tropical Ocean Global Atmosphere (TOGA) Programme Sea Level Centre (TSLC) (Honolulu, USA) in collaboration with the US National Oceanographic Data Centre (NODC) has prepared a package (Caldwell, 1991) for sea level data processing designed for any IBM PC or compatible microcomputers under the DOS operating system (DOS 3.1 or later). The package is geared towards people with some experience of DOS and sea level data processing; it is interactive and self-descriptive. The package and accompanying manual are freely available and updates and modifications are delivered to users. The software occupies 1.9 Mbytes of hard disk, although not all of the programs need to be loaded at the same time. The goal of the software is the establishment of a permanent archive of hourly, daily and monthly data, written in a standardised format suitable for incorporation into international archives where sea level data are available to the scientific community for exchange and analysis.

The package includes software for:

a) Tidal Analysis and Prediction

This software facilitates the use of the tidal analysis and prediction programs of the Institute of Ocean Sciences, Victoria, British Colombia (Foreman, 1977). It consists of self-descriptive, interactive batch jobs and programs which prepare the input and output to the Foreman programs.

b) Quality Control

Quality control ensures the scientific validity of the data. The software contains plotting programs which are considered to be an integral part of the package as they are the primary means used to quality control the input data and verify the processed data. This component consists of three sections:

- Inspection of reference level stability: This allows comparison with tide staff measurements and is usually carried out on a monthly basis, with values compared month to month.
- Correction of timing errors: This is normally carried out annually; timing problems are detected on plots of residuals and corrections of a whole number of hours can be applied.
- Filling gaps and correcting data spikes: The software produces a list of gaps; where possible these are replaced by data from auxiliary gauges. If this is not possible gaps can be filled by interpolation. It is recommended that gaps less than 24 hours only are replaced. This method can also be used for correcting individual incorrect points (spikes) and glitches (1 - 6 consecutive obviously wrong points).

c) Filtering Software

Programs are provided for obtaining daily values from hourly sea level data by a two-stage process. Firstly the dominant diurnal and semi-diurnal components are removed and secondly a 119-point convolution filter, centred on noon, is applied to remove the remaining high frequency energy and to prevent aliasing. Monthly values are calculated from the daily values with a simple average. Programs to enable comparison of two daily or monthly series are also included.

5.1.2 FIAMS SOFTWARE

The Flinders Institute for Atmospheric and Marine Sciences (FIAMS) has prepared time-series software (FIAMS, July 1990) for sea level processing designed for use on Personal Computers under the DOS operating system. The package includes software for:

a) Data Entry and Utilities

A program is provided for manual entry of data. There is also the capability to reformat data files and the facility to change the time zone and units of constituents. Other utilities include comparison of two card-image tidal level files and software to check for obvious errors in the data. Simple statistics can be calculated (i.e. maximum, minimum, mean for each file) and data files can be split into monthly files.

b) Analysis and Prediction

This software facilitates the use of the extensively modified tidal analysis (TIRA) and prediction (ELSIE) programs first developed at the Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside, UK (Murray, 1963) and consists of self-descriptive, interactive batch jobs and programs which prepare input and output to the programs. Hourly tidal predictions or high and low water predictions can be calculated. Residuals can be computed and statistics and histograms of the residuals produced. Generation and display of constituent differences from two appropriately formatted constituent files is also possible. Programs are also provided to compute and plot the results from the spectral analysis of time-series.

c) Quality Control

Quality control ensures the scientific validity of the data. The software contains plotting programs which are the primary means used to quality control the input data and verify the processed data by comparison with predictions. Data can be compared by plotting the difference between two series and/or observed and predicted levels. A program for filling gaps using a Cosine-Lanczos filter in Fourier Transform space is provided.

REFERENCES

Bloomfield, P., 1976. Fourier Analysis of Time Series: An Introduction. New York: John Wiley and Sons. pp 129-137.

Caldwell, P.C., April 1991. Sea Level Data Processing Software on IBM PC Compatible Microcomputers. TOGA Sea Level Centre, University of Hawaii.

FIAMS., July 1990. Tidal Time-Series Software Designed for use on a Personal Computer. FIAMS Tidal Laboratory. The Flinders University of South Australia.

Foreman, M., 1997. Manual for Tidal Height Analysis and Prediction. Institute of Ocean Sciences, Patricia Bay, Victoria, British Columbia. Pacific Marine Science Report 77-10. "Unpublished Manuscript".

Murray, M.T., 1962. Tide Prediction with an Electronic Digital Computer. Cahiers Oceanographiques. XIV, 10.

Murray, M.T., 1963. Tidal Analysis with an Electronic Digital Computer. Cahiers Oceanographiques. XV.

6. SEA LEVEL CENTRES

Sea level data have been collected for many years and historically, in some cases, data may have been archived at a national level, albeit in a rather ad hoc fashion, with little or no uniformity between one centre and the next. The one exception to this nationally based system is the Permanent Service for Mean Sea Level (PSMSL), an international sea level centre, responsible for monthly and annual mean sea levels, which is described in more detail below in section 6.3. More recently there has been a need for sea level measurements to be made available as part of large scale science programmes, for example the Tropical Ocean Global Atmosphere (TOGA) Programme and the World Ocean Circulation Experiment (WOCE).

The advantages of maintaining data in a recognised centre include the protection of the long term value of the data by storing them in a professionally managed archive, making value added products available - and high quality data will be available to a wide user community. Interactions between scientists, data collectors and data centres will result in data banks of benefit to the scientific community. In addition to the above, research workers will be encouraged to edit and document their data. The data will be available in a single format rather than in a multiplicity of formats.

To be fully effective, a sea level data bank must be more than simply a collection of numerical values; these must also be qualified by additional information concerning methods of measurement and subsequent data processing. The accompanying information needed is given in Table 6.1. A certain amount of validation and quality control will be carried out on the data by the data centre. This may vary depending on the function of the data centre, but should include checking data values for spikes, gaps and physically unreasonable values. For hourly values the residuals produced by tidal analysis of the data can be screened to check for datum shifts, timing problems and other errors. Data from adjacent stations may be compared to check out unusual signals. Qualifying information accompanying the data can also be checked.

Science programmes like TOGA and WOCE bring with them their own special needs - for example, there is a demand for quality controlled data, easy access for researchers to the data and for the data to be made available on a reasonable time scale. Perhaps more importantly, scientific experiments have a finite lifetime, and so at the end of a project, the data must be passed on to a long term archive to protect both the data and the investment in effort and money in the collection of the data.

Moreover, it is becoming increasingly important to have access to long time series of data for studies relating to climate change. The length of sea level records is a unique asset here with some records extending back 100 years or more. As more science turns to look at long term trends these interdecadal data sets will assume even greater importance. Thus it is essential that these valuable data sets are maintained.

In addition to compiling a high quality bank of sea level data these data must be made readily available to users in a suitable form. This may be a magnetic tape in the IOC standard format GF3 of sea level data series or it may be some other value added product - for example, the IGOSS Sea Level Programme in the Pacific (ISLP-Pac) produces monthly mean sea level

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.

TABLE 6.1: Information required to accompany the data

anomaly maps. These are distributed as hard copy maps, but additionally, the data that goes to make up the maps are available over computer networks.

A brief description is given below of a selection of the major sea level centres currently in existence showing the variety of work in progress. Contact names and addresses are given in Appendix 2.

6.1 TOGA SEA LEVEL CENTRE

Through interest in ocean-atmosphere coupling and the predictability of climate changes from months to years, the World Climate Research Programme initiated the Tropical Ocean Global Atmosphere (TOGA) Programme, a ten-year programme that began in 1985 and continues until 1995. One of the key observational components of the TOGA programme is the sea level. In 1985, the TOGA Sea Level Centre (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 data are received at the TOGA SLC from the sea-level stations located in tropical and sub-tropical zones of the World's Oceans.

The TOGA programme requires daily sea level values from sites identified in the implementation plan (International TOGA Programme Office, 1987). However, requests are made for hourly heights, which have proven necessary for thorough quality control.

As the quantity of data collected by the TOGA SLC increased, expertise in data management was provided by the National Oceanographic Data Centre (NODC) 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, standardised sea level data sets of hourly, daily, and monthly values. As of July 1993, 239 stations (Figure 6.1) with 2650 station-years of quality assured data from the tropical oceans have been passed to PSMSL and the World Data Centre-A for Oceanography, which ensures wide spread advertisement of the data availability and allows easy access for the scientific and public communities (TOGA Sea Level Centre: Annual Report for the year ending July 1993. Data Report No. 11).

6.2 WOCE SEA LEVEL DATA ASSEMBLY CENTRES

The international WOCE programme is establishing two sea level data assembly centres, responsibility for this has been vested jointly in the University of Hawaii and the British Oceanographic Data Centre. The first goal of WOCE requires sea level data for joint use with satellite altimetry data and for geostrophic computations of specific currents, for example, through straits. Sea level data will also serve as a check on the validity of numerical model outputs. The second goal of WOCE, determining the representativeness of the WOCE data set for the long term behaviour of the ocean, will be addressed by comparing by comparing sea level measurements made during WOCE with those held by the Permanent Service for Mean Sea Level. The University of Hawaii will build upon its experience gained in the TOGA experiment and will make higher frequency (i.e. hourly) data available in a more timely way. The sea level data set for WOCE must be not only delivered more quickly, but also must have

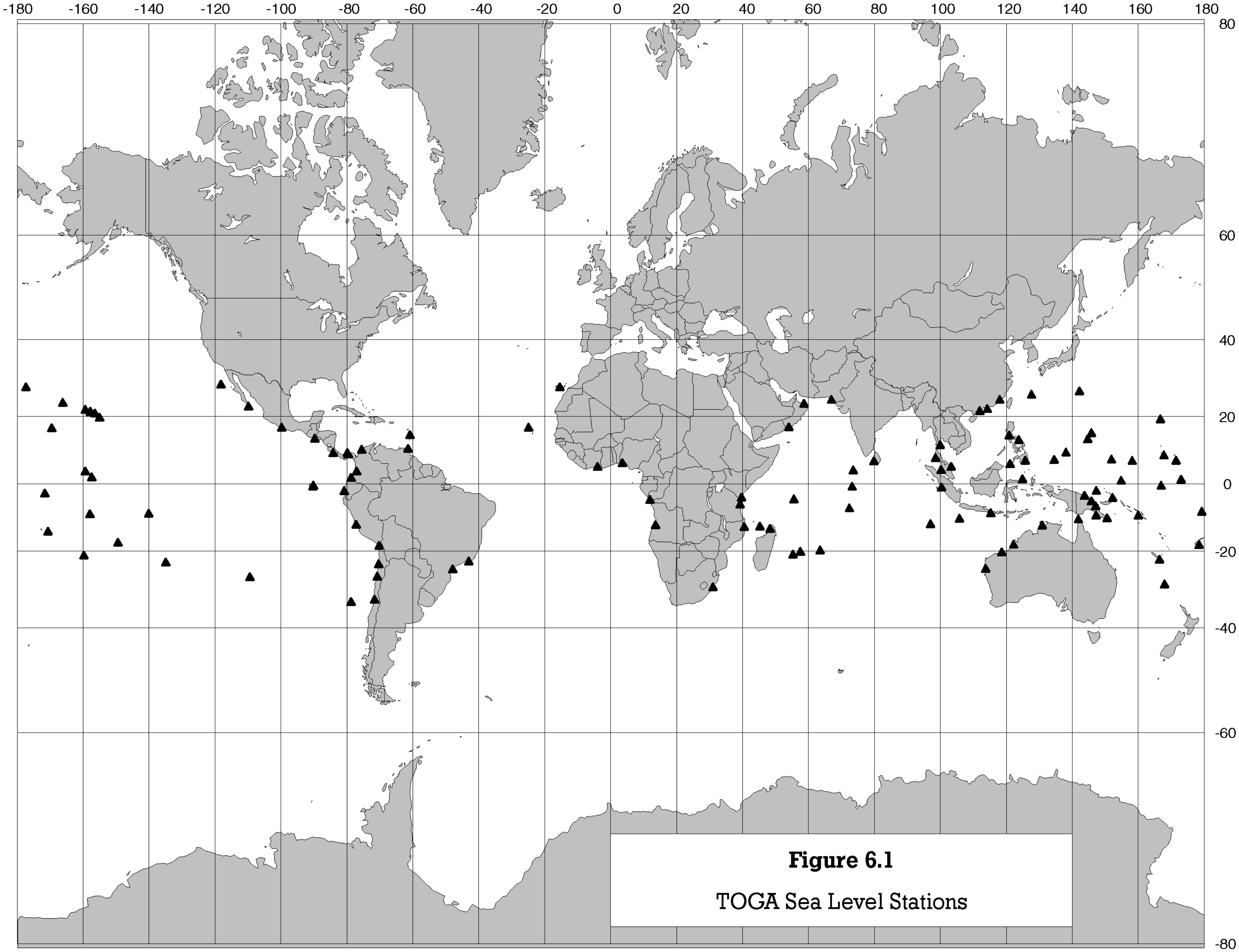


Figure 6.1

TOGA Sea Level Stations

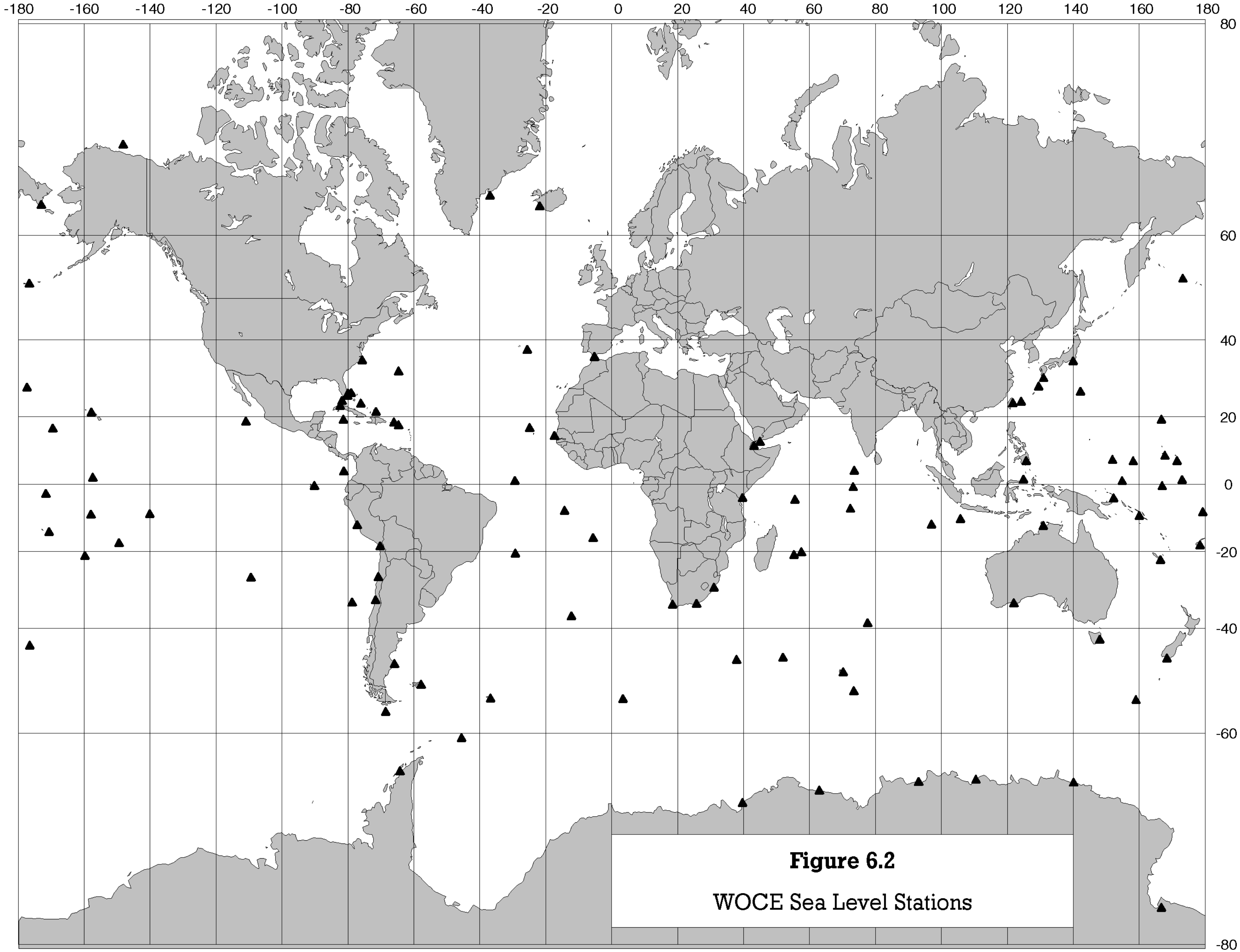


Figure 6.2

WOCE Sea Level Stations

a good global distribution to be of maximum use for the global altimetry data sets. Data will primarily be from gauges transmitting data by satellite, but will also include other data which can be rapidly supplied. Between 40 and 100 gauges will be included in the network. The data processing and distribution system will be improved to enable processed data to be available within 2-3 months of collection, that is, on a similar timescale to the satellite altimetry data.

BODC will assemble, distribute and supply sea level data to the full extent of quality control possible covering all of the 100 or so gauges (Figure 6.2) in the WOCE network. WOCE requires that the elevations should be accurate to 1cm, the timing to 2 minutes and the atmospheric pressure measurements to 1 mbar. Quality control will include checking for reasonable values, tidal analysis to remove tidal variation to enable screening of the residuals as a diagnostic for datum shifts and timing errors. Unusual signals will be compared against adjacent stations. Regular summaries of the data available are being produced for the scientific community. Close collaboration will be maintained between the scientists, BODC, TOGA centre and the PSMSL. Distribution of the data to the scientific community should be possible within 18 - 24 months after data collection. BODC will also ensure archival of the sea level data as a WOCE data set in the World Data Centre system.

6.3 THE PERMANENT SERVICE FOR MEAN SEA LEVEL (PSMSL)

Established at Bidston Observatory, Birkenhead, U.K. in 1933, PSMSL acts as an international repository for mean sea level information. PSMSL also acts as a global mean sea level assembly centre for GLOSS. PSMSL is a member of the Federation of Astronomical and Geophysical Data Services (FAGS) of the International Council of Scientific Unions (ICSU). Under the aegis of the International Association of the Physical Sciences of the Ocean (IAPSO), the PSMSL is charged with the collection, dissemination and analysis of mean sea level data. The activities of the PSMSL are supported through FAGS, through the IOC, and by the United Kingdom Natural Environment Research Council (NERC). Monthly and annual mean values of sea level are sent to PSMSL by national authorities, together with details of gauge location, missing days of data and a definition of the datum to which the measurements are referred. Received data are checked for consistency. If possible values are reduced to Revised Local Reference (RLR); this involves the identification of a stable permanent benchmark close to the tide gauge and the reduction of all data to a single datum which is referred to this benchmark. This ensures continuity with subsequent data. Records of monthly and annual values of mean sea level have been assembled from over 1500 sea level stations in more than 100 countries (Figure 6.3). There are 518 stations for which the PSMSL has at least 20 years of data and 115 stations have data from before 1900. In addition from 1991, geodetic measurements are being data banked at PSMSL.

Analyses produced from the mean sea level data bank include statistics of local and global trends and seasonal variations. They also include the identification of anomalously high or low levels which may occur in particular areas. The aim is to produce summaries which may be used for direct comparison with data from other scientific studies, such as climatology, ocean circulation variability and vertical land movements.

In 1991 PSMSL produced a report 'Data Holdings of the PSMSL' which contains an updated catalogue of their data holdings together with addresses of national sea level authorities. Data

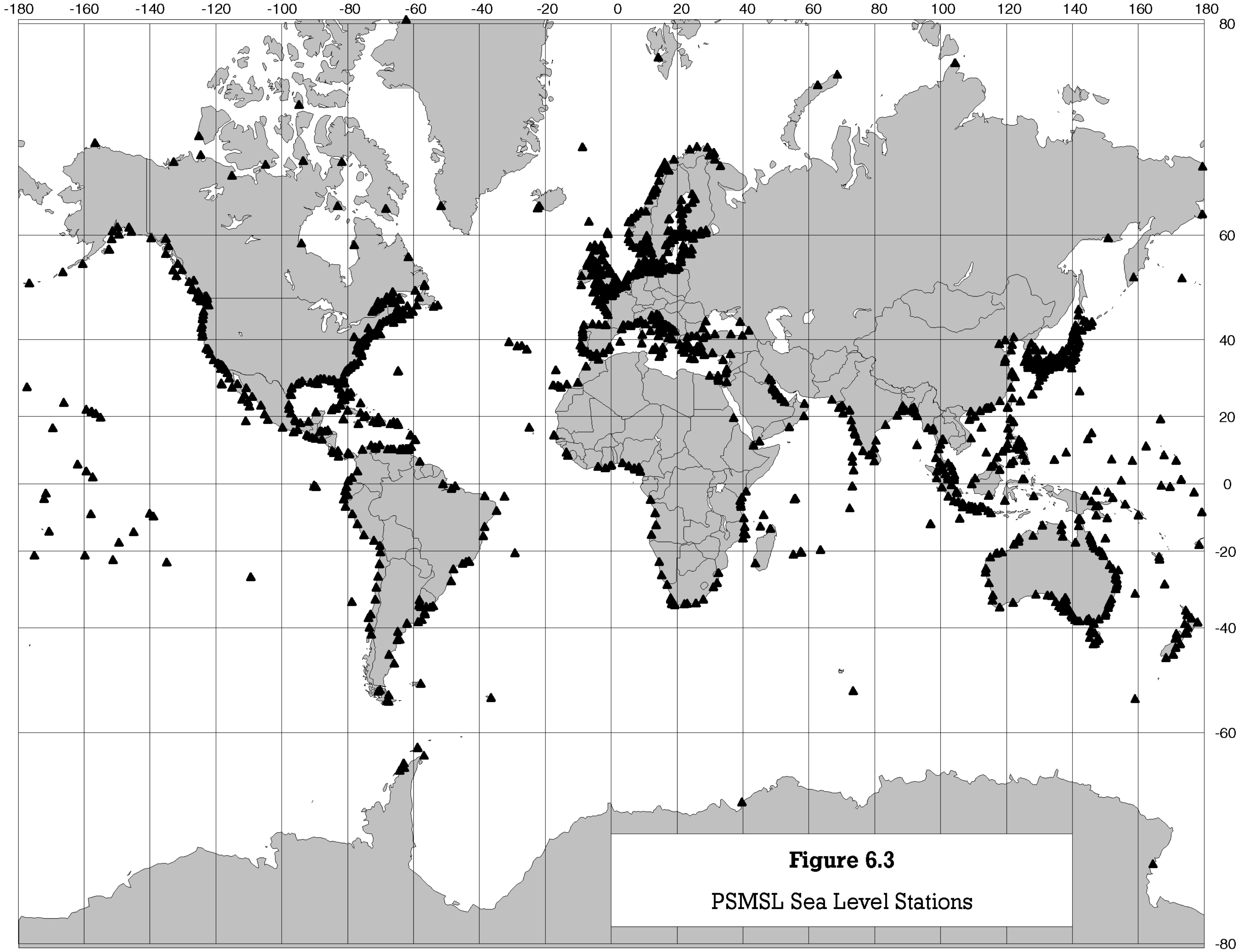


Figure 6.3

PSMSL Sea Level Stations

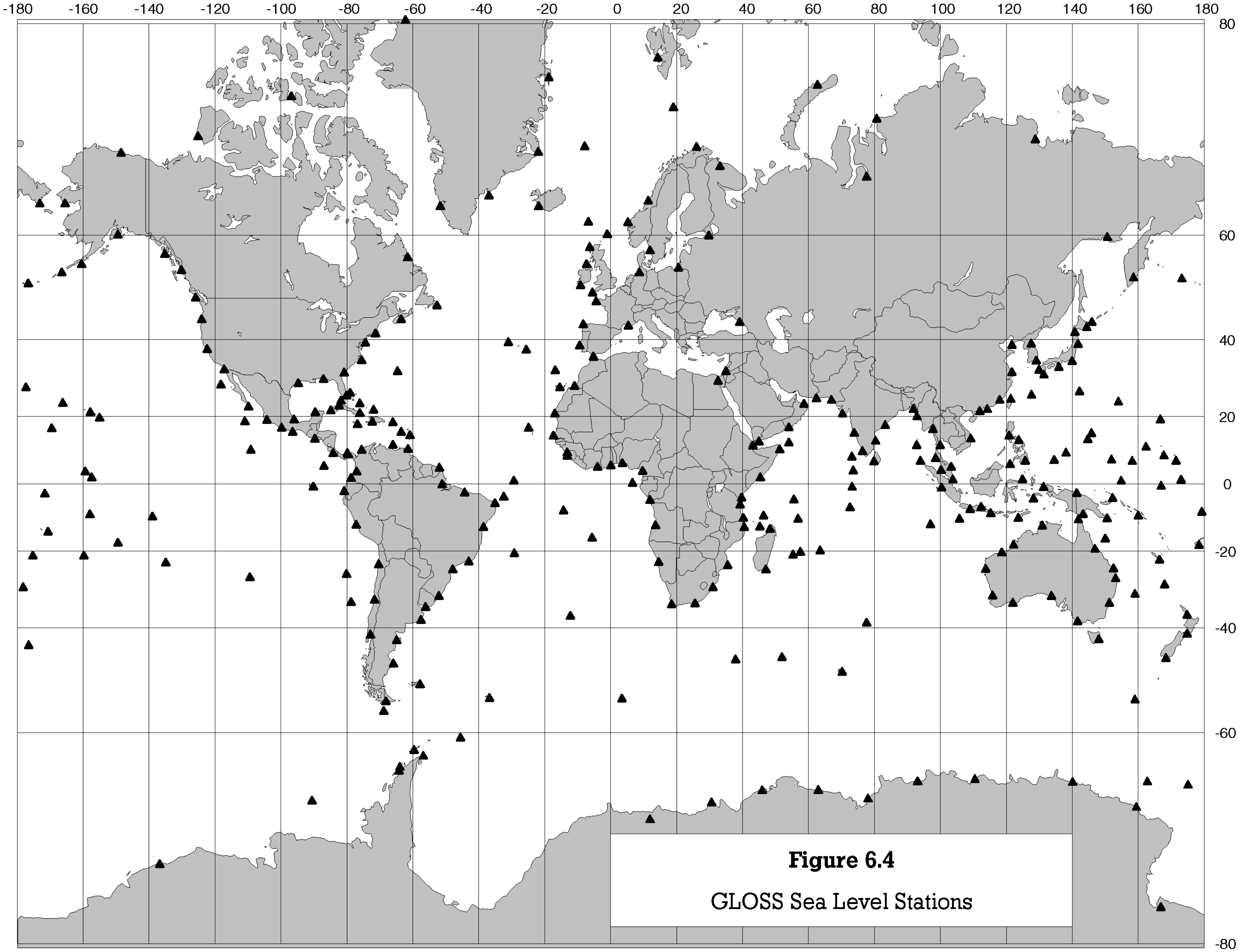


Figure 6.4

GLOSS Sea Level Stations

are available from them either across Internet, or on magnetic tape in GF3 format, or, for small selections of data, on floppy disk or as hardcopy listings. PSMSL can also provide copies of the GLOSS Handbook, a PC package giving details and site maps of each gauge (Figure 6.4) within the GLOSS network.

7. TRAINING COURSES

The IOC co-ordinated Global Sea Level Observing System (GLOSS) is one of the key existing elements of the Global Ocean Observing System (GOOS).

The success of GLOSS depends on the enthusiasm and expertise of the people responsible for the operation and maintenance of each GLOSS gauge, and for the reduction of data and supply of mean sea levels to the data centres. The role of training is crucial, in order to instill and maintain common, high standards throughout the GLOSS network.

Up to 1993, training courses have been held in Brazil (1993), France (1990), the People's Republic of China (1984), and the United Kingdom, 9 courses, (1983-1991).

In addition to the continuation of training courses for technicians (preferably on a regional basis) more emphasis should be given to the training of scientists to enable them to use fully and efficiently data resulting from GOOS for scientific and practical applications.

Core topics for the technicians' course should include:

1. Installation, maintenance and operation of tide gauges
2. Tide gauge levelling to local benchmarks
3. Absolute geodetic fixing
4. Data reduction and banking
5. Exchange of sea level data - e.g. TOGA, WOCE
6. Uses of MSL - Climate, Geodesy
7. Uses of higher frequency sea level data (hourly heights or similar) on a global basis e.g. the symbiosis with satellite altimetry data
8. GLOSS and the IOC, including IGOSS and PSMSL
9. GLOSS organisation and Publicity
10. Discussions on sea-level measurement in each participant's country

Information on intended future training courses can be obtained from the GLOSS Technical Secretary at the IOC.

APPENDIX 1

SUPPLIERS OF TIDE GAUGE EQUIPMENT AND SERVICES

FLOAT GAUGES

Fieldings Fisher and Porter Equipment, 1928N Warbler Place, Orange, California 92667, USA.

Kyowa Shoko Co., Ltd, 17-11, Nihonbashi Kayabacho 2 chome, Chuo-ku, Tokyo, 103, JAPAN

Leupold and Stevens Inc., PO Box 688, Beaverton, Oregon 97075, USA.

PRESSURE GAUGES

Aanderaa Instruments, Fanaveien 13B, 5050 Bergen, Norway.

Endeco Inc., 13 Atlantis Drive, Marion, MA, USA.

MORS Environment Division, 2-4 rue Isaac Newton, BP90, 93152 Le Blanc Mesnil, France.

OTT, GMBH, 8960 Kempten, Jugerstrasse 4-12, Postf. 2120, Germany.

Pacer Systems Inc., 900 Technology Park Drive, Billerica, MA 01821, USA.

Valeport Marine Scientific Ltd., Unit 7, Townstal Industrial Estate, Dartmouth, Devon TQ6 9LX, UK.

W.S. Ocean Systems Ltd., Unit 4, Omni Business Centre, Omega Park, Alton, Hants GU34 2QD, UK.

ACOUSTIC GAUGES

Bartex Inc., 613E Bayview Hillsmore, Annapolis, MD 21403, USA.

Sonar Research and Development Ltd., Unit 1B, Grovehill Industrial Estate, Beverley, Humberside HU17 OJW, UK.

STEPPED GAUGES AND DATUM SWITCHES

Bestobell Mobrey, 190-196 Bath Road, Slough, Berkshire SL1 4DN, UK.

Etrometa, Kerkewal 49, PO Box 132, 8400 AC Gorredijk, The Netherlands.

PRESSURE TRANSDUCERS

Druck Ltd., Fir Tree Lane, Groby, Leicester LE6 OFH, UK.

Honeywell Corp., 677 Ala Moana Blvd., Suite 301, Honolulu, Hawaii 96813.

Paroscientific Inc., 4500, 148th Avenue, NE Redmond, WA 98052, USA.

Robinson-Halpern Co., 1 Apollo Road, Plymouth Meeting, PA 19462, USA.

DATA COLLECTION PLATFORMS

Applied Satellite Technology, Unit 72, Hellesdon Park Road, Hellesdon Industrial Estate, Norwich NR6 5DR, UK.

Handar, 1380 Borregas Avenue, Sunnyvale, California 94086, USA.

Sutron Corporation, 2190 Fox Mill Road, Herndon, Virginia 22071, USA.

SATELLITE DATA SYSTEMS

CLS ARGOS, 18 Avenue Edouard Belin, 31055 Toulouse Cedex, France.
Suite 10, 1801 McCormick Drive, Landover, MD 20785, USA.

INMARSAT, 40 Melton Street, London NW1 2EQ, UK.

APPENDIX 2

INTERNATIONAL CONTACTS

A. Intergovernmental Oceanographic Commission (IOC)

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B. Permanent Service for Mean Sea Level (PSMSL)

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Tlx:	650-247-8678

D. TOGA Sea Level Centre

Prof. K. WYRTKI and Dr. M. MERRIFIELD
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E. WOCE Sea Level Data Analysis Centres

Dr. M. MERRIFIELD
(same address as above)

Dr. L.J. RICKARDS
British Oceanographic Data Centre (BODC)
Proudman Oceanographic Laboratory
Bidston Observatory
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UNITED KINGDOM

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Fax:	(44 151) 652 3950
E-mail:	bodcmail@pol.ac.uk

F. Specialized Oceanographic Centre for the IGOSS Sea Level Pilot Project in the North and Tropical Atlantic

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Department of Fisheries and Oceans
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Fax: (1 613) 990 5510
Tlx: 534228
E-mail: bolduc@ottmed.meds.dfo.ca

G. Regional Co-ordinators for GLOSS

IOC Regional Committee for the Co-operative Investigation in the North and Central Western Indian Ocean (IOCINCWIO)

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Fax: (254 11) 47 22 15
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IOC Regional Committee for the Central Eastern Atlantic (IOCEA)

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Fax: (234 1) 61 95 17
Tlx: OCEANOGRAF

IOC Sub-Commission for the Caribbean and Adjacent Regions (IOCARIBE)

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Director
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Florida Institute of Technology
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Tel:	(1 407) 768 8000
Fax:	(1 407) 984 6461
E-mail:	gmaul@pelican.marine.fit.edu

H. Co-operating International Organisations

International Hydrographic Bureau (IHB)

Mr. Hans-Peter ROHDE
(Hydrography)
International Hydrographic Bureau
7, Avenue President J.F. Kennedy
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Principality of Monaco

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IAPSO Sea-Level Commission

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PC BASED TIDAL SOFTWARE SUPPLIERS

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APPENDIX 3

ABBREVIATIONS AND ACRONYMS

ACCLAIM	Antarctic Circumpolar Currents Levels by Altimetry and Island Measurement
ARGOS	Automatic Remote Geomagnetic Observatory System
BODC	British Oceanographic Data Centre
CDDF	Central Data Distribution Facility
CLS	Collecte Localisation Satellites
CNES	Centre National d'Etudes Spatiales
DATARING	Data Acquisition for Tidal Applications for the Remote Interrogation of Network Gauges
DCP	Data Collection Platform
DOS	Disk Operating System
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FIAMS	Flinders Institute for Atmospheric and Marine Sciences
FAGS	Federation of Astronomical and Geophysical Services
GCOS	Global Climate Observing System
GF3	General Format 3
GLOSS	Global Sea Level Observing System
GMS	Geostationary Meteorology Satellite
GOES	Geostationary Operational Environmental Satellite System
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GTS	Global Telecommunications System
IAPSO	International Association for the Physical Sciences of the Ocean
ICSU	International Council of Scientific Unions
IERS	International Earth Rotation Service
IGOSS	Integrated Global Ocean Services System
INMARSAT	International Maritime Satellite Organisation
IOC	Intergovernmental Oceanographic Commission

IPCC	Intergovernmental Panel on Climate Change
ISLP-Pac	IGOSS Sea Level Programme in the Pacific
JASL	Joint Archive for Sea Level
LAT	Lowest Astronomical Tide
METEOSAT	Geostationary Meteorological Satellite
NERC	Natural Environment Research Council
NESDIS	National Environmental Satellite and Data Information Service
NGWLMS	Next Generation Water Level Measurement System
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
POL	Proudman Oceanographic Laboratory
PSMSL	Permanent Service for Mean Sea Level
PSTN	Public Switched Telephone Network
PTT	Platform Transmitter Terminal
PTWC	Pacific Tsunami Warning Centre
RLR	Revised Local Reference
SLC	Sea Level Centre
SLR	Satellite Laser Ranging
SOC	Specialised Oceanographic Centre
STWS	Storm Tide Warning Service
TGBM	Tide Gauge Bench Mark
TGI	Tide Gauge Inspectorate
TOGA	Tropical Ocean Global Atmosphere
UH	University of Hawaii
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
VLBI	Very Long Baseline Interferometry
WMO	World Meteorological Organisation
WOCE	World Ocean Circulation Experiment