

Intergovernmental
Oceanographic
Commission

Manuals and Guides **14**



MANUAL ON SEA LEVEL MEASUREMENT AND INTERPRETATION

Volume III - Reappraisals and Recommendations
as of the year 2000

2002 UNESCO

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IOC Manuals and Guides No. 14, Volume III
February 2002
English only

(SC-2002/WS/10)

FOREWORD

In 1985 the Intergovernmental Oceanographic Commission (IOC) published the “Manual on Sea Level Measurement and Interpretation” as part of its Manuals and Guides series (Number 14). The manual had been prepared by the staff of the Institute of Oceanographic Science, Bidston Observatory, UK (now the Proudman Oceanographic Laboratory) who had been associated with summer courses on sea-level observation and data reduction held under the auspices of IOC in support of the recently established Global Sea Level Observing System (GLOSS) programme. The manual was concerned almost entirely with the float tide gauge technology then used at most locations around the world. In 1994 the original manual was reprinted as Number 14, Volume 1 (Basic Procedures) and an additional document was published as Volume 2 (Emerging Technologies) which summarized new developments in the field. These two volumes have served as the basic training materials for IOC sea level courses held in many countries up to the present.

At the sixth meeting of the GLOSS Group of Experts in Toulouse in 1999, the decision was made to embark on a partial-rewriting of the two old volumes into a new document (Volume 3) which would update the information on the rapidly developing different technologies and which would provide updates to other information on GLOSS. The decision was made for two main reasons. First, it is clear that there will be a need for a considerably greater amount of sea level-related training in the next decade as programmes such as C-GOOS add to the requirements of GLOSS. Consequently, there is a need to get our training materials in better order and up-to-date. Second, it was our intention that the new document would make firmer statements of what constitutes a suitable technology for GLOSS, rather than just review the available technologies as the earlier volumes did.

This new Volume 3 simply refers back to sections in the earlier volumes if we felt there was nothing to change or new to add, even if it must be admitted that the style of the old volumes is now somewhat dated. This does not imply that we considered the old material was not worth including in the new volume. In fact, much of the contents of Volumes 1 and 2 (e.g., the description of float gauge operations using paper charts) is still valid and educational. Rather, our decision was taken knowing that Volumes 1 and 2 can still readily be found on the web at:

<http://www.pol.ac.uk/psmsl/training/training.html>

Volume 3 also uses web references for other reasons. For example, it has enabled us to produce this document in a reasonable time without the worry that some of its contents (lists of addresses etc.) will be out-of-date as soon as it is printed. We intend to keep as many as possible of the web addresses the same over the next few years while keeping their contents as up-to-date as possible.

We hope that this new Volume 3 will fulfil its objectives and that it will contribute towards unifying procedures for sea-level measurements in Member States of IOC who wish to install or reactivate sea-level stations. The GLOSS Group of Experts has endorsed its publication, and members of the Group are thanked for contributing towards its preparation.

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March 2000

TABLE OF CONTENTS

	page
1. INTRODUCTION.....	1
1.1 HISTORICAL BACKGROUND	1
1.2 TIDE GAUGES.....	1
1.3 GLOSS REQUIREMENTS.....	2
1.4 LAYOUT OF VOLUME 3	3
2. TIDE GAUGE TECHNOLOGIES.....	3
2.1 ACOUSTIC TIDE GAUGES.....	3
2.1.1 Acoustic Gauges With Sounding Tubes	4
2.1.1.1 <i>The NOAA NGWLMS System.....</i>	<i>4</i>
2.1.1.2 <i>The Australian SEAFRAME System</i>	<i>5</i>
2.1.1.3 <i>Other Users of Acoustic Sounding Tube Gauges and Calibration Comments.....</i>	<i>6</i>
2.1.1.4 <i>Similar Hardware Available.....</i>	<i>6</i>
2.1.2 Acoustic Gauges in the Open Air	7
2.1.2.1 <i>Experience in Spain</i>	<i>7</i>
2.1.2.2 <i>Experience in South Africa</i>	<i>8</i>
2.2 PRESSURE SENSOR TIDE GAUGES.....	8
2.2.1 Single Transducer Systems.....	9
2.2.1.1 <i>The Datum of a Single Transducer Pressure System.....</i>	<i>10</i>
2.2.2 Multiple Pressure Transducer Systems ('B Gauges').....	10
2.2.3 Pressure Transducers in Stilling Wells	11
2.2.4 Bubbler Pressure Gauges	11
2.2.5 Bottom Mounted Pressure Gauges	12
2.3 FLOAT GAUGES IN STILLING WELLS.....	12
2.4 RADAR TIDE GAUGES AND OTHER NEW TECHNOLOGIES.....	13
2.5 GENERAL PRINCIPLES OF CHOICE OF A TIDE GAUGE SITE.....	14
2.6 COMMENTS ON DESIRABLE RECORDING FREQUENCY.....	15
2.7 SYNTHESIS OF THE MERITS OF DIFFERENT TECHNOLOGIES	16
3. DATA TRANSMISSION METHODS	27
3.1 INTRODUCTION.....	27
3.2 SATELLITE AND GLOBAL MOBILE PHONE DATA LINKS.....	28
3.3 PACKAGES AVAILABLE WITHIN GLOSS.....	28
4. DATUMS AND DATUM CONNECTIONS AT TIDE GAUGES.....	29
4.1 SOME DEFINITIONS (EXTENDED FROM VOLUME 1).....	29
4.2 LEVELLING BETWEEN LOCAL BENCHMARKS.....	32
4.3 LEVELLING BETWEEN WIDER AREA MARKS.....	32
4.4 GEODETIC FIXING OF TIDE GAUGE BENCHMARKS.....	33
4.4.1 Introduction	33
4.4.2 Geocentric Co-ordinates of Tide Gauge Benchmarks and Monitoring of Vertical Land Movements at Tide Gauges	33
4.4.3 GPS Measurements	34
4.4.4 DORIS Measurements	36
4.4.5 Absolute Gravity Measurements	36
4.5 GEODETIC CONTACT POINTS	37

5.	DATA DOCUMENTATION AND PROCESSING	38
5.1	DOCUMENTATION AND ARCHIVING	38
5.2	PC-BASED SOFTWARE	38
	5.2.1 Comments on Tidal Predictions.....	39
	5.2.2 Tidal Filters for ‘Mean Sea Level’.....	39
	5.2.3 Comments on Computations of Extremes.....	40
6.	DATA EXCHANGE PROCEDURES	41
6.1	BACKGROUND.....	41
6.2	CONSEQUENT DATA EXCHANGE ACTIONS	42
6.3	FAST DELIVERY DATA	42
6.4	REGIONAL PROGRAMMES.....	43
7.	TRAINING MATERIALS, TRAINING COURSES AND MORE INFORMATION	43
7.1	TRAINING MATERIALS	43
7.2	SEA LEVEL TRAINING COURSES.....	43
7.3	FURTHER INFORMATION	44
8.	REFERENCES.....	44
9.	ACKNOWLEDGEMENTS.....	47

APPENDICES

1. GLOSS REQUIREMENTS FOR GAUGES
2. LIST OF ACRONYMS

1. INTRODUCTION

1.1 HISTORICAL BACKGROUND

Since ancient times observers of the ocean have attempted the measurement of changes in sea level in order to understand the mechanisms responsible for phenomena such as the tides and the catastrophic floods due to storms and tsunamis. The study of the ocean tides has a particularly rich history, with even prehistoric societies able to associate the regular changes in the level of the sea to the movements of the Moon and Sun, while in more recent times tidal studies have preoccupied some of the world's greatest scientists. It is now known that sea level changes on all timescales from seconds (due to wind waves) through to millions of years (due to the movement of continents). A student interested in the history and science of tides and sea level changes could begin by reading Pugh (1987), Open University (1989), Emery and Aubrey (1991), Bijlsma *et al.* (1996), Pirazzoli (1996), Warrick *et al.* (1996), Cartwright (1999) and Douglas and Kearney (2000).

This manual is concerned primarily with techniques for the measurement of what are called **relative sea level changes** which means changes relative to the level of the land upon which the measuring instrument (the tide gauge) is located. The subject of changes in the level of land itself is reviewed later in this document but is given more detailed presentation in other reports to which we refer. The manual also concerns itself primarily with the part of the frequency spectrum of sea level change from minutes through to centuries by means of *in situ* devices at the coast (tide gauges). Such changes are sometimes called **still water level changes**, being changes over a period long enough to average over wind waves. The devices employed to make these measurements are usually called **tide gauges**, although **sea level recorders** might be a more appropriate term. In this manual we have kept the older, conventional term.

Tide gauges themselves have a long history. The first devices were simply graduated markings inscribed on rocks, or on masonry or boards at the entrances to harbours, with measurements of sea level made visually. The long sea level records collected from several European ports (e.g. Amsterdam, Stockholm, Brest and Liverpool) were all obtained this way, with most measurements restricted to observations of just high and low water levels. These data sets of **Mean High Water, Mean Low Water** and their combination into **Mean Tide Level** have proved to be of great importance to climate change studies. Only in the 1830's did the first mechanical gauges appear in near to modern form, equipped with clocks and chart recorders and with a stilling well and float arrangement for the damping of high frequency wave activity. These provided the first, routine (although not the first overall) means of measurement of the complete tidal curve which could be inspected in detail by digitization (typically every hour) of the pen traces on the paper charts, and which could thereby provide a determination of **Mean Sea Level**, or a true average of the sea level over a period such as a month or a year.

1.2 TIDE GAUGES

Tide gauges nowadays come in many different forms (for a recent review, see Joseph, 1999). The well-known float gauge in a stilling well remains a popular type, although electronic digitization of the rise and fall of the float has replaced the chart recorder. Gauges can also be purchased based on the principles of the measurement of sub-surface pressure, or of the time-of-flight of a pulse of sound, or of a pulse of radar. Gauges have been developed using stepped sensor techniques and other ingenious methods. Alongside the range of available technologies, there is a range of prices which can be paid for similar-looking devices, and also a range of hidden costs associated with installation, maintenance, data acquisition and data processing which have to be taken into account before one can make a proper choice. This Volume 3 attempts to make the choice easier. However, a major factor to keep in mind is that IOC's main interest in the publication of this volume is the provision of sea level information for the Global Sea Level Observing System (GLOSS) and Global Ocean Observing System Coastal Module (C-GOOS) programmes which have scientific and operational requirements for high quality data. This will explain the bias in this Volume 3 towards certain gauge technologies, which we feel are the most appropriate for GLOSS and C-GOOS.

One might ask why programmes like GLOSS need tide gauges at all these days, in the modern age of precise radar altimetry from space. However, even within the scientific context of global sea level change, information from gauges is essential for the acquisition of knowledge on local mean sea level trends and extremes, which can be analyzed alongside the global data provided by altimetry. In addition, gauges are also an essential component of the altimetric system, through the provision of precise calibration information. Consequently, one can expect sea level recording by means of gauges to have a healthy future as well as a long history.

Of course, gauges have many applications apart from scientific research. These include coastal engineering, navigation, hydrography, flood-warning etc. and the choice of a gauge for these practical purposes will usually depend upon the cost and ancillary factors such as remote operation capability. The choice of an appropriate gauge, even a nominated 'GLOSS gauge', by a tide gauge agency will in practice almost always be made with multiple applications in mind. If the various applications do not compromise each other, and especially if low cost does not compromise scientific quality data, then an ideal arrangement will have been reached. However, as with all products, it is important to realize what one is purchasing and what its capabilities are.

1.3 GLOSS REQUIREMENTS

With so many different technologies available, it is best to summarize the measurement requirements for a GLOSS-quality tide gauge in as general a way as possible. These have been stated in the Implementation Plan for GLOSS 1997 (IOC, 1997) and are summarized in Appendix 1. In brief, the gauge must be capable of measuring to centimetre accuracy in all weather (especially wave) conditions for the temporal averaging indicated (typically hourly). An important principle is that if one technology is replaced by another, then there should be a period of overlap during which both are operated in parallel and inter-compared in order to validate the centimetric requirement. An ideal period would be a decade, which in tropical areas would allow full sampling of inter-decadal ocean changes (especially temperatures). However, such a long period will be impractical in most cases, and several years will be more suitable.

A reasonable question is to ask why one should be satisfied with the centimetre requirement, given that these days one can easily measure in a laboratory to much higher precision with a laser, for example. One part of the answer is that some gauge-types can certainly measure to much better than 1 cm (or at least can do so under most conditions) and, therefore, are certainly to be preferred over other types. A second part, however, is connected with a proper appreciation of the physical characteristics of the sea surface, and therefore sea level, given the presence of waves, spume, bubbles etc. It is pointless to be capable of measuring such high frequency 'noise' on the surface if there is no clear scientific requirement to do so, and if the demands of the measurement process result in high cost and/or unreliable continuous operation over long periods. There are few ocean processes from tides to seasonal cycles to interannual variability, which cannot be addressed with a 1-cm accuracy instrument. In addition, the 'red' (predominantly low-frequency) character of sea level variability at most locations, with typically decimetre amplitudes at decadal timescales, means that one could not measure secular trends (with typical magnitudes of 1 cm/decade) with even the most precise device without a record at least 50 years long. Therefore, the emphasis of programmes such as GLOSS with a long-term measurement component has been placed upon the ability to conduct reliable long-term measurements in most parts of the world to adequate 1-cm) accuracy and at reasonable cost.

In environmentally hostile areas, it may not be possible to measure to the same accuracy as elsewhere. The general rule here will be to do 'as well as one can'. Several workshops have been held on the theme of sea level (or sub-surface pressure) measurements in hostile areas and their reports (IOC, 1988, 1991, 1992) are still useful.

1.4 LAYOUT OF VOLUME 3

The following Sections 2.1-2.4 describe each of the various tide gauge technologies based on material provided by members of the GLOSS Group of Experts. A large number of other members of the sea level community have also provided input based on their own experiences. After considering other aspects of tide gauge installation and operation, the final part of Section 2 attempts a synthesis of opinions and provides recommendations to operators intending to install new gauges for GLOSS and C-GOOS.

Sections 3 and 4 are concerned with the technologies of data communications and of surveying and geodesy. Section 4 is essential reading for a proper appreciation of the required good quality control of the datum's of tide gauge observations. In addition, advances in geodesy mean that independent (of the gauge data) measurements of changes in land level will eventually be obtained which will provide a decoupling of sea and land level changes within the sea level records, and which place tide gauge sea level data within the same global geodetic reference frame as altimeter observations.

Sections 5 and 6 discuss aspects of data documentation, processing and exchange and provide updates to sections of earlier documents (e.g., to Volumes 1 and 2 and to the GLOSS Implementation Plan 1997). Section 7 summarizes the situation with regard to training materials, training courses and other information.

2. TIDE GAUGE TECHNOLOGIES

2.1 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.

The most suitable arrangement for reliable long-term operation is obtained by constraining the acoustic pulses within a narrow vertical sounding tube. By this method, it is possible to automatically provide a first-order compensation for the dependence of the speed of sound on air temperature: the speed of sound varies significantly with changes in temperature and humidity (about 0.17%/°C) and this temperature-compensation is essential for accurate sea level measurements. The compensation is made by use of an acoustic reflector at a fixed level in the air column beneath the transducer, by relating the reflection time of the sound pulse from the sea surface to that from the fixed reflector. In addition, the narrow sound tube is usually contained within an outer protective tube (or well) within which temperature gradients can be monitored. By this means, a further study of the temperature-gradient effects can be made if required in order to obtain the highest possible accuracy. The outer well can also be constructed to provide some degree of surface stilling.

Another type of acoustic gauge makes measurements in the open air with the acoustic transducer mounted vertically above the sea surface. However, in certain conditions the reflected signals may be lost. In addition, operations in the open air make it difficult to monitor the temperature gradients, which are necessary to determine corrections to the speed of sound. Several groups have attempted to partially overcome this problem by deploying the 'open air' instruments inside conventional stilling wells (minus the float gauge of course), thereby providing some degree of temperature stability in addition to wave damping. In both the 'tube' and 'open air' methods, sea level measurements are performed by averaging soundings over a large number of acoustic 'pings'.

2.1.1 Acoustic Gauges With Sounding Tubes

2.1.1.1 *The NOAA NGWLMS System*

In the early 1990's the US National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS) began the implementation of the Next Generation Water Level Measurement System (NGWLMS) based on acoustic gauges with sounding tubes. These gauges now form the basis of the US national tide gauge network. The new acoustic systems were operated alongside the previous analogue-to-digital (ADR) float and bubbler tide 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 were maintained at a few stations for several years to provide long term comparison information.

The NGWLMS tide gauge uses an Aquatrak water level sensor made by Bartex with a Sutron data processing and transmission system. The Aquatrak sensor sends an acoustic pulse down a 13-mm diameter PVC sounding tube towards the water surface. The elapsed time from transmission until the reflection of the pulse from the water surface returns to the transducer is used as a measure of the distance to the water surface. The sound tube has a discontinuity (the calibration reference point), which causes a decrease in acoustic impedance as the pulse passes it, resulting in another reflection, which propagates back towards the transducer. The elapsed time for this reflection is also measured. Since the distance to the calibration reference point is known (approximately 1.2 m), this distance and the travel time can be used as a measure of sound speed in the calibration tube (i.e. the section of the tube between the transducer and the calibration reference point). This information is then used to convert the travel time of the reflection from the water surface into a distance. Air temperature affects the speed of sound, but as long as the temperature is the same throughout the whole tube, the resulting measurement will be very accurate. However, if the temperature in the tube below the calibration point is different from that above it, an error in the water level measurement will occur. (For example, for water level 2 m below the calibration point and temperature 1 °C higher in the calibration tube than the mean for the whole tube, an error of 3.6 mm will occur.)

Field installations are designed to minimize the significance of temperature gradients by painting the protective wells in a light colour, ventilating them to promote air circulation, and avoiding the head of the tube being in the tide gauge hut while most of the lower part of the tube is exposed to the sun. Even with these precautions, there may still be situations where significant temperature gradients could result in errors, especially for the long tubes required in areas of high tidal range. Therefore, as a further precaution, two thermistors are placed in the tube, one at the middle of the calibration tube above the reference point, and one beneath it. With each acoustic range measurement, the temperatures are also recorded in the data loggers and can be used in further analysis to remove temperature gradient related errors.

The PVC acoustic sounding tube (bottom section copper to stop bio-fouling) is mounted inside a 15 cm diameter PVC protective well which has a symmetrical 5 cm diameter double cone orifice at the bottom. The protective well is more open to the local dynamics than the traditional stilling well used for float gauges and does not filter as much of the wind waves and chop. (Nevertheless, in principle, the same criticisms can be made about the PVC protective well as about a traditional stilling well.) 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; these may be dispensed with in areas of low currents. Figure 2.1 is a schematic of a typical NGWLMS installation.

The NGWLMS also has the capability of handling up to 11 different ancillary oceanographic and meteorological sensors (e.g. a sub-pressure transducer (Druck) is often used to provide backup to the acoustic system). 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 3 mm (0.01 foot) resolution. Data are transmitted via telephone or satellite connections.

For further information on US acoustic gauge deployments, see Gill *et al.* (1993) and Porter and Shih (1996) and <http://www.opsd.nos.noaa.gov/>.

2.1.1.2 The Australian SEAFRAME System

The Australian SEAFRAME (Sea Level Fine Resolution Acoustic Measuring Equipment) system is essentially the same as the NGWLMS and is being used to detect sea level changes around Australia and the Pacific Island Countries. The SEAFRAME station acquires, stores and transmits water level, weather and other data from a field unit, the main requirement for which is to measure sea level with low power consumption, high reliability and high (millimetric) resolution, often in hostile conditions. The main field unit is a Sutron 9000 Remote Terminal Unit (RTU) which is a modular unit containing:

- power supply;
- communications controller;
- UHF satellite transmitter;
- central processor unit;
- memory expansion module;
- telephone modem; and,
- "Aquatrak" controller.

The unit receives data from up to 16 sensors which measure the water level and meteorological parameters. Six channels are currently used in the unit used in Australia taking data from five sensors:

- primary water level sensor (the Bartex Aquatrak acoustic-in-air sensor) (6 minute interval);
- wind speed, direction and maximum hourly gust (1 hour interval);
- air temperature (1 hour interval);
- sea water temperature (1 hour interval); and,
- atmospheric pressure (1 hour interval).

A sixth channel contains data from the backup data logger in the Sutron 8200 unit described below. The Sutron 9000 RTU data logger runs unattended, collecting and storing data from all the sensors. Each sensor is represented by a data record created by the data logger, which records at 1 to 10 records per hour, depending on the type of the sensor.

As for the NGWLMS, the SEAFRAME's acoustic head emits a sound pulse, which travels from the top of the tube to the water surface in the tube, and is then reflected up the tube. The reflected pulse is then received by the transducer, and the Aquatrak controller, or water level sensor module. The Sutron 9000 unit then calculates the distance to the water level using the travel time of the sound pulse. As well as the reflected pulse from the water level, there is a reflected sound from a hole in the side of the tube at an accurately known distance from the transducer head. This measured reflection is used by the computer software in the Aquatrak controller to continually "self-calibrate" the measuring system. The Aquatrak sensor is able to resolve variations in sea level to the required accuracy and precision. Temperature variations in the tube can affect the speed of sound, so the temperature is measured at two locations on the sounding tube and a correction factor can be applied if required.

Each SEAFRAME has a stand-alone backup data logger which measures and stores water level data from a pressure transducer (IMO Delavel) mounted close to the seabed, and water temperature from a separate thermistor. The readings are averaged over three minutes and logged every six minutes into the memory of the 8200 data logger as well as to one of the channels of the Sutron 9000 unit, via a one-way communication link. The memory of the Sutron 8200 can hold three months of data. Should there be problems with the primary data logger, the data is retrieved during an on-site visit. This 8200 unit uses a 12 Volt 24 Ah Gel-cell battery, which is "trickled-charged" by a solar panel. The SEAFRAME unit itself can use a variety of power sources, including mains power, solar panels or wind generators. A trickle-charged 40 Ah Gel-cell battery provides about ten days reserve operating

power in case of loss of primary power. The operating system and data memory are also supported by back-up lithium batteries.

The sampling rate for all parameters is one sample per second. However not all of this data is stored. The primary water level measurements are averaged over a three-minute period and are stored in the memory every six minutes. Each weather parameter is stored hourly, and is the average of two minutes of sampling on the hour. The expanded memory of the unit has a "rolling log" which retains the last 30 days of data. The SEAFRAME station has the capacity to operate with various, site-specific combinations of sensors, averaging and sampling intervals. These combinations can be adjusted by using a personal computer connected to a communication port in the unit, either directly at the site, or remotely with a telephone modem. Data can be retrieved from the Sutron 9000 unit by (a) on-site retrieval, using a personal computer communication programme, and (b) remote retrieval, where data is retrieved by automated modem dialup or by automatic hourly satellite transmissions via the Japanese Geostationary Meteorological Satellite (GMS) and by telephone links direct to the Australian National Tidal Facility (NTF). For more information on the Australian SEAFRAME gauges, see:

<http://www.ntf.flinders.edu.au/TEXT/PRJS/PACIFIC/seafame.html>

2.1.1.3 Other Users of Acoustic Sounding Tube Gauges and Calibration Comments

Experience of acoustic sounding tube gauges such as those deployed in the US and Australia has been obtained in a number of other countries:

- India, see Joseph *et al.* (1997);
- Saudi Arabia where systems were deployed at Al Wedj, Jeddah, Haql and Gizzan on the Red Sea coast in 1992. (Although the first 2 are not functioning at the time of writing, we understand they still exist and that efforts are being made to bring them back on-line);
- Caribbean, see <http://www.ima-cpacc.gov.tt/index.htm>
- New Zealand, an installation at Jackson Bay in collaboration with the Australian NTF;
- Several Pacific islands, see <http://www.soest.hawaii.edu/UHSLC/>
- UK where one gauge (no longer operational) was tested at Holyhead by Vassie *et al.* (1993) with comparisons to conventional (float stilling well and bubbler) systems. In addition, gauges have been deployed in several countries, including Cape Verde Islands, Senegal, Nigeria, Argentina and Azores (Portugal), by NOAA as part of its former Global Sea Level programme. Operations at these sites are now the responsibility of the host country.

Essential to both the US and Australian networks is a calibration facility in which the acoustic transducer and its sounding tube are calibrated in a laboratory over a range of temperatures prior to deployment at the tide gauge station. Of course, the acoustic unit (i.e., the acoustic transducer and calibration tube) will have been delivered from the supplier together with calibration information. However, to obtain the best accuracy it will be desirable to check the calibration from time to time, at typically yearly intervals. In this procedure, the acoustic sensor is re-calibrated by reference to a stainless steel tube of certified length, and the zero offset is re-determined (Lennon *et al.*, 1993). The experience with each particular gauge unit adds significantly to the accuracy achievable by an off-the-shelf unit. The US and Australian agencies should be contacted for advice on the calibration methods they have developed.

2.1.1.4 Similar Hardware Available

The manufacture of acoustic sounding tube systems similar to the NGWLMS/SEAFRAME has been attempted by other groups during the past decade (e.g. in South Africa, now discontinued). The only system known to be under manufacture at present is that of the Indian National Institute of Ocean Technology which is claimed to use novel calibration methods to handle temperature-gradients and is currently subject to patent application, see <http://www.niot.ernet.in/m4/ATG.html>

Although US and Australian stations are based primarily on Sutron equipment, alternatives (e.g., data loggers by Vitel, see the suppliers file on the PSMSL training web page) are available.

2.1.2 Acoustic Gauges in the Open Air

The HT200 Harbour Tide Gauge 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 up to 15 metres. These systems have been deployed at a number of locations in France and at other sites (Dupuy, 1993). The manufacturers claim an accuracy of 2 cm.

An instrument by Sonar Research and Development (SRD) has been developed which operates at 50 KHz with a similar beamwidth. It can be operated in the open or, as the manufacturers recommend for permanent installations, in a plastic tube. Compensation for variation in the velocity of sound is achieved by use of a bar reflector mounted 75cm from the acoustic transducer. The manufacturers claim an accuracy of 0.05% over a range of 15 m, which would correspond to 0.2 cm over a typical range of 4 m (but see following sections).

For both these systems, datum control needs to be verified externally, for example by long periodic tide pole checks (see Sections 2.2.1.1 and 2.5).

2.1.2.1 Experience in Spain

The REDMAR network of Puertos del Estado (Spanish Harbours) was established in 1992 for harbour operations. It consists of 14 stations along the Spanish coast, two of which are in the Canary Islands. The selected equipment is the SRD acoustic tide gauge with real time radio transmission to the harbour office. The characteristics of the equipment are:

- height measurement range: 10 meters;
- height measurement resolution: 1 cm;
- height measurement accuracy: 0.05 % (better than 1 cm for instantaneous levels);
- time measurement resolution: 1 s;
- time measurement drift lower than 1 minute per month;
- acoustic frequency: 50 KHz;
- telemetry output: RS 232 every minute
- sampling period: 1,2,3,4,5,6,10,15,20 and 30 minutes
- averaging period: number of measurements used to provide averaged tide height can be: 1,2,4,8,16,32,64.

The transducer is located above the sea surface, at a distance not less than 2 m during high tide and not more than 9 m during low tide (highest tide range in Spain is around 5 m). The transducer has to be mounted within 2° of horizontal to achieve optimum results. The view of the transducer should be unobstructed within a 10° conical angle to avoid interfering with targets. For permanent installations it is strongly recommended that the system operates down a plastic tube.

The distance to the water (air distance) is obtained from the sound velocity and the time the ultrasonic ray needs to reach the water surface and travel back to the transducer. The distance from the sensor to the reference level or zero is called the datum; sea level is then calculated as the difference between the datum and the obtained air distance. As sound velocity depends on environmental conditions, especially on the temperature, it is calculated before each measurement by sending ultrasonic pulses to a fixed target located at 0.75 m from the sensor (this distance is factory set). In this way, each measurement lasts around 36 seconds: the first 10 seconds are used to determine the sound velocity by sending 128 valid echoes to the target; then another 128 valid echoes are sent to the water surface and a mean value is calculated to filter the high frequency waves. For most of the REDMAR stations the transducer measures inside a 0.30 m diameter plastic tube, with its lower extreme at a point

below the lower low water and a small hole of 3 cm. The role of the tube is of course not only to filter the waves but also to protect the ultrasonic ray's path. In some places, like Santander, it was possible to install it in an existing stilling well, inside a small building.

Although the reference target is employed to take into account variations in temperature and other parameters, this is done in the first 1-m distance of the tube, so it is still possible that strong temperature gradients along the tube affect the signal. This has happened especially in southern harbours where the summer is very hot. Recommendations to the harbour authorities are the same as for other acoustic sensors: to employ white painted tubes, to avoid different ambient temperatures along the tube, to make small holes above the higher high water to facilitate ventilation and even to construct a protection from the sun. This has proven to be a very good solution.

From experience gained in Spain, the above mentioned requirements for the installation are critical to get the accuracy claimed by the manufacturer. It has also been noted that the system works perfectly inside a building above a stilling well, like the station in Santander harbour. Even without a stilling well, as is the case for Villagarcia, the careful design of the installation to protect the tube from the sun has provided data with accuracy better than 2 cm. The principal disadvantage of this type of acoustic sensor is that it is very dependent on these conditions of the installation.

The tide gauge Contact Point (CP) is a ring around the centre of the transducer. The responsible tide gauge maintenance person levels this to the Tide Gauge Benchmark (TGBM) with a few mm precisions. As recommended by the supplier, the datum is initially adjusted to give the expected tide height as indicated on a local tide staff, or by measuring manually (e.g. an electric tape datum probe) the distance to the water surface; this allows any small anomalies between the reference measurement and the tide measurement to be assessed. Experience is that this calibration is needed the first time the gauge is installed, and is checked twice a year, together with the levelling of the tide gauge CP to the TGBM. However, due to the resolution of the datum value (1 cm), the reference level for this equipment is fixed at best with 1-cm accuracy.

Also the conditions to make the manual measurement or the reading of the tide staff influence very much the accuracy of the first establishment of the reference. It is very easy when the gauge is measuring inside a stilling well where the water is quiet (for example the station in Santander), but when the acoustic system is used in a tube, it is not possible to open it and measure inside without affecting the sensor, so it has been suggested to the harbour authorities to make an installation of a parallel calibration tube that filters the waves, in order to check the reference with more reliability.

The ultrasonic transducer is connected to an intelligent unit (LPTM: Low Power Telemetry Unit), which allows selection of the sampling interval (5 minutes at the moment for all REDMAR stations), the averaging period, the station number and to establish the tide gauge datum, as well as to adjust the clock time, display the data and store them. It also provides the power supply. The LPTM may be connected to a personal computer and transmit data by modem to the harbour and to the central station in Madrid or, as is the case for most of the stations of REDMAR, it may transmit the data by radio to the harbour office, where data are stored in a PC and transmitted by mail to the central station. More information on REDMAR can be found via <http://www.puertos.es/Mareas> (in Spanish).

2.1.2.2 Experience in South Africa

Extensive experience on SRD acoustic gauges has been obtained in South Africa. However, at the time of writing, information has not been collected together. The South African Hydrographic Office may be contacted for details hydrosan@iafrica.com.

2.2 PRESSURE SENSOR TIDE GAUGES

Pressure transducers can form the basis of cost-effective, versatile tide gauges as long as their limitations are fully recognized. The principle of all pressure systems is the measurement of the hydrostatic pressure of the water column above a fixed pressure point and the conversion of that

hydrostatic pressure into a sea level equivalent after correction for water density and local acceleration due to gravity:

$$h = (p - p_a) / (\rho g)$$

where h is the sea level above the pressure point, p is the total pressure due to both the sea level and atmosphere measured at the pressure point, p_a is the atmospheric pressure at the sea surface, ρ is average water density in the water column above the sensor, and g is local acceleration due to gravity. (If the sensor is deployed very deep, changes in density with depth will have to be considered, see discussion by Verstraete in IOC, 1993).

2.2.1 Single Transducer Systems

Sea level is measured at many locations by means of a simple pressure transducer fixed just below the lowest expected tide level (Figure 2.2) with the transducer's power/signal cable connected to an on-shore data logger unit or other data acquisition system in the tide gauge hut. If an **absolute** pressure transducer is employed, the sensor will provide a measurement of the total pressure 'p'. Therefore, a separate barometer will be required, also located probably in the tide gauge hut, which will provide a separate measurement of 'p_a'. It will be essential that both pressure channels are recorded using the same clock so they can be readily subtracted to yield sea level. An alternative method is to use a **differential** pressure transducer which has a vented power/signal cable in which the reference side of the transducer is vented to atmosphere providing a continuous correction for changes in atmospheric pressure.

An advantage of the differential option stems from the cost of the system, as only one transducer is required. On the other hand, vented systems are known on occasion to suffer from condensation in their cables, and our experience suggests that the absolute option is probably to be preferred. In addition, as oceanographic studies will almost certainly require access to air pressure information from a barometer at the site, it seems that the two-transducer option has many advantages.

Pressure sensors use strain gauge or ceramic technology in which changes in water pressure cause changes in resistance or capacitance in the pressure element. The most accurate sensors use a quartz element, the resonant frequency of which varies with the strain applied to it. The resulting signal, which is normally a frequency proportional to the applied pressure, is carried down the signal cable to the gauge electronics where it is converted into physical units (mbar of pressure) and can be displayed and stored in the data logger.

All pressure transducers are sensitive to temperature changes and this must be borne in mind when purchasing instruments. In Volume 2 it was recommended that, if temperature-uncompensated systems were to be purchased, then the expected range of temperatures to be experienced at a site should not produce an error greater than 0.01% of the full working range of pressure. If this was not possible, then it was recommended that the transducer temperature be monitored for later correction of the recorded pressure data by means of calibration information supplied by the manufacturer. It is our recommendation now that any users always purchase good-quality systems which record temperature alongside pressure and that subsequent temperature-dependent corrections be applied to the recorded values of pressure in the analysis software. That way, the best possible pressure data will be acquired. Users with access to a test facility can also subject purchased instruments to a range of temperatures to ensure that supplied calibration constants are correct. Experience has shown that calibration coefficients supplied by leading manufacturers are quite constant over periods of several years, and periodic re-calibrations have confirmed that any drift in the sensors is generally confined to its datum value.

Single transducer systems like those of Figure 2.2 can be deployed in environmentally hostile areas where other forms of gauge will not work. For example, they can be safely positioned on the sea bed under the winter ice at polar sites with the signal cable to the tide gauge hut on the shore protected in a steel pipe. They can be operated at sites with harsh weather conditions where the exposed

structures of a stilling well or acoustic gauge may be subject to extreme forces of winds and waves. In tropical locations they can be deployed safely below the sea surface where equipment may be prone to damage by tree trunks etc. In some locations with excessive marine growth, the pressure systems may need to be taken out of the water and cleaned from time to time.

2.2.1.1 The Datum of a Single Transducer Pressure System

The two major problems with a single transducer system are connected with the monitoring of its datum, which is the effective level to which one attempts to measure sea level. The first problem is to find where that effective level is, and the second is to monitor it if it changes over a long period, as it is an unpleasant fact that the pressure values provided by even the most expensive transducer will demonstrate a long term instrumental drift which is associated to some extent with the aging of the transducer.

The pressure point of a transducer mounted underwater is obviously its sensor diaphragm or pressure cell. However, even if that position is well known from a diving survey at the time of installation, there can be offsets in the electronics or the transducer itself which mean that the effective pressure point is somewhat different to the apparent one. This problem can be accommodated if the sensor has previously (and periodically) been calibrated within a test facility.

However, the only safe method for determining the datum of the gauge, if a somewhat low-technology one, is by means of tide staff measurements at regular intervals. Individual tide staff measurements should be accurate to 2-3 cm. By this means it should be possible to fix the datum of what could be a good quality sea level time series to approximately centimetre accuracy.

2.2.2 Multiple Pressure Transducer Systems ('B Gauges')

In the early 1990's, a method was developed at POL for the precise datum control of sea level records from pressure tide gauges. By means of an additional pressure point at approximately mean sea level, it was found that an effective temporal discrimination of the sea level record could be used to impose a datum upon itself. The technique was found to be extremely reliable and precise and now forms the basis of gauges (called 'B gauges') in POL's South Atlantic and Antarctic networks (Spencer et al., 1993). As the principle of the technique was described in Volume 2 and in the scientific literature (Woodworth et al., 1996), only an abbreviated version is given here. At the time of writing, it is not possible to purchase a 'B gauge' although expressions of interest for their manufacture have been obtained from major suppliers.

A schematic 'B gauge' setup is shown in Figure 2.3 with an absolute pressure sensor in the water ('C') and another in the atmosphere ('A'). Parascientific digiquartz sensors are employed throughout. It is the difference C-A which gives sea level, after seawater density and acceleration due to gravity 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 or the ocean itself may drift (i.e., through density changes). In a 'B gauge', another pressure gauge 'B' is placed at 'datum B' which is a datum approximately at mean sea level. Datum B is geodetically connected to the local levelling network (see Section 4 below). 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 2.3(a) shows schematically the C-A record while Figure 2.3(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 2.3(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 provide an extremely precisely defined shape which is immune to any problems with datum offsets and low-frequency instrumental drifts. The computation now involves overlaying the full curve of (a) on to (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.

In order to work properly, the method 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. 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. 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. The accuracy of the technique 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. Experience suggests that the accuracy is several millimetres on average. Fifteen minute or higher frequency sampling are to be much preferred to 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. For further information, including details of performance of the system in a realistic situation in the presence of waves (Figure 2.3(c)), see Woodworth et al. (1996).

2.2.3 Pressure Transducers in Stilling Wells

A variant on the 'B gauge' method described above is to install an absolute pressure sensor below low water at the bottom of a stilling well which has been used hitherto for a float system. This transducer will be functionally the same as sensor 'C' and will be complemented by a transducer 'A' to record atmospheric pressure, as described above. (Alternatively, a 'differential' sensor could be used to provide C-A.) However, instead of a third sensor 'B' employed in a 'B gauge' (Figure 2.3), datum control to the C-A pressure difference (and hence sea level) time series is provided by means of regular (preferably daily) electronic datum probe checks of the level in the well relative to the tide gauge CP and TGBM. Comparison of the values of C-A (corrected for density and acceleration due to gravity) to the well soundings thereby provides an ongoing datum to the time series which can accommodate transducer drift of C and/or A and/or ocean density.

This method has many of the advantages of ease of use of pressure systems and of electronic datum probes, combined with the recognized disadvantages inherent in the use of stilling wells (Lennon, 1993). However, it may be a preferred option if measurements are required at the same location and in the same well as float gauge measurements have been conducted for many years.

2.2.4 Bubbler Pressure Gauges

Figure 2.4 shows the basic essentials of a bubbler system. Air is passed at a metered rate along a small bore tube to a pressure point fixed under water well below the lowest expected tidal level. The pressure point normally takes the form of a short vertical cylinder with a closed top face and open at the bottom. A small hole is drilled about half way down its length and metered air is entered through a connection on the top surface. As air from the tube enters the pressure point it becomes compressed and pushes the water down inside the chamber until the level of the bleed hole is reached when the air bubbles out through the hole and back to the surface. Provided that the air flow rate is low and the air supply tube is not unduly long the pressure of air in the system now equals that of the pressure due to the depth of the water above the bleed hole plus atmospheric pressure. A pressure recording instrument connected into this supply tube will now record the changes in water level as changing pressures according to the law:

$$h = (p - p_a) / (\rho g)$$

Most pneumatic instruments using the bubbler principle operate in the differential mode, sensors being so constructed that the system pressure is opposed by atmospheric pressure within the instrument. Hence, the resultant pressure experienced by the sensor becomes $(p - p_a)$ making height directly proportional to the pressure.

To a great extent, a bubbler gauge can be thought of a variation on the single (differential) transducer system (Section 2.2.1) with several aspects in common, one major advantage and one perhaps large disadvantage. The common aspects include the need for establishing a datum to the pressure time series. At POL a procedure has been followed for many years by determining the exact depth of the pressure point bleed hole during installation (i.e., its height below the TGBM) combined with absolute calibration of the transducer in POL's calibration facility (supplemented at some sites with 'mid-tide sensors' akin to the 'B gauge' sensors described above). Another common aspect is that in both systems the pressure point (the bleed hole in this case) can be located safely below the water level out of harm's way from the weather etc. In addition, the absence of large structures means that they can both be used at locations where structures would not be allowed (e.g., on a busy quayside) or may be subject to vandalism.

The major advantage of a bubbler over the single transducer system (and over some other gauge types) is that there are no active elements located at or below the water line; only the small bore tube and cylinder are in contact with the water. This simplifies maintenance in the event of transducer failure. A major disadvantage concerns the performance of a bubbler in the presence of large waves, which was discussed to some extent in Volume 2. In spite of much experimentation with the optimum design of cylinders etc., it is clear that the accuracy degrades below the required 1-cm level with large waves present.

Transducers, compressors, data loggers etc. can be purchased from the major gauge manufacturers within ready-to-go packages. The agency with the most experience of using bubblers (now that the US has changed to the use of acoustic systems) is probably the UK Tide Gauge Inspectorate based at POL. The POL bubbler network consists of 45 sites and was established primarily for storm surge monitoring around the UK coast. Bubblers have been found to be capable of trouble-free operation for extended periods without site visits (up to perhaps a year). However, their sea level data are clearly affected by operation in rivers (where an assumption of constant density is not valid) and at locations exposed to high wave conditions, such as the coast of Norfolk.

For more details of operation of bubbler systems, see the Volumes 1 and 2 of this manual.

2.2.5 Bottom Mounted Pressure Gauges

Bottom pressure gauges, which sit on the seabed and record pressure at intervals over periods of a year or more, are beyond the scope of this discussion. Readers are referred to IOC (1993) and Spencer and Vassie (1997) for reviews of the technique.

2.3 FLOAT GAUGES IN STILLING WELLS

Float gauges were described extensively in Volume 1 and additional information was provided in Volume 2, particularly with regard to the use of 'switches' in the well to provide a form of continuous calibration. The information contained in those volumes contains important advice which operators of float systems, which still comprise the majority of gauges in use around the world, would do well to read.

In fact, float gauges in a well can be thought of as another type of 'pressure' gauge as the level of a float in the well reflects the pressure at the orifice which in turn reflects the sea level outside the well. If the densities inside and outside the well are the same, then the same sea levels will be obtained.

Float systems may not be new, but for a site with a long historical sea level record from a float gauge, it would be irresponsible to recommend a change to a new technique without detailed

consideration. The main object of our research is the production of good long **time series** of sea level changes. If the time series contains an overall bias because of a limitation of a particular technique (e.g., due to systematic bias of a stilling well due to ambient current or hydrographic conditions), then this should not affect the analysis of its temporal characteristics. However, if a new method with a different set of biases is introduced in the middle of a record, the different set of systematic errors introduced may well affect the correct representation of the sea level time series.

Another reason for an operator to choose a float system is the advantage of its being 'low tech' and, therefore, relatively low cost. However, there are major improvements which any present-day float gauge operator must implement to bring his equipment up to modern standards. These stem from the requirement to provide data in electronic form as rapidly as possible. This can be achieved by means of adding potentiometer or shaft encoder devices to the float arrangement, in addition to the use of electronic datum probes (Volume 2). By that means, data can be stored on a local data logger in electronic form, or can be transmitted immediately to a data centre via a modem. This enables gauge malfunctions to be detected as soon as possible and data to be used for near real time applications. The slow, labour-intensive digitization of paper charts must be consigned to history for GLOSS purposes, although it may be found that paper charts might be of interest as a source of ancillary information (e.g., of higher frequency seiche or tsunami activity). Of course, all historical charts from GLOSS sites must be preserved in a good archive.

Advice on upgrading float gauges to modern standards can be obtained from several agencies that have had experience of this process in recent years. For example, Japan and Norway now operate float gauges with shaft encoders and electronic data transmissions. Italian float gauges have recently been upgraded, with acoustic gauges operated inside the stilling wells as backup systems.

Some manufacturers (e.g., Ott) now offer simple shaft encoder float systems at relatively low prices which can record either by sampling (e.g., every minute) or by integration. Experience in the GLOSS community has been confined so far to the former (the Ott Thalimedes sampling system) which has been tested in South Africa, Spain and the UK. It is clear that these systems suffer from the range of problems float gauges always exhibit, such as long term drift (possibly due to 'tidal hysteresis') and jumps when float and counterweight collide if disturbed. However, if such systems could be combined with a simple chart recorder and with regular electronic datum probe ('dipping') checks as described in Volumes 1 and 2, we believe that an affordable float system could be provided to many countries. At the very least, this could serve to demonstrate the utility of sea level data in local applications and to make the case for more advanced systems in future.

2.4 RADAR TIDE GAUGES AND OTHER NEW TECHNOLOGIES

Several companies now supply water level recorders, which use the time of flight of a pulse of radar, rather than sound, to measure level. In principle, radar should be insensitive to the temperature effects, which can affect acoustic gauges.

Examples of radar gauges include the Kalesto instrument from the Ott company, which 'shines' a radar source down onto the water from a sensor in the open air. The sensor transmits the pulse and receives the return pulse, thereby determining time of flight and range. Its 5° beam width needs to be free of structures (e.g., harbour walls) to ensure clean reflections, and experience in France has shown that the system cannot be used in a stilling well. (The system was designed primarily for monitoring river levels.)

The Krohne BM100 gauge uses pairs of cables or rods (or a coaxial cable), between which the radar pulse is transmitted as a waveguide. It could, therefore, be deployed in a stilling well. Sales literature for both instruments claim resolution of the order of a millimetre and accuracy of the order of a centimetre, see: <http://www.pol.ac.uk/psmsl/training/suppliers>

Saab also makes a radar device for wave and sea level measurement. Unfortunately, experience with such systems is limited. For example, it is not known how their range measurements depend on wave conditions. At the time of writing, radar gauges have been installed for evaluation at several locations in France and one is undergoing test in the UK.

Other new technologies, about which we can express little opinion at this time, include:

- The Aquarod (www.sequoiasci.com) which is basically a tube with inserted central rod between which capacitance is measured. Low priced, but probably subject to bio fouling.
- Interferometric observations of GPS signals (see K.A. Andeson, Journal of Atmospheric and Oceanic Technology, 17, 1118-1127, 2000).

2.5 GENERAL PRINCIPLES OF CHOICE OF A TIDE GAUGE SITE

Before a gauge can be deployed, it is clearly important to have done one's homework on what it is really intended for and where it will be best located. In some practical instances the choice of site will be obvious. For example, if the requirement is to monitor tidal levels at a specific point, such as a dock entrance, the gauge will have to be located nearby.

In many instances, however, the choice of site will not be so clear and can only be made by judging which of the constraints listed below are more significant and which can be given greater emphasis. Those emphases may depend, for example, on whether the gauge is intended for oceanographic research, in which case one clearly requires it to be located with maximum exposure to open ocean levels, and not situated in a river. Most GLOSS Core Network sites have been selected with this aspect in mind as far as possible. For programmes such as C-GOOS, where the process to be studied may be coastal erosion or storm surge activity, then clearly the gauge will have to be situated optimally for that purpose.

Further general considerations include:

- (a) The installation must be capable of withstanding the worst environmental conditions (winter ice, storms etc.) likely to be encountered. This is clearly an issue relevant to the type of gauge purchased (see sections above) and to its intended position. Positions known to be exposed to environmental extremes should clearly be avoided so as to enable the eventual construction of long time series.
- (b) The ground on which the installation is made be 'stable' as far as possible, not being liable to subsidence because of underground workings or land subsidence (e.g. due to the area being reclaimed land). It must also not be liable to slippage in the event of heavy prolonged rain (i.e. the area must be adequately drained) or being eroded by river or sea action. An installation on solid rock is the ideal.
- (c) River estuaries should, if possible, be avoided. Estuarine river water will mix with seawater to a different extent during the tidal cycle and during different times of the year, resulting in fluctuations in water density. This may have important impacts on float gauge measurements in stilling wells because of 'layering' of water drawn into the well at different times resulting in different densities inside and outside the well. It will also impact on pressure gauge measurements, as the density assumed for the conversion of pressure to sea level will not be constant. Currents due to the river flow may also cause drawdown in stilling wells (including the outer container of acoustic gauge sounding tubes), and following heavy rainstorms debris-floating down-river could damage a gauge. (For a discussion of the problems in connection with stilling wells, see Lennon, 1993).
- (d) Areas where impounding (becoming cut-off from the sea) can occur at extreme low tide levels should be avoided. Similarly, sandbars slightly below the surface between the site and the open

sea can result in uncharacteristic levels being measured. Monitoring across long shallow sloping beaches should also be avoided for the same reasons.

- (e) Sharp headlands and sounds should be avoided since these are places where high tidal currents occur which tend to result in unrepresentative tidal constants and in a drop of MSL (Pugh, 1987).
- (f) Proximity to outfalls can result in turbulence, currents, dilution and deposits, and should be avoided.
- (g) A study should be made of shipping passing or mooring close to the proposed site, since there will be a risk of collision and propeller turbulence causing silt movement.
- (h) Investigations should be made to determine if there is a possibility of construction work occurring in the area at some future time which may affect the tidal regime at the site (e.g. by construction of new quays or breakwaters) and/or which may cause the tide gauge to be moved to a new location, interrupting the sea level time series.
- (i) A gauge site should have continuous mains electrical power (or adequate storage batteries or generator) and telephone or satellite accesses for transmission of data to an analysis centre.
- (j) There must be adequate access to the site for installation and maintenance and the site must be secure from vandalism or theft.
- (k) The area of the site must be capable of containing the benchmarks required for geodetic control of the sea level data (Section 4). In particular, it must have good TGBM and GPSBM marks, which will also be secure from accidental damage.
- (l) If stilling well or acoustic gauges are to be installed, then the stilling well or acoustic tube must be tall enough to record the highest sea levels. This may require permission from port authorities if, for example, the installation is on a busy quayside.
- (m) The water depth must extend at least two metres beneath Lowest Astronomical Tide (LAT) for successful operation of a stilling well. The outlet of the stilling well should be clear of the sea bed and be set deep enough to allow the float to operate about one metre below LAT.

Finally, it is clear that tide gauge datum control is an essential issue for any installation. Consequently, even if the station is equipped with the most modern equipment, it is common sense to provide confirmation of the datum from time to time by means of an inexpensive tide 'pole' or 'staff'. Measurements by tide staff are not especially accurate, and their datum control readings are not to be preferred to those by more accurate methods, such as those described in Section 2, but they at the very least guard against gross errors in datum. In addition, in some methods a staff may not be just desirable, but essential; for example, see Section 2.2.1.1.

2.6 COMMENTS ON DESIRABLE RECORDING FREQUENCY

The GLOSS Implementation Plan explains that hourly values of sea level (preferably integrations rather than spot values) are the basic requirement for the GLOSS programme. These values can be filtered to yield 'daily means', which can in turn be averaged to monthly and annual mean values. The delivery of good hourly values which can be sent to the GLOSS-associated sea level centres (see Section 6) is, therefore, the main purpose of these Volumes.

The tradition of using hourly values as the basic recording frequency stems from it being a natural temporal unit to use; from the fact that most tide, surge and longer timescale phenomena can be studied with it; and from the limitations during the chart recorder era of digitizing at a higher rate. In

addition, at many locations there is often a few cm of amplitude of sub-hourly higher frequency 'noise' due to seiches etc. which are of no scientific interest (other perhaps than to people interested in harbour seiches) as those signals are not present in the open ocean. Consequently, the practice was to one way or other low-pass filter this noise during digitization (see Volume 1).

In the electronic era nowadays, however, most agencies record at a higher frequency than hourly for a number of reasons, not least because there is no major benefit in not doing so. In the USA, the standard with the older float gauges and bubblers was always to record every 6 minutes (i.e. 1/10 of an hour) and this standard has continued in the NGWLMS. In the UK, the standard with the national bubbler network is to record every 15 minutes, which is a higher rate than the hourly formerly used for digitization of charts, as this leads to a better description of the development of storm surges around the coast. In the UK 'B gauge' network, 15 minute recording is much preferred over hourly if the 'inflexion points' are to be well defined. Our impression is that the choice of recording frequency is not a critical one for GLOSS as long as it results in good-quality hourly values.

One obvious application which does require a much higher sampling rate is tsunami research or tsunami warning. Ironically, the 6, 15 or 60 minute integrations of many electronic gauges installed for GLOSS will not be optimized for tsunamis, whereas the low-technology continuous chart recorders we have encouraged people to throw away could at least provide data for research into any tsunamis which have occurred. GLOSS has tended not to concern itself with tsunamis during the last decade, although the Implementation Plan 1997 does at least recognize their existence. In the Pacific, and increasingly more so in the Indian Ocean, almost separate sets of gauge exist for 'tsunami' and 'sea level' research, although some have dual-use. It is clear that new installations in areas prone to tsunamis should be capable in principle of recording at rates optimal for both applications, requiring probably two sets of electronic data loggers and data communication systems.

Pressure and acoustic systems are clearly the technologies, which can be most readily adapted to the higher frequency sampling required for tsunamis. For example, in the Caribbean, plans have been made to programme NGWLMS systems to test for the rate of sea level change. If it exceeds a preset value, the system goes from 6-minute sampling into a continuous once-per-second mode. That way the standard 6-minute sample is preserved and the tsunami is also sampled. This serves two purposes: (i) the sample is adequate, and (ii) it automatically sets off a tsunami alarm. Engineers consulted claim that continuous sampling would not be detrimental to the NGWLMS equipment, and with improved power sources and computer chips, there is no reason why all sampling cannot eventually be once per second and stored or transmitted once per minute. By this means, it should not be necessary to have duplicate sites for different parts of the sea level spectrum.

The measurement of waves has not been included in this volume, as in most cases different technologies are involved. Most of the sensors discussed above are unsuitable for wave measurements. However, pressure transducers are one means by which sea level and wave measurements can be combined within the one sensor (e.g., Foden *et al.*, 1998).

2.7 SYNTHESIS OF THE MERITS OF DIFFERENT TECHNOLOGIES AND RECOMMENDATIONS

In this section we attempt a synthesis of the relative merits of different tide gauge technologies for scientific research, operational oceanography and for localized practical purposes such as harbour operations.

The GLOSS Programme has scientific research as its core *raison d'être*, although it is intended that the development of the GLOSS networks will serve to improve standards overall (see IOC, 1997). However, we can use a short-hand of 'GLOSS' to indicate the most demanding requirement of scientific-quality performance of a gauge. These systems must be calibrated as frequently as possible, the required frequency depending on the technology (see earlier sections).

The C-GOOS programme is concerned with operational uses of oceanographic data within topics such as marine infrastructure (e.g., offshore industry, transport, coastal recreation) and coastal defenses (e.g., flood protection from surges, and studies of coastal erosion or sea level rise impacts). Many of these applications overlap with GLOSS interests, the study of secular changes in sea level being an obvious example. However, the particular applications will vary from country to country. In this section, therefore, we use the short-hand of 'C-GOOS' to indicate gauges which are capable of deployment for extended periods, but perhaps not to the same high standards as for 'GLOSS', and are affordable for use in larger numbers than for GLOSS, especially by developing countries.

Finally, we use the short-hand 'Practical' to indicate the requirement of a cheap instrument capable of showing the state of the tide at any moment but not accurate enough for GLOSS or C-GOOS.

Table 2.1 presents a summary of the main conclusions on the relative merits of each gauge technology based on the previous sections of this Volume. The Table also includes an estimate of the likely cost of a basic system with gauge, data transmission (e.g., modem) and meteorological package, although this is an extremely difficult thing to quote given the large number of manufacturers, monetary exchange rates etc. For example, the cost of a pressure transducer will vary by a factor of 3 depending if one wants a good-quality device or not. With these reservations in mind, Cost Band 3 has been set as the highest cost which might be of the order of 12-20K US\$ (at the time of writing and within a large band, say 30%); Band 2 might be of the order of 8-12K and Band 1 approximately 5-8K. However, in our experience the real costs of any tide gauge station are those of installation (e.g. some kind of engineering support will be needed for installation of a stilling well, acoustic sounding tube gauge, or 'B gauge'; diver support will be needed for pressure gauge installations etc.), ongoing maintenance and data analysis (with implications for staff resources). Anyone planning a gauge installation, therefore, has to take into account all the local costs as well as the up-front costs of gauge hardware. Agencies participating in GLOSS which require the input of expertise may wish to explore the possibilities of collaboration with other GLOSS participants.

Our recommendations are:

If one is planning a new 'GLOSS' tide gauge station in a mid- or low-latitude location, one should probably opt for:

- (1a) an acoustic gauge with sounding tube, unless
- (1b) a 'B gauge' is a feasible option.

If low tidal range or other factors preclude the use of a 'B gauge', then a single transducer pressure gauge, a bubbler pressure gauge or a pressure transducer in a stilling well would be options.

If one is planning a new 'GLOSS' station at a higher-latitude site which has sea ice cover for part of the year, one should probably opt for:

- (i) a single transducer pressure gauge, or
- (ii) a bubbler pressure gauge.

Although it is true to say that float gauges have been operated in Antarctica, and the longest tide gauge record in Antarctica is from the Faraday/Vernadsky float gauge in a heated stilling well, we do not recommend their future use in ice areas. Bubbler and acoustic gauges have also been tried in Antarctica but our recommendation is to use the single transducer systems if possible, with summer-time datum control using either tide poles or 'temporary B gauges'.

If one were planning to upgrade an existing float gauge 'GLOSS' installation at most places, then we would recommend:

First consider simply upgrading the existing system to electronic data acquisition and transmission. (Charts must go as the main recording system although they can remain to provide ancillary information.) This will provide instructive experience with real time data.

Second consider the use of a pressure gauge system within the stilling well.

Then consider installation of a new station alongside the old one (either acoustic sounding tube or 'B gauge' etc. as described above) but keep both operational for inter-comparison of their data for an extended period (possibly as much as a decade).

If one were planning to use relatively cheap gauges (but perhaps many units) for 'C-GOOS' purposes, then we would recommend:

- (i) single transducer pressure gauges;
- (ii) if existing (or easily installed) stilling wells are available, fairly inexpensive shaft encoder float systems now on the market;
- (iii) if wells are available, pressure transducers in the well.

If one required a 'cheap and cheerful' gauge for 'Practical' harbour operations or approximate flood level estimates, then we would recommend:

- (i) single transducer pressure gauge;
- (ii) acoustic gauges in open air.

Such installations would not need the ancillary parameters needed for GLOSS (Appendix 1, point vi) but they may require components such as 'user friendly' real time displays.

Whichever type of gauge is selected, advice will be needed. The GLOSS-related scientists listed in Table 2.2 have agreed to provide detailed advice on each gauge type if contacted.

Table 2.1

Acoustic Gauges with Sounding Tubes

Pro

Complete ready-to-go packages (acoustic transducer, sounding tube, met package, ancillary sub-pressure sensor, modem etc.) can be purchased from several manufacturers. This technology is now used in some of the largest networks (e.g. US, Australia) and hence there is considerable experience of it.

Con

For best accuracy a calibration facility is required. In areas of large tidal range a long sounding tube is required which may result in magnified temperature and/or temperature gradient effects.

Consensus Accuracy < 1 cm

Cost Band 2

Acoustic Gauges in the Open Air

Pro

Relatively low cost.

Con

Larger errors due to air temperature effects than for the sounding tube method. Less rigorous method of establishing a calibration (by use of a sounding bar in the open air rather than the acoustic reflector in the sounding tube).

Consensus Accuracy >1 cm depending on the quality of the installation

Cost Band 1

Table 2.1 (Cont'd)

Single Transducer Pressure Gauges

Pro

Precise (if not accurate datum) time series of pressure can be acquired (temperature calibration required for best results) with less potential noise due to surface effects than in an acoustic or float gauge. Can be readily purchased from several manufacturers. Systems, which integrate over a time period rather than spot-sample, are to be preferred.

Safe location beneath the water line and no large structures (e.g. stilling well) required. Suitability therefore for operation in environmentally hostile areas.

Con

Difficulty of establishing a datum and of monitoring changes in the effective datum. Therefore a need for additional datum information (e.g. from regular tide pole measurements).

Consensus Accuracy several mm precision (but not datum accuracy)

Cost Band 1-2

Multiple Pressure Transducer Systems (B Gauges)

Pro

Extremely accurate systems with automatic datum control and, as a by-product air pressure data without a separate barometer in addition to air and sea temperatures.

Con

(So far as is known) the technique is used only by POL to date although there are plans for commercial manufacture. Three transducers result in a relatively expensive system. Technique can work only given a sizeable (> 1 m) tidal range.

Consensus Accuracy several mm precision and accuracy

Cost Band 3

Table 2.1 (Cont'd)

Pressure Transducers in Stilling Wells

Pro

As for 'B gauges' above, without the cost of a third ('B') transducer, as long as a stilling well is available.

Con

Well-known problems associated with the use of stilling wells.

Consensus Accuracy 1 cm approximately. Absolute accuracy will be limited by the characteristics of the well.

Cost Band 2

Bubbler Pressure Gauges

Pro

Many of the same advantages as the single transducer system.

Con

Slightly more maintenance-intensive than single transducer systems, requiring compressor and bubbler gas flow system, in addition to pressure transducer and data logger. Degraded performance in the presence of high wave conditions.

Consensus Accuracy 1 cm (worse in high wave conditions)

Cost Band 2

Table 2.1 (Cont'd)

Float Gauges

Pro

Tried and tested traditional, relatively unsophisticated technology, which (in principle) measures exactly the parameter, required (sea level) rather than an indirect parameter (e.g. pressure or sound).

Con

Stilling well density and siltation problems. Need for bulky stilling well installations and consequent heavy civil engineering in areas of large tidal range.

Comments

Paper charts are no longer acceptable as the main data recording method (but are acceptable as an ancillary method) as they contain many sources of inaccuracy and require labour-intensive digitization. Also note the GLOSS requirement for other parameters to be measured at a gauge site (e.g. air pressure) which implies that an electronic data logger system is anyway required at the station. Relatively cheap new shaft encoder systems may have possible useful application at some locations.

Consensus Accuracy 1 cm approximately (a complicated site-dependent function of many factors)

Cost Band 1-2

Radar Gauges

Consensus Little experience in the GLOSS community

Cost Band 1

Table 2.2

Sources of Advice on Different Gauge Types and Data Transmission Methods and on Geodetic Methods

The following people may be contacted for advice (given in good faith with no legal guarantee!) on technical aspects of different gauge types based on their experiences with the technologies:

Acoustic Sounding Tube Gauges	Allan Suskin, NTF Australia allan@pacific.ntf.flinders.edu.au Steve Gill, NOS/NOAA stephen.gill@noaa.gov Antony Joseph, NIO India joseph@csnio.ren.nic.in David J.Dixon, Plymouth UK djdixon@talk21.com (for Saudi Arabia experience)
Open Air Acoustic Gauges	Begona Perez Gomez, Puertos del Estado, Spain bego@puertos.es Mike Thomson hydrosan@jafrica.com
Single Transducer Systems	Dov Rosen, NIO Israel rosen@ocean.org.il Peter Foden, POL UK prf@pol.ac.uk
Multiple Transducer Systems ('B gauges')	Peter Foden, POL UK
Pressure Transducers in Stilling Wells	as for other pressure systems
Bubbler Pressure Gauges	David Smith, POL UK des@pol.ac.uk
Bottom Mounted Pressure Gauges	Ian Vassie, POL UK imv@pol.ac.uk
Float Gauges in Stilling Wells	Mark Merrifield, UHSLC USA markm@soest.hawaii.edu
Optical Shaft Encoders (especially for river and lake records)	Dave Johnstone, NIWA NZ d.johnstone@niwa.cri.nz
Radar Tide Gauges	Serge Allain, SHOM France allain@shom.fr

Advice in Spanish on bubblers and other pressure systems and on acoustic (NGWLMS-type) systems may be obtained from Juan Fierro (jfierro@shoa.cl) and on pressure and acoustic systems with special application to Antarctica from Roger Handworth (roger_han@antdiv.gov.au).

The following people may be contacted for advice on data transmission methods:

David Meldrum, DML UK	d.meldrum@dml.ac.uk
Dov Rosen, NIO Israel	rosen@ocean.org.il

The following people may be contacted for advice on geodetic methods:

GPS	Mike Bevis, Univ. Hawaii USA bevis@soest.hawaii.edu
DORIS	Anny Cazenave, GRGS France anny.cazenave@cnes.fr
Absolute Gravity	Trevor Baker, POL UK tfb@pol.ac.uk

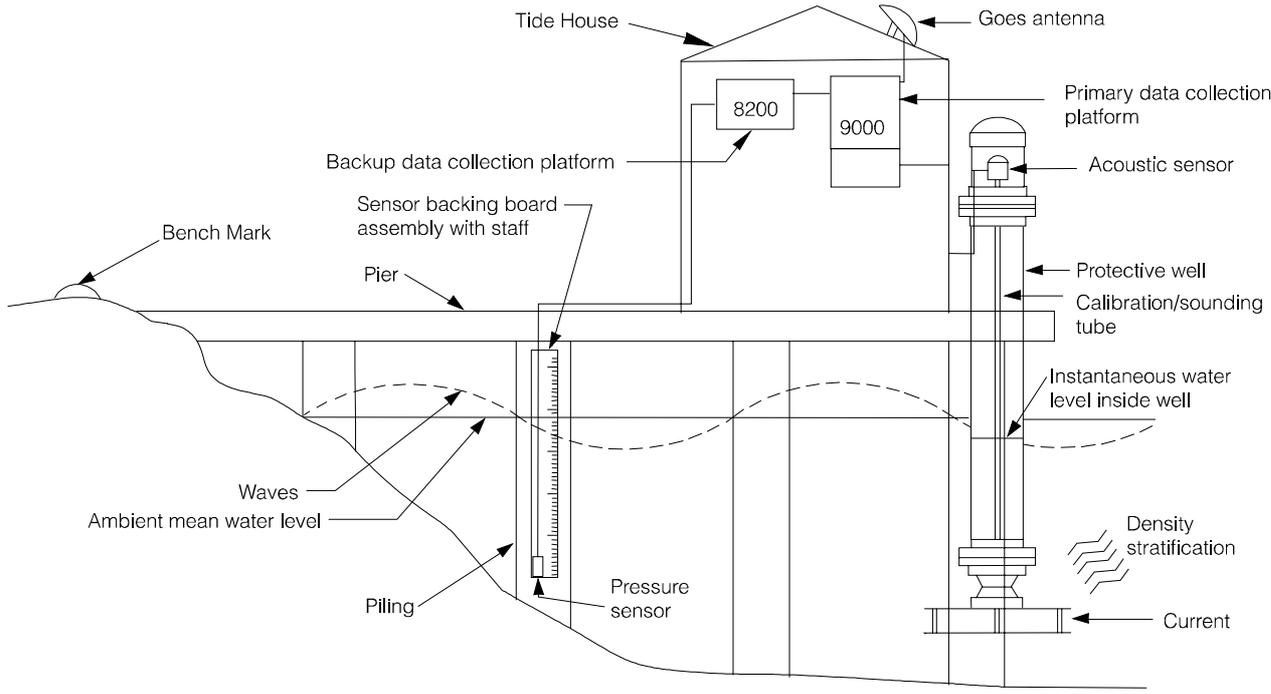


Figure 2.1 Schematic of the NGWLMS/SEAFRAME System

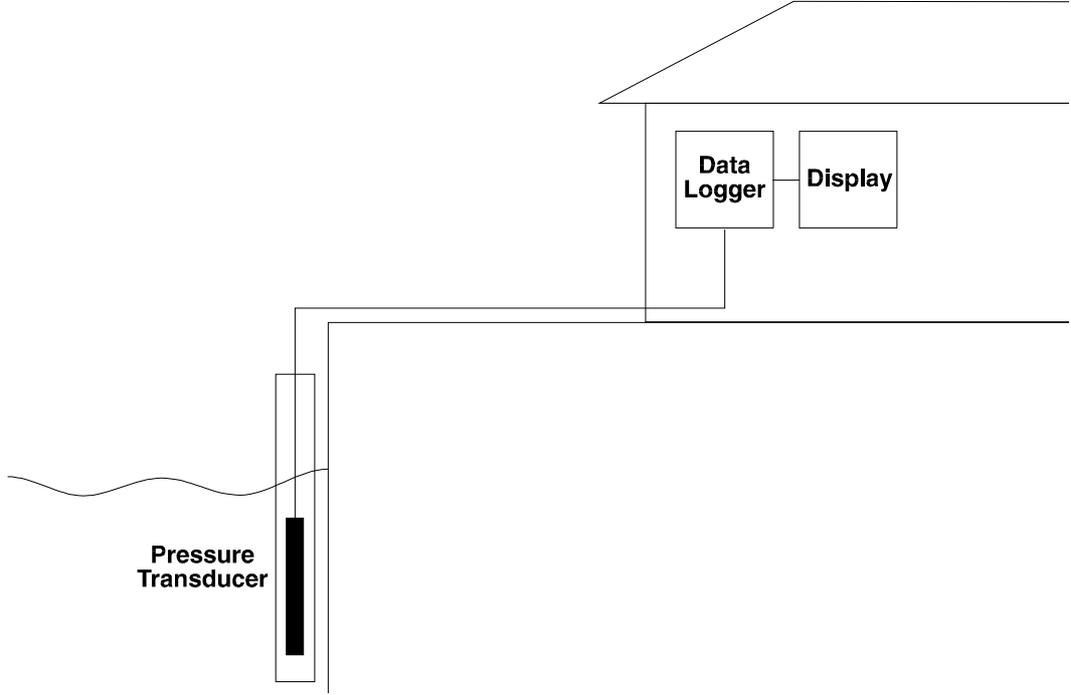
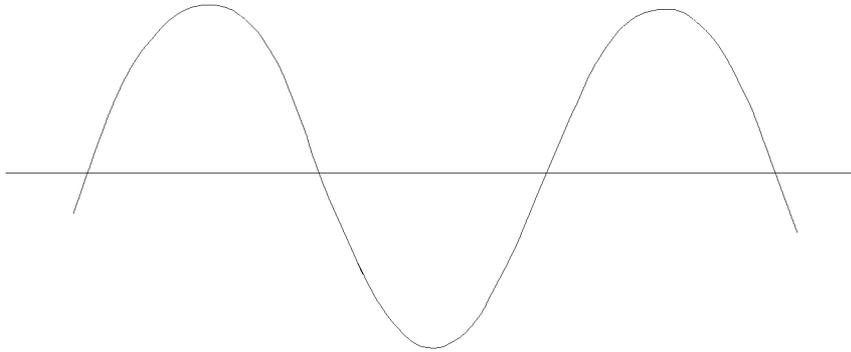
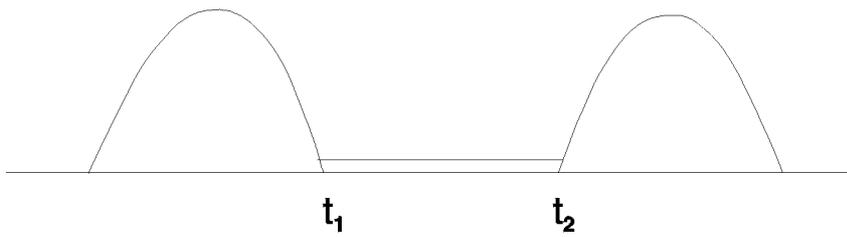


Figure 2.2 Schematic of the Single Transducer Pressure System

C - A (a)



B - A (b)



B - A with waves (c)

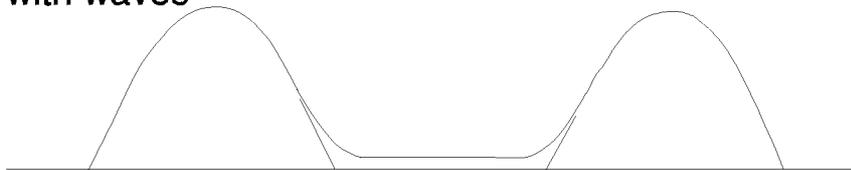


Figure 2.3 Principle of the B Gauge Method

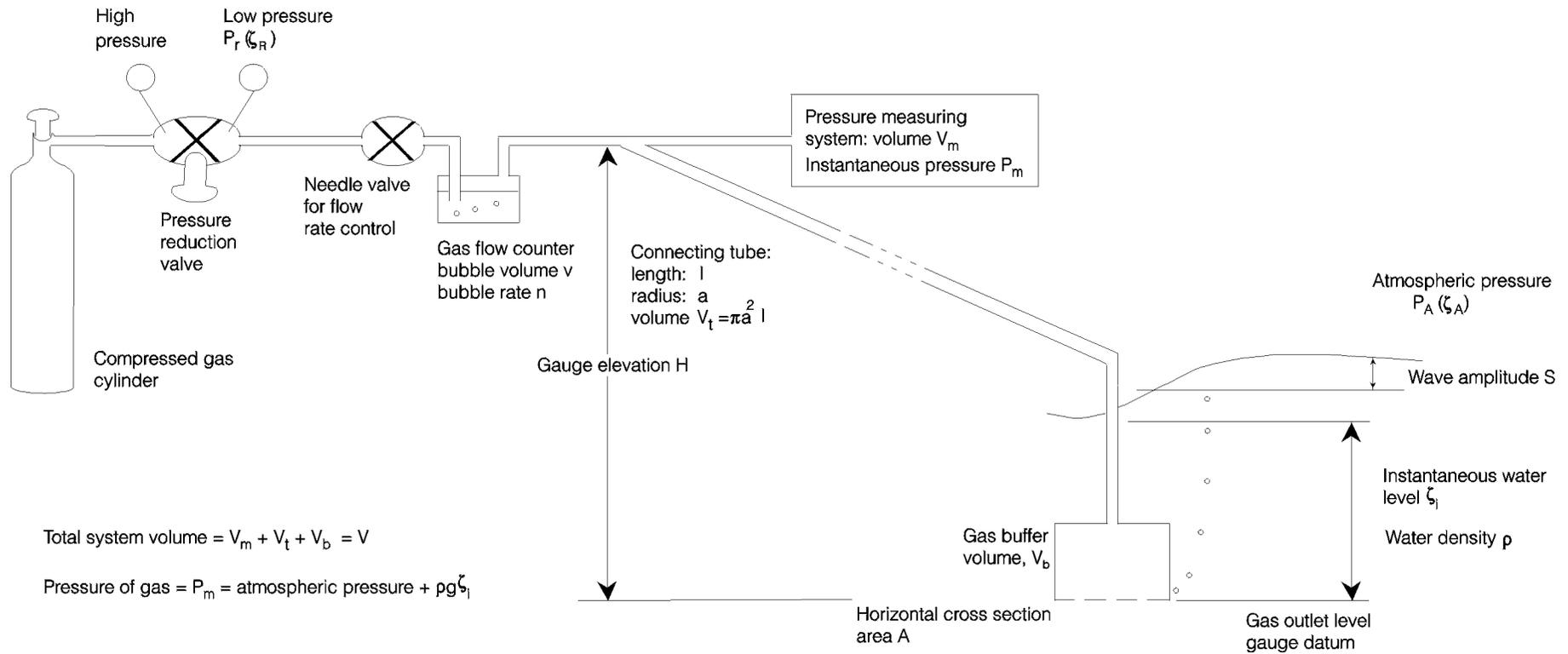


Figure 2.4 Schematic of a Bubbler Pressure Gauge System

3. DATA TRANSMISSION METHODS

3.1 INTRODUCTION

Sea level data acquired by a tide gauge will almost always be required at some other location, unless the gauge was installed for very local purposes such as harbour operations. The method of data transmission used depends on the time delay considered adequate and the distance involved. Time delays can vary from zero (i.e., 'real time' data) to perhaps a year or longer (e.g., if a data logger is to be recovered from a remote site such as Antarctica) and the distances can vary from zero (e.g. displays alongside the gauge) to global.

If long time delays are acceptable, then the tide gauge and ancillary data (e.g., air pressures) can be stored in a local data logger alongside the gauge until the logger is recovered and returned to a laboratory, or until its contents are down-loaded at the site into a PC. The logger's memory has to be large enough to store all the data acquired between site visits. Many gauges in remote areas are still operated this way, although the development of global communications systems means that direct communication with any gauge anywhere is now feasible.

Direct communication with the gauge is clearly necessary for real time applications, usually implying a telephone line which can take the form of a dedicated line or, more likely, a fixed or mobile (GSM) public line. Nowadays, all these forms of telephony are merging into one, with telephone links provided by a supplier for which the connection method is transparent to the user. Other communication methods include radio links (useful primarily for short distances), satellite links (e.g., Meteosat, see below), or a combination of more than one. Access through the Internet via a local Internet Service Provider (ISP) is also now quite feasible. For example, many of the GPS stations of the global network of the International GPS Service, which has some similarities to the global tide gauge network in terms of number of sites and amount of data to be transmitted, report through the Internet. The tide gauges at Ascension and St.Helena now communicate with POL using the Internet.

Tide gauge data processing units, whether interfaced with a local data logger storage or to the outside world via a telephone modem, use programmable microprocessors to control and implement the data acquisition from the gauge and to make the subsequent calculations required (e.g. the conversion of transducer frequency to pressure in a pressure tide gauge). Some processor units are 'two way' enabling an operator to talk by telephone to a unit, which may be on the other side of the world, and to update software or calibration constants. This allows the system to be 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 those faults can be quickly rectified.

A number of manufacturers, including tide gauge and data logger manufacturers, sell relatively inexpensive (e.g., compared to the cost of a PC) ready-to-use communications systems suitable for tide gauges with which the local data loggers can be interrogated by a remote PC by telephone. For a list of manufacturers, see: <http://www.pol.ac.uk/psmsl/training/suppliers>

Purpose-built sets of hardware continue to be used for particular applications, usually by groups with in-house electronics expertise and/or with considerable investment in a particular type of technology. One example is the DATARING system used by the UK Storm Tide Warning Service (STWS) to obtain real time data from gauges around the UK coast as described in Volume 2. However, developments in global communications and electronics mean that it is usually now more cost-effective for most organizations to purchase data acquisition equipment from a major supplier than to develop such specialized systems in-house.

3.2 SATELLITE AND GLOBAL MOBILE PHONE DATA LINKS

Data from remote tide gauge installations, or from widespread national or international networks, can be transmitted via several satellite systems including ARGOS, GOES/Meteosat/GMS and INMARSAT. Characteristics of each system (e.g., cost of hardware, bandwidth, latitude limitation) differ.

ARGOS operates worldwide using polar orbiting satellites with an orbital period of about 100 minutes. A platform transmitter terminal (PTT), with a data bandwidth capacity of 256 bits per satellite pass, is located at the gauge and, depending on location, there may be a delay of up to several hours before data is available to users through the Argos Global Processing Centres at Toulouse, France and Largo, USA. The number of accessible satellite passes to be expected per day is latitude dependent, varying from about 7 at the equator to 28 at the poles. Users of ARGOS for tide gauge data acquisition include GRGS in France which will be able to provide advice to potential users.

GOES-E (USA), GOES-W (USA), Meteosat (Europe), and GMS (Japan) form a network of geostationary satellites offering compatible near-global coverage. Because geostationary satellites are in orbit above the equator, there is no coverage above a latitude of about 75°. Each data collection platform (DCP) located at the gauge 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. Users of these systems include POL in the UK and NOAA and the University of Hawaii in the USA.

INMARSAT Standard-C also uses a network of geostationary satellites giving worldwide coverage except for latitudes above 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 about 8 Kbytes. Tide gauge users of INMARSAT in the past include the Australian Hydrographic Service.

Although satellite systems such as Meteosat continue to be used by many groups, the availability of direct-dial telephone lines to almost all locations in the world has resulted in the replacement of the satellite systems by telephone modem systems which are capable of transmitting considerably greater amounts of information (Mbytes rather than few 100 bytes) at reasonable cost. For example, POL is now able to instruct its South Atlantic data loggers to sample gauge pressure transducers in rapid sampling mode to measure wave conditions in addition to sea level, and to transmit the information back to POL by telephone.

Data transmission through ARGOS, Meteosat and GOES satellites may now be arranged most easily through companies such as Collect Localization Satellites (CLS) in France or Service Argos Inc. in the USA (see suppliers page mentioned above).

The advent of a new generation of satellite-based global mobile phones and messaging systems promises to offer further choice of carrier for communications with tide gauges. Unfortunately, many systems are competing for an as yet unrealized market for global personal communications, and it will be some time before there will be clear choices for tide gauge traffic.

3.3 PACKAGES AVAILABLE WITHIN GLOSS

A software system called ISRAMAR consists of a package of computer programs integrated in a unified system for near real-time provision of meteorological and oceanographic data from remote stations, transmitted via modem through a normal telephone line. This has been developed at the Israel National Institute of Oceanography and is available to participants in MedGLOSS and GLOSS. For information, email rosen@ocean.org.il

4. DATUMS AND DATUM CONNECTIONS AT TIDE GAUGES

Nineteenth and early twentieth century scientific studies of changes in sea level were concerned primarily with vertical land movements in the belief that the average ‘real’ level of the sea is constant over long periods of time. Indeed, the original motivation for the establishment of the IUGG Mean Sea Level Committee, which became the Permanent Service for Mean Sea Level, was the requirement for a better sea level data set for the study of post-glacial rebound in Scandinavia (Woodworth, 1993).

Of course, it is now appreciated that neither land nor sea levels are constant over long periods. There are vertical movements of the land associated with a range of natural processes such as tectonics (e.g., earthquakes) in addition to post-glacial changes, and with a range of anthropogenic processes (e.g., ground water pumping); for a review, see Emery and Aubrey (1991). Long term changes in mean sea level relate to variations in ocean currents and to changes in the volume of water in the oceans and therefore to climate change. It is clear that to understand relative sea level changes properly we have to decouple the different sea and land signals in the records.

4.1 SOME DEFINITIONS (EXTENDED FROM VOLUME 1)

Datums and Benchmarks

In everyday matters we subconsciously use datums. For example, when we say a tree is 10 m high, we naturally assume the ground surface to be the datum from which we are measuring the height. However, when we come to consider the height of a large building on sloping ground we need more information to determine ‘height’, since our datum can no longer be the unlevel ground. In this case, we need another clearly defined point for our datum reference. In the same way, tidal observations must be referred to some fixed datum.

For tidal observations, a land benchmark is used as the primary reference point. A benchmark is a clearly marked point located on a stable surface such as exposed rock, a quay wall or a substantial building. When a benchmark is on a horizontal surface, it normally takes the form of a round headed brass bolt, the highest point of the domed head being the reference level. When on a vertical surface, it can be in the form of a horizontal groove in the surface or on a metal frame attached to the surface, having a horizontal reference edge to which a measuring staff support can be fixed.

It is not good practice to depend upon the stability of a single benchmark but to have a number (we suggest a minimum of 5 within a few 100 metres, or at most 1 km, of the gauge) which should always keep the same elevation relative to each other. If no changes are observed over long periods, it is safe to assume that the area of land around the gauge is ‘stable’. (Or, at least, it is internally stable. The port area could, of course, exhibit vertical movement with respect to a much wider area. This can be demonstrated only by means of larger scale geodetic levelling or GPS surveys.)

It is desirable, although not essential, that all benchmarks are tied into the national levelling network, and periodically checked with respect to that network. The benchmarks will then be given elevations referring to the datum of the national network. However, national levelling networks tend to be redefined at intervals. For that reason, in sea level studies we do not rely on national levelling network information for any scientific purpose, although, of course, it may provide interesting ancillary information. It is important that the benchmarks be clearly identified, containing an inscription of a name or number. In addition, they should be unambiguously documented in the tide gauge metadata with a description of the mark itself, photographs, national grid reference and a local port map.

Tide Gauge Benchmark (TGBM)

The Tide Gauge Benchmark (TGBM) is chosen as the main bench mark for the gauge from the set of approximately 5 marks described above. The TGBM is extremely important as it serves as the datum to which the values of sea level will be referred. The choice of TGBM is a somewhat subjective one; in principle it should be the 'most stable' or 'most secure' mark of the set, although if the port area is largely stable then the choice should be fairly arbitrary. Often the nearest mark to the gauge is chosen. Over a period of time it may be necessary to redefine the TGBM if the original is destroyed due to harbour developments. The benefit of having a set of 5 local marks, regularly interconnected by high precision levelling, is that it allows a new TGBM to be defined in terms of the old one if circumstances require it.

In some countries the historical practice has been not to define one mark as the TGBM, but to use some kind of weighted average of several marks as the gauge datum. For GLOSS, we recommend that the single, unique TGBM approach be adopted as the standard.

GPS Benchmark (GPSBM)

The GPS Benchmark (GPSBM) is another special mark of the available set that is the reference mark for GPS measurements near to the gauge. In some busy ports, the GPSBM may be several 100 m from the TGBM and the gauge. As for the other marks, it must be connected by high precision geodetic levelling to the TGBM at regular intervals. (See below for more details on GPS measurements at gauges).

Gauge Contact Point

The Contact Point (CP) of a tide gauge is a type of 'benchmark', or vertical reference mark, associated with the gauge which, after a geodetic connection has been made between the TGBM and CP, enables the gauge's sea level data to be expressed in terms of the TGBM datum. The essential point to note is that the CP comes with the gauge; if a different type of gauge is installed at the site it will have a different CP associated with it which will require geodetic connection to the TGBM, which will of course not have changed.

For conventional float and stilling well gauges, the CP will often be located at the top of the well inside the tide gauge hut. Sometimes in older stations the CP is located in a most difficult and inaccessible location for levelling to and new stations should take care to enable ready access. For acoustic gauges with sounding tubes, the CP will be located at a point at the top of the gauge on the container holding the acoustic transducer. For 'B gauges', the effective CP will be the 'B datum' level.

In the case of float gauges located in a tide gauge hut, the Contact Point should not be used as the TGBM itself as it is always possible for the building and the well to gradually settle over a long period. With a good set of local benchmarks, this settling will be evident by check levelling between TGBM and CP.

Tide Gauge Zero

The Tide Gauge Zero (TGZ) is the level for which the gauge would record zero sea level (if sea level were to be at that level). In a conventional float gauge arrangement, the TGZ can be related to the CP after performing dipping checks in the well (see Volume 1).

Revised Local Reference (RLR) Datum

The Revised Local Reference (RLR) Datum at a gauge site is a datum defined as a simple offset from the TGBM such that values of sea level expressed relative to RLR datum have numerical

values around 7000 mm. The concept of RLR datum was invented by the PSMSL so that long time series of sea level change at a site could be constructed, even if parts of the time series had been collected using different gauges and different (but geodetically connected) TGBM's. The approximate value of 7000 mm was chosen so that the computers of the time (the late 1960's) would not have to store negative numbers. RLR datum is defined for each gauge site separately and RLR at one site cannot be related to RLR at any other site (without further knowledge of connections between TGBM's at the different sites).

When sea level data are contributed to the PSMSL (and other sea level centres) it is essential that full information on the geodetic relationships between TGBM and TGZ etc., accompany the data. Without this information, it is impossible for the PSMSL to include such data in the RLR data set.

National Levelling Network

Most countries have during the last 100 years constructed national levelling networks which are defined usually in terms of Mean Sea Level at one or more stations. Levelling connections within these networks then allow the heights of objects (e.g., mountains) to be related to MSL at the coast. For example, the UK national levelling network expresses heights in terms of 'Ordnance Datum Newlyn (ODN)', which was the average level of the sea at Newlyn in SW England during 1915-21.

ODN can be thought of as an imaginary datum plane extending over a large area (i.e. over the whole of Great Britain). The heights of bench marks, for example, can be expressed in terms of ODN as can, therefore, Chart Datum at the port.

The concept of a national levelling network has undergone revolutionary change during the last decade, primarily due to the advent of GPS. However, it was already a defective concept from the point of view of sea level studies for several reasons. First, sea level has risen at Newlyn since 1915, as it has done at many other places around the world, so ODN no longer represents the present average Newlyn levels. Second, the mean sea surface around a coast is not 'flat' (i.e., the same shape as what geophysicists call the geoid) but varies due to ocean currents, density differences, meteorological effects etc. Consequently, MSL was never a perfect choice for a national datum plane. Third, rates of change of MSL are different at different locations, thereby complicating the time dependence of the network. Fourth, all national levelling networks (with the possible exception of that of the Netherlands) contain multi-decimetric errors due to systematic, instrumental errors in the levelling. Fifth, as levelling networks tended to be redefined at intervals (e.g., every 20 years), their redefinition in itself was a potential source of error as 'heights' were redefined.

Consequently, while interaction between sea level specialists and national surveyors will be inevitable at some point, we advise most sea level specialists to take great care with the concept of a national levelling system.

Chart Datum

Chart Datum (or Admiralty Chart Datum in the UK) is the low water plane below which the depths on a nautical chart are measured and above which tidal levels are often presented for practical purposes such as tide tables for harbour operations. Chart Datum is a horizontal plane over a limited area and the elevation of this plane will vary around the coastline dependent on the tidal ranges at the places considered. In the UK, Chart Datum at a port is the same as 'Lowest Astronomical Tide' (Pugh, 1987).

Working Datums

Practical working datums are often used in ports where they describe sea level (or water depth) more clearly than perhaps a scientifically rigorous reference to a benchmark. Examples of such datums include the levels of the sill of a lock or a shallow point in the channel to a harbour, so that the

level indicated by the tide gauge shows the depth of water above these hazards. Working datums such as these often functioned as the first TGBM's for Europe's sea level records (e.g., the 'Old Dock Sill' datum at Liverpool).

4.2 LEVELLING BETWEEN LOCAL BENCHMARKS

Levelling will need to be made between all the marks of the local network at regular intervals. For GLOSS purposes, the recommendation is that the exercise be repeated at least annually with results fully documented by the responsible agency. The exact frequency of required levellings will depend on the geology of the area. On unstable ground (hardly suitable for GLOSS) more frequent leveling may be necessary.

Personnel familiar with the best practices of the technique should perform levelling with a good quality level and staff. For example, if marks are far apart, it will be necessary to establish 'staging points' clearly identified about 50 metres apart on a hard surface. This can be done by painting a small ring around the point and on softer surfaces by driving in a round-headed pin (see Volume 1). The levelling instrument can then be set up between a benchmark and the first staging point and readings of the staff taken at the two positions. This is then repeated throughout the whole network. It is important that the pairs of readings are taken in the correct sequence, otherwise an erroneous height difference will result. (Modern levels with in-built data loggers can remove most of the tedious arithmetic associated with the use of simple level.)

As with many other aspects of tide gauge operations, the main principle of levelling is that 'practice makes perfect'. For advice on good levelling methods, see:

<http://www.pol.ac.uk/psmsl/training/levelling.doc>

which is a set of notes used by Prof. Charles Merry at the University of Cape Town GLOSS Training Course in 1998.

4.3 LEVELLING BETWEEN WIDER AREA MARKS

The previous sections have described how the TGBM should be regularly connected by levelling to a local network of bench marks (we suggest 5), extending a few 100 m or up to 1 km from the gauge, to check the stability of the TGBM. In principle, as Volume 1 recommended, the height of the TGBM should also be related to a wider area network extending typically 10 km. This would provide a verification of whether the sea level measured relative to the TGBM is also consistent with being sea level relative to the average height of the surrounding wider area.

First order geodetic levelling is accurate to 1 or 2 mm over distances of a few kilometres and, therefore, annual re-levellings are very suitable for detecting any vertical movements of the TGBM with respect to the local benchmarks. However, levelling over longer distances has been found to be influenced by many significant systematic errors. Owing to these systematic errors, national re-levellings or readjustments of previous wider area levellings can give spurious apparent changes in the height of the TGBM. (This is the reason that the PSMSL requires MSL data defined with respect to the TGBM rather than with respect to the national datum levels, as explained above.)

Consequently, while it is desirable in principle to be able to perform regular wide area levellings, their accuracy has always to be considered, especially as the areas considered become wider. At some distance scale (order 10 km), the errors involved in levelling will become comparable to those achievable nowadays by means of repeated GPS surveys. Therefore, while the choice of technology for the wider area surveys is clearly evolving in most countries from levelling to GPS, the principle of the measurements described in Volume 1 remains valid: one needs to know that the relative sea level measurements provided by the gauge data are applicable to studies for the surrounding area, and not just at the gauge itself. Table 4.1 summarizes the accuracies required (and usually obtained) in the procedures of the above discussions.

Wider area levellings will benefit from the availability of geological surveys of the area.

4.4 GEODETIC FIXING OF TIDE GAUGE BENCHMARKS

4.4.1 Introduction

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 (primarily GPS but also DORIS) and absolute gravity. The space geodesy measurements can be used to geocentrically fix the GPSBM (which in turn can be connected to the TGBM by levelling) and, therefore, the MSL at the tide gauge will be defined in a global geocentric reference frame. This will, therefore, give an **absolute mean sea level**, rather than MSL relative to each local TGBM, or even to the wider surrounding area. 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 in the late 1980's 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. These resulted in the so-called 'Carter reports' (Carter *et al.*, 1989; Carter, 1994). The following sections describe developments since 1994 and Volume 2 was published. The reader is referred to Neilan *et al.* (1998) for further details.

4.4.2 Geocentric Co-ordinates of Tide Gauge Benchmarks and Monitoring of Vertical Land Movements at Tide Gauges

Over the past few years, considerable developments have taken place with the Global Positioning System (GPS) and other advanced geodetic techniques (e.g., DORIS) in order to provide precise geocentric positioning of tide gauge benchmarks, and, over periods of typically a decade of repeated or continuous monitoring, of rates of vertical movement of the marks.

Geocentric co-ordinates of the benchmarks are required if the tide gauge measurements are to be located within the same global geodetic reference frame as altimeter data. As the benchmarks will move over time for geological reasons, repeated (or continuous) GPS measurements are required. Absolute gravity measurements are now also accurate enough to detect these vertical crustal movements.

Vertical land movements have been known for many years to be an important signal in tide gauge sea level records. However, it was not until the recent developments of the new geodetic techniques that it became possible to consider monitoring them. As Volume 2 explains, in 1993 the IAPSO Commission on MSL and Tides (CMSLT) organized the 'Surrey Workshop' on this topic and produced the second 'Carter report' which recommended:

- The President of the IAPSO CMSLT should formally request that the International GPS Service for Geodynamics (IGS) take on the additional duties of organizing and managing the operation of the GPS global sea level monitoring network as a fully integrated component of the IGS-IERS International Terrestrial Reference Frame (ITRF). The products should be co-ordinates and velocities of the tide gauge stations' bench (reference) marks in the ITRF system; and

- The PSMSL archiving system should be designed to provide the vertical crustal velocities derived from selected IGS solutions, along with explanatory information including experts that can be contacted by users of the system.

In March 1997, the IGS and PSMSL organized a GPS workshop focused on the implementation of the 'Surrey recommendations', particularly with regard to the science requirements for long term sea level monitoring at tide gauges, and for altimeter calibration (i.e. the GLOSS-ALT network, see the GLOSS Implementation Plan). For the first time, practical propositions for network organization and data processing were developed. The IAPSO CMSLT and IAG Section V, in consultation with other relevant bodies, will be required to oversee 'Science Working Groups' that interface with the IGS or are components of the IGS, at the Associate Analysis Centre level (such as the Regional Network Analysis Centres RNACC), following conventions established by the IGS Densification Project. These arrangements will be relevant especially to the processing of GPS data from potentially 100s of sites for GLOSS-LTT (i.e. the GLOSS Long Term Trends network, see the GLOSS Implementation Plan) studies. For the altimeter calibration set of several 10s of sites, the IGS itself will be requested to accommodate data processing within existing IGS global analysis and data flow. The workshop also provided recommendations concerning the frequency of generation of GPS products and product types, and working groups on mechanisms for free data exchange. The workshop proceedings are available via: <http://www.pol.ac.uk/psmsl/training/training.html> and provide essential background scientific discussions of the need for GPS at gauges. These confirm that priority sites to be monitored by GPS are those identified in the previous sections i.e. for GLOSS-LTT, -ALT and -OC (the GLOSS Ocean Circulation set), with further prioritization within the large LTT set identified by regional working groups.

With regard to the various remaining technical questions related to operating GPS near to gauges, and to the major question of the desirability of permanent receivers as opposed to the use of scarce receivers in campaigns (and to the major organizational problems associated with campaigns in general), the IGS/PSMSL workshop established a Technical Committee to address these issues as soon as possible. The Chairman of the Committee is Prof. Mike Bevis of the University of Hawaii, email bevis@soest.hawaii.edu

In May 1999, a further IGS/PSMSL workshop was held in Toulouse, France to review progress with the report of the Technical Committee. It is now planned that this report will be available some time during 2000, as a 'living document' on the web and with links to it from the PSMSL training web page. This will provide a guide to 'how to operate GPS near to gauges' for potential installers of GPS equipment.

4.4.3 GPS Measurements

Over the past decade, the GPS technique has developed rapidly to the extent that it is of fundamental importance to many areas of geophysical research. (Web links to pages giving introductions to the GPS technique can be found on the PSMSL training web page.) The IGS receives data from a global network of GPS stations and produces information on the orbits of the GPS satellites which is significantly more precise than the ephemerides routinely transmitted by the satellites themselves. This information is employed subsequently by researchers with GPS receivers (for example, at tide gauges) in precise positioning computations. GPS data from the IGS network are archived at the IGS Central Bureau.

A number of groups in Europe, North America, Japan, Australia etc., are performing GPS measurement campaigns at tide gauge sites. However, there are several concerns with regard to data flow. In particular, there are as yet no clearly defined mechanisms for archiving the GPS data from these campaigns (or from permanent GPS receivers at the gauges) other than by the groups themselves, many of which are small teams of university researchers. In addition, there are a number of software packages for GPS data processing which may provide systematically different results. Resolution of these questions, which will require further research and organization by the GPS

community, were discussed most recently at the March 1997 workshop (see above) and the IGS/PSMSL Technical Committee will consider these topics in greater depth.

Whilst the detailed procedures for making GPS measurements at tide gauges are still the subject of further research, and are still being discussed by the IGS/PSMSL Technical Committee, there is already a general agreement about the main principles. Using GPS for measuring horizontal crustal movements is now well established. However, for the vertical component, the measurement of the land movement to better than 1mm/year is still a major challenge. There are many effects, which have a greater influence on the vertical component. Amongst the effects that are still topics of ongoing research are improvements in modelling the wet component of the troposphere and modelling the deformation of the Earth due to surface loading (ocean tides, sea level variations, atmospheric pressure variations etc.). On the technical side, there are problems of multipath signals, accurate modelling of the electrical phase centre variations of the antenna, the effects of changing the antenna and the problem of site monumentation and stability. All these factors have to be considered when setting up and operating a GPS station at a tide gauge for an extended period (typically 10 years or more).

The recommended procedure is that, whenever it is feasible, a **dual frequency continuously-recording permanent** GPS receiver should be installed directly at the tide gauge so that, as far as possible, it is monitoring the movement of the TGBM, which is often adjacent to the tide gauge hut. (If the receiver is placed exactly at the TGBM, then the GPSBM discussed above and the TGBM are the same marks.) As discussed in previous sections, the TGBM and GPSBM should be regularly connected (at least annually) to the CP and TGZ and also levelled to a set of local benchmarks. The TGBM is, therefore, the fundamental point, which is geocentrically located by the GPS measurements and to which all the sea level measurements are related. In order to reduce the effects of multipath signals on the GPS measurements, it is recommended that a choke ring antenna be used. Whenever possible, the raw GPS data (normally 30 sec sampling rate) should be automatically downloaded and transmitted every day to a central GPS data processing and archiving centre.

Normally, when choosing a new permanent GPS site careful consideration is given to the surrounding environment (e.g., access to bedrock, low multipath environment etc.). In the case of a tide gauge, the environment is usually far from ideal, particularly in a busy port. However, it is still recommended that the GPS measurements should, if at all possible, be made at the tide gauge. For a station where it is impossible to make GPS measurements directly at the tide gauge (e.g. due to obscured sky visibility, excessive multipath or radio interference), then a site should be chosen that is as close as possible to the tide gauge. Ideally this should be within a few hundred metres of the gauge. The GPSBM and GPS antenna then need to be levelled to the TGBM at least annually. Experience shows that these regular levelling connections are often neglected over the years. This is particularly true if the distance involved is more than a few hundred metres. For greater distances, the levelling error can also become a significant part of the total error budget. In no circumstances can it be assumed that even relatively close sites are not moving differentially at the mm/year level.

In some countries, a second continuously recording GPS receiver is also being installed a few, or several, kilometres inland at a site with good multipath environment and with a better connection to bedrock. Whilst such a site might be a better place for testing geophysical models of vertical crustal movements, it cannot be considered to be a substitute for the permanent GPS receiver at the tide gauge. This is because of the difficulties (and cost) of connecting the inland GPS receiver to the tide gauge with an error significantly less than 1 mm/year. The GPS measurements at the tide gauge are required to remove the vertical movements of the tide gauge (whether geophysical or more local) from the trend in mean sea levels in order to give the absolute or climate related change in mean sea levels. If the additional resources are available, then one (or ideally several) inland permanent GPS stations will show any differential vertical movements with respect to the tide gauge. This gives important information on the spatial variations of relative mean sea levels in the wider area, which is needed for flood defense work (see Section 4.3 above).

Ideally, every tide gauge should be equipped with a permanent/continuous GPS receiver. However, in practice the financial resources are not available to do this, so many countries are installing permanent GPS receivers at some tide gauges and then densifying the GPS/tide gauge network with GPS campaign measurements. For example, using the results from 8 different UK GPS campaigns between 1991 and 1996, Ashkenazi *et al.* (1997) showed that the repeatability of the heights of the TGBMs are of the order of 15mm. This is sufficient for vertical datum work (where geoid errors and national levelling errors dominate) and also for applications such as the calibration of satellite altimeters. There is clearly an advantage in concentrating on tide gauges with existing long PSMSL RLR mean sea level records (e.g., what the GLOSS Implementation Plan refers to as the GLOSS-LTT set) for the installation of permanent GPS receivers, and then using GPS campaigns for the other tide gauges in a network with shorter records so far. The exact mix between permanent and campaign GPS tide gauges will change in the future as the cost of GPS receivers continues to decrease. See papers in Neilan *et al.* (1997) for several other examples of the use of permanent and campaign GPS measurements; for example, Nerem *et al.* discuss permanent GPS measurements around a bay near to gauges while Johansson *et al.* discuss permanent GPS measurements at inland (bedrock) sites.

4.4.4 DORIS Measurements

The DORIS technique has also been proved to be capable of monitoring vertical land movements with a precision of approximately 1 mm/year for the 'secular' component and 1-2 mm for the seasonal component. For example, comparisons of secular vertical motions at co-located geodetic sites show that the differences between GPS, VLBI and SLR results is of the order of a few mm/year and that DORIS results fall well into this level of accuracy. For recent results concerning secular and seasonal vertical motions with DORIS, as well as the use of DORIS to correct tide gauge sea level measurements for crustal motions, see Soudarin *et al.* (1999), Cazenave *et al.* (1999) and Mangiarotti *et al.* (2001).

This level of precision is that obtained with the DORIS system of the first generation (0.3 mm/sec instrumental precision, single channel receivers and a mini-constellation of 3 satellites consisting of SPOT-2, SPOT-4 and TOPEX/Poseidon). In the near future, a new generation of DORIS instruments will be placed on-board JASON-1, ENVISAT and SPOT-5, consisting of multi-channel receivers and an instrumental precision of 0.1 mm/sec. Simulations performed at LEGOS-GRGS/CNES in France have shown that with the new DORIS system, the geodetic performance will increase by a factor of 2-3. For instance, the precision of vertical (secular) motion determination should reach the 0.3 mm/year level with about 5 years of data on 3 or 4 satellites in orbit simultaneously.

4.4.5 Absolute Gravity Measurements

The 'Carter reports' also recommended that absolute gravity measurements should be made in the vicinity of tide gauges. This will give an important check upon the vertical crustal movements in an area independent of GPS.

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 laser interferometer. By counting and timing the occurrences of interference fringes, the position of the falling mass is measured as a function of time. A lot of effort has been put into reducing or eliminating various sources of systematic error. The latest portable absolute gravimeter is the FG5 instrument produced by Micro-g solutions, Inc., USA (Niebauer *et al.*, 1995). The specifications for this instrument are a precision of better than 1 μgal and an accuracy of 2 μgals (N.B. 1 gal = 1 cm/sec^2 so 1 μgal = 10 nm/sec^2). For further details of the absolute gravimeter and a bibliography of published papers see <http://www.microgsolutions.com/>.

The gravity value at a site is found by automatically making repeat drops of the test mass for typically one or two days and making corrections for tides and atmospheric pressure variations. Various intercomparison experiments have been made between different FG5 absolute gravimeters and typically show agreements at the 1 to 2 μgal level (e.g., Sasagawa *et al.*, 1995). At good sites, measurements made over a number of years show a repeatability of order 2 μgal .

The gravity gradient in free air, at the Earth's surface, is 3 $\mu\text{gal}/\text{cm}$. 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 $\mu\text{gal}/\text{cm}$. Thus, it can be seen that absolute gravity and GPS are both approaching the equivalent accuracy of 1 cm that is required for measuring vertical crustal movements (see Table 4.1).

The absolute gravity measurements are normally made in a convenient building, which provides reasonable temperature control and this site then needs to be connected to the TGBM and the local benchmarks using high precision levelling. Corrections for ocean tide loading and attraction are important at near coastal sites and also need to take into account the additional ocean tide attraction due to the elevation of the site.

Due to the higher cost of absolute gravimeters compared to GPS receivers, the number of tide gauges being monitored for gravity changes is likely to be only a small sub-set of the tide gauges with GPS. It is recommended that the measurements of absolute gravity should be concentrated at key tide gauges in the GLOSS-LTT network, where they will be most useful in contributing to the challenge of determining vertical crustal movements to better than 1mm/year.

4.5 GEODETIC CONTACT POINTS

Table 2.2 provides contact names for advice on aspects of GPS, DORIS and absolute gravity.

Table 4.1

Geodetic Accuracies Required at Tide Gauges	
<u>Technique</u>	<u>Distance: Accuracy</u>
(1) Local BM levelling network	0 to 1km : < 1mm
(2a) Wider area levelling	1km to 10km : < 1cm
(2b) Wider area GPS	ditto
(3) Absolute gravity at sites near tide gauges	< 2 μgal
(4) GPS at sites near tide gauges	< 1 cm

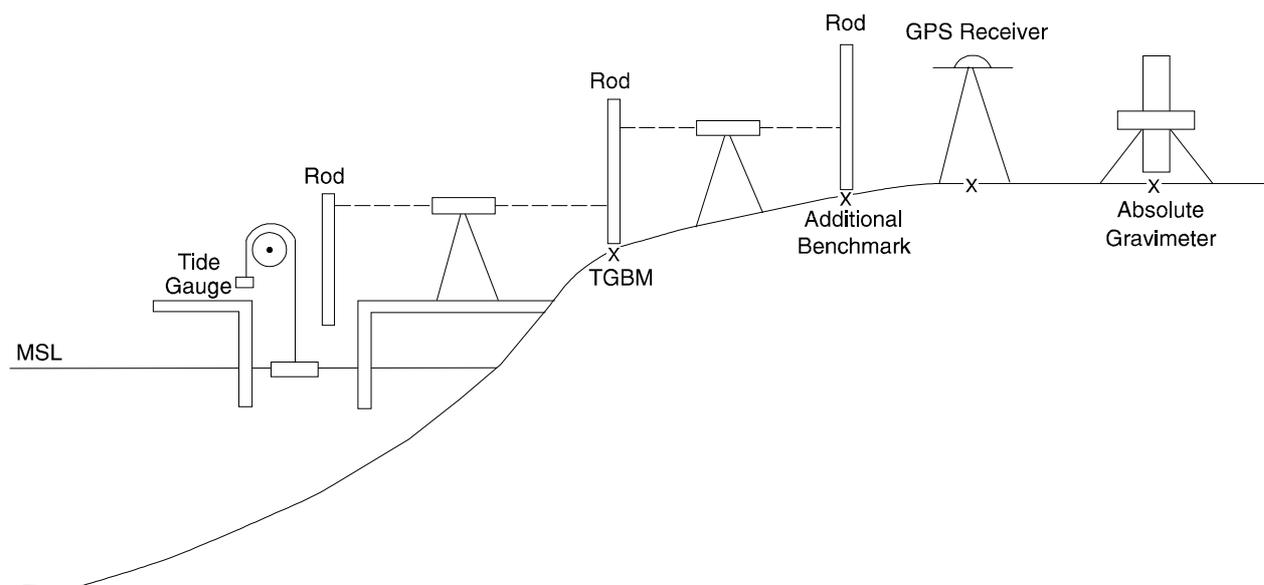


Figure 4.1 Schematic of GPS and absolute gravity at tide gauges

5. DATA DOCUMENTATION AND PROCESSING

5.1 DOCUMENTATION AND ARCHIVING

A sea level agency should aim to not only operate gauges to its best ability, but also to provide proper documentation, data processing and archiving functions. Documentation has already been alluded to in previous sections. All tide gauge operations (equipment change notes, calibration records, maps, photographs etc.), must be documented within an overall, preferably computerized system so that the information is not lost to future analysts. The tide gauge data themselves must be checked (and if necessary corrected) for their quality and properly documented before being passed to scientists in the wider community.

5.2 PC-BASED SOFTWARE

The aim of data processing software should be to ensure the quality of any data that are subsequently archived and used for scientific analysis. Tide gauge data which are nowadays collected by electronic methods tend to have fewer errors than existed in the days of paper charts and inaccurate clocks. However, there is still a need to check for timings, data spikes and gaps etc. by, for example, ‘buddy checking’ with respect to predicted sea level time series (determined from historical tidal constants) or to data from a nearby gauge.

Many organizations have developed their own processing software to validate incoming data in varied formats and media that are specific to their requirements. However, three organizations have developed PC-based software as a contribution to GLOSS with the aim of enabling participating countries to be able to process and validate their own records. These organizations are:

- The University of Hawaii, which has produced a package led by Patrick Caldwell, which is probably the most commonly used package within the GLOSS community for sea level data quality-control purposes.
- The PSMSL/Proudman Oceanographic Laboratory, which has produced a package led by Colin Bell, Ian Vassie and Philip Woodworth called TASK-2000 (Tidal Analysis Software Kit) which is based in the TIRA etc. programmes used at POL for many years.

- The Australian National Tidal Facility, which has own package derived originally from POL software.

For contact addresses and emails, see:

<http://www.pol.ac.uk/psmsl/training/training.html> or email psmsl@pol.ac.uk.

The manuals accompanying these packages describe the data processing and quality control procedures used.

Each of these packages runs at the present time under DOS only. We understand that each set of authors has plans to develop the packages under later versions of Windows. However, at the time of writing, they are not yet available.

5.2.1 Comments on Tidal Predictions

Each of these packages has been developed primarily for sea level data quality control. However, each also has the capability for determining tidal constants and for calculating tidal predictions. However, a user should be aware that the tidal software is not the same in each package. The Hawaii package contains tidal software constructed by Dr. Mike Foreman from Canada, whereas the TASK and NTF packages contain tidal software originally written at Bidston Observatory. ‘Tidal constants’ can have slightly different meanings depending on the software and should never be mixed between packages. For example, constants determined by one package should never be used to compute predictions with another one.

So far as we know, this problem is restricted to the annual harmonic (what tidalists call S_a). However, there may be other differences which we are not aware of. (See the manual which accompanies the TASK-2000 package for more information on this topic.)

5.2.2 Tidal Filters for ‘Mean Sea Level’

Volume 1 of this Manual was somewhat ambiguous in its recommendations for computations of monthly mean values from hourly data, prior to submission of the monthly and annual means to the PSMSL. Volume 1 demonstrated:

- The summation of a month’s high and low waters to make Mean Tide Level (MTL) for the month.
- A method by which a simple filter (the Doodson X0 filter) could be used as a ‘tide killing filter’ to compute so-called ‘daily mean values’ which could then be summed over the month to make the monthly Mean Sea Level (MSL).
- A method by which the simple arithmetic average of hourly values for a month can be used to calculate the monthly MSL.

Some comments on these options are appropriate. First, one has to realize that MTL is not the same quantity as MSL because of shallow water tidal effects and, while time series of MTL are adequate for many purposes, they should never be mixed with time series of MSL because of the systematic offsets between them (see Pugh, 1987 for explanation of the shallow water tides which cause the offsets). Of course, MTL was frequently used in former times rather than MSL, when agencies did not have access to adequate computing capacity to handle hourly values. The PSMSL always strives to keep MSL and MTL time series separate in its data bank.

Second, the filter described in Volume 1 for MSL computation (the Doodson X0 filter), which is the filter in the TASK package, is not the same one as used in the Hawaii software. The former is a simple 39-point moving arithmetic filter. The latter performs a pre-whitening tidal reduction for 4 constituents (M2, S2, O1 and K1) for each month of data and then low-pass filters the

residuals using a 119-point filter. The resulting ‘daily means’ are then summed in each case to compute the monthly mean.

One might ask, how similar (or dissimilar) are the daily means produced with the Doodson and Hawaii filters? (Obviously a ‘daily mean’ computed by simple averaging will be contaminated by the tidal signal). And how similar are the monthly means computed in the three cases?

A test was performed by the PSMSL in January 2000 using over 800 station-years of hourly data from a CDROM of sea level data produced by the University of Hawaii, using two years of data from each station. Each year of data was subjected to the three averaging methods. Results showed that the standard deviation of the difference between daily means produced using the Hawaii and Doodson filters was 4.7 mm. The standard deviation of differences between (monthly means determined by the Hawaii filtering to dailies then summation to monthlies) and (Doodson filtering to dailies then summation to monthlies) was 1.3 mm. Meanwhile, the standard deviation of differences between (monthly means determined by the Hawaii filtering to dailies then summation to monthlies) and (simple monthly arithmetic average) was 1.2 mm. All these tests were performed for complete months of data only as spurious differences can be obtained from filtering data with gaps.

The conclusions to be made from this from the point of view of monthly MSL computation are:

- If one only has high and low water data, then the summation to MTL described in Volume 1 is acceptable as long as the resulting monthly means are clearly documented as MTL and not MSL.
- The choice between (filtering with either filter to dailies and then averaging to monthlies) or (simple arithmetic averaging over a month) is not critical. However, the former is probably a more mathematically rigorous procedure in principle and is the one we recommend in this Manual for future research.

The conclusion to be made from the point of view of daily mean computation follows from the Hawaii filter being wider than the Doodson. Consequently, it should provide a tighter rejection of tidal bands and a better definition of daily means. However, the differences are almost always sub-centimetre and, if significantly different values are obtained with the use of the two filters, it probably means that the period under study contains considerable energy (e.g., due to a large storm surge) which will require further study with hourly values.

5.2.3 Comments on Computations of Extremes

The study of sea level extreme levels is an important subject both within the scientific (e.g. climate change) and engineering communities. For a discussion of the statistical analysis of extremes, see Pugh (1987) or Coles and Tawn (1990). However, it seems that there has never been a formal definition of how to compute the ‘turning points’ at each high and low tide, from which to find the extremes from a set of data (e.g. the single annual extremes from one year of data, or the ‘N-largest’ from the year), with which to perform the statistical analyses.

There are two common methods used to find the turning points. The first is to use (perhaps 6) hourly values of sea level spanning high (low) tide, and to interpolate them using a cubic spline in order to find the maximum (minimum) value for each tide. The highest (lowest) turning point for the year is then defined as the annual extreme. A second is to simply find the highest and lowest hourly values as observed in the data set for the year. Clearly, the first method will produce higher (lower) annual extreme maxima (minima).

The situation is more complicated if one samples at intervals of 6 or 15 minutes rather than an hour. Does one define the extremes based on the original sample of 6-minute data or from low-pass filtered hourly values? Common sense suggests that one should use the highest rate of sampling one

has available in order to find the real extremes because, even if the real extreme persisted only for instant, it might be enough to result in over-topping and flooding. In addition, it is well known that in many applications hourly sampling is insufficient to provide a full description of the sea level time evolution (e.g. in storm surge research in NW Europe).

In practice, one suspects that the resulting data set of annual extreme levels, and the results of the statistical analyses based on that data set, will be relatively insensitive to the method used to find the turning points, given the wide range of level within any distribution of annual extremes. However, for the purpose of this Manual we recommend:

- if only hourly values of sea level are available, the turning points should be defined by means of cubic spline interpolation of (perhaps 6) values spanning each high and low tide;
- if higher frequency sampling of sea level is available (e.g., 6 or 15 minutes), spline interpolation could again be used, but one suspects the turning point levels will be little different to simply noting the observed maximum (minimum) values at each tide.

6. DATA EXCHANGE PROCEDURES

6.1 BACKGROUND

The previous chapters of this manual, together with Volumes 1 and 2, have given advice on purchase and operation of tide gauges and on data processing software. By this stage you should, therefore, have some sea level data sets from your station. This section describes what you should do with them.

For many years, all tide gauge authorities (whether involved in GLOSS or not) have contributed monthly and annual means of sea level to the Permanent Service for Mean Sea Level (PSMSL). The PSMSL was established in 1933 as an international data centre for mean sea level. Its responsibilities include collection, publication and distribution of data and the analysis and interpretation of these data. Advice on practical aspects of sea level measurement and data reduction is also given. An example of the way in which PSMSL encourages uniform standards and procedures is the preparation of this manual, which is itself based on courses given at the Proudman Oceanographic Laboratory, Bidston Observatory, United Kingdom, where the PSMSL is housed. For more information on the PSMSL and GLOSS, see: <http://www.pol.ac.uk/psmsl/psmsl.info.html> and <http://www.pol.ac.uk/psmsl/gloss.info.html>

When the GLOSS Programme was first proposed in the mid-1980's, and in the first GLOSS Implementation Plan (IOC, 1990), the main purpose of the programme was stated to be the improvement in the quality and quantity of MSL information delivered to the PSMSL. The success of GLOSS in this regard can be seen from the annual reports of the PSMSL on GLOSS status (see web pages above).

With the advent of the World Ocean Circulation Experiment (WOCE) in the late-1980's, the sea level community recognized the need for a worldwide effort for the collection of 'higher frequency' (i.e., typically hourly) sea level data. Such collections had already been made on a regional basis (e.g., MEDALPEX, TOGA) but this was the first time that collections were attempted from a global network. This resulted in the establishment of two WOCE Sea Level Centres: a 'fast' centre based at the University of Hawaii, and a 'delayed mode' centre at the British Oceanographic Data Centre (BODC) at Bidston Observatory alongside the PSMSL. These Centres are still active as of 2000 and a Southern Ocean Sea Level Centre (SOSLC) has joined their international activities at the Australian National Tidal Facility.

These experiences with WOCE during the 1990's convinced GLOSS that it was quite feasible to propose the collaborative collection of higher frequency data from all GLOSS sites. This collection would not only allow access by analysts to the higher frequency part of the sea level variability spectrum, but would provide an essential archive of the original sea level data. Consequently, when the GLOSS Implementation Plan was rewritten in 1997, it was decided to make it an essential requirement of participation in GLOSS for an agency to make their higher frequency data available to the international community in some way. For more details of these recommendations, see Chapter 7 of the Implementation Plan 1997 on the web at: <http://www.pol.ac.uk/psmsl/gip97/> (and read the README file), or as a paper report from the GOOS Project Office at IOC. The full IOC Assembly subsequently endorsed these recommendations in 1997.

6.2 CONSEQUENT DATA EXCHANGE ACTIONS

An agency willing to make sea level data available to the international community must, therefore, take some actions consistent with the decisions described in the previous section. For agencies with stations which are not part of the GLOSS programme, we strongly recommend that they should:

- take steps to preserve the original higher frequency data safely in a national archive, together with all ancillary data (e.g., meteorological data) and metadata;
- if the national archive, or its catalogue of holdings, has a web interface, then the web address should be made known to the PSMSL so that it can be included in a list of national web addresses (see http://www.pol.ac.uk/psmsl/sea_level.html). Any user can then at least see what higher frequency data are available from the agency and can contact the agency directly to obtain them (depending on that agency's data policy including charging policy);
- Monthly means of sea level should be sent to the PSMSL, as they have been for many years, together with associated information. For advice on sending data to the PSMSL see <http://www.pol.ac.uk/psmsl/psmsl.info.html>

For agencies with stations which are part of the GLOSS programme, they should implement the requirements of Chapter 7 of the Implementation Plan, which comprise:

- take the three actions described above, and
- send copies of their original higher frequency data to an International Archiving Centre for safe-keeping and for distribution to the international community, or make their original data available on their own web servers which are made known to GLOSS (in which case one of the IAC's will take copies of the data).

At the present time the recognized GLOSS International Archiving Centres are:

- The PSMSL and BODC at Bidston Observatory;
- The University of Hawaii Sea Level Center;
- The Australian National Tidal Facility.

Each agency participating in GLOSS should send its data to whichever of the three IAC's is most convenient.

For more information on GLOSS and on the various international, regional and national sea level data centres, see: http://www.pol.ac.uk/psmsl/sea_level.html

6.3 FAST DELIVERY DATA

Since the WOCE Programme, and the development of satellite radar altimetry into a reliable and accurate technique for quasi-global sea level monitoring, the community has begun to require

access to near real-time, or 'fast delivery', tide gauge data. The first main driver for this need is that data centres (in virtually real time can now provide altimetric data sets very fast for some preliminary products and in a week or so for the best scientific products). Consequently, analysts who require tide gauge data for comparison to altimetry need the gauge information in a similar timescale. The second main driver comes from the numerical ocean modelling community which is involved in altimeter and tide gauge data assimilation into ocean models and which provides various types of ocean forecasting (e.g., of El Niño development). To be useful to the modellers, the information has to be available much more rapidly than hitherto, even if the data have not been subjected to the final control expected of most GLOSS sea level data sets. (The situation is analogous to weather forecasting which requires timely wind and air pressure data.)

At the GLOSS Group of Experts Meeting in 1999 the decision was made to ask the University of Hawaii Sea Level Center to function in the future as the 'GLOSS Fast Centre', as an extension of its role as the WOCE Fast Centre. The UHSLC will be contacting tide gauge operators which it hopes will be able to supply quasi-real time data to the GLOSS Fast Centre.

6.4 REGIONAL PROGRAMMES

The GLOSS Implementation Plan 1997 recognized that regional activities have been some of the most successful of the GLOSS programme and provided a summary of regional activities known at the time. Since 1997, there have been initiatives started in Europe, the Caribbean, West Pacific, Africa etc. which it is to be hoped will result in their own data centres and products of various kinds in future. Connections to these many activities will be attempted through web links such as:

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

7. TRAINING MATERIALS, TRAINING COURSES AND MORE INFORMATION

7.1 TRAINING MATERIALS

PSMSL maintains a web page that attempts to provide a range of sea level and GLOSS information and training materials in electronic form. The page is:

<http://www.pol.ac.uk/psmsl/training/training.html>

The page contains copies of a number of the documents mentioned in this volume (mostly in Acrobat Reader PDF format or in Word format). It provides links to available software packages and to general information on sea levels and tides such as publications, glossary, acronyms etc. It is our intention that this page will be expanded as much as possible in future. Suggestions for additions are welcome, and contributions in languages other than English are especially welcome.

7.2 SEA LEVEL TRAINING COURSES

A sea level training course has been held almost every year since 1983 with funding from IOC and with various national inputs (e.g., offers to host the courses, offers to provide expert lecturers) as part of a country's national contribution to GLOSS. As of 2000, the most recent courses have been at POL (1997) and the University of Cape Town (1998), both in English, at the University of Sao Paulo (1999) in Portuguese and Spanish, and in Jeddah, Saudi Arabia (2000) in Arabic and English. It is IOC's intention that such courses should continue at a similar rate over the next few years, probably in conjunction with other GOOS training activities. 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.

Following each course, the organizers usually write a short report, with input from guest lecturers and attendees. Copies of the reports for all recent courses may be obtained from IOC and may be instructive to anyone considering holding a similar course. Offers to host such a course should be sent to the GLOSS Technical Secretary at IOC (t.aarup@unesco.org). Announcements of future courses will be sent to GLOSS Contacts by IOC and will be posted on the PSMSL training web page (see above). Formal application to attend IOC-funded courses has to be obtained from IOC.

7.3 FURTHER INFORMATION

IOC maintains a list of National GLOSS Contacts in each country which contributes the GLOSS programme, in addition to a small number of Regional Contacts and leaders of the various GLOSS sub-programmes. A list can be obtained via: <http://www.pol.ac.uk/psmsl/gloss.contacts>

Any GLOSS Contact, the GLOSS Technical Secretary (t.aarup@unesco.org), the PSMSL and other sea level data centres should be able to provide further information on GLOSS.

For further technical information on aspects of tide gauge techniques etc. discussed in this and earlier Volumes of the Manual, please write to the PSMSL or email psmsl@pol.ac.uk or contact the GLOSS Technical Secretary at IOC.

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9. ACKNOWLEDGEMENTS

We are very grateful for information from the following people: Serge Allain (SHOM, France), Philip Axe, Trevor Baker, David Smith, Ian Vassie (POL, UK), Mike Bevis (Univ. of Hawaii, USA), Anny Cazenave (GRGS, France), David J. Dixon (Plymouth, UK), Steve Gill (NOAA/NOS, USA), David Johnstone (NIWA, New Zealand), Antony Joseph (NIO, India), George Maul (Florida Inst. Technology, USA), David Meldrum (DML, UK), Gary Mitchum (Univ. South Florida, USA), David Pugh (SOC, UK), Dov Rosen (NIO, Israel), Allan Suskin (NTF, Australia), Mike Thomson (Hyd. Office, South Africa).

APPENDIX 1

GLOSS REQUIREMENTS FOR GAUGES

The aim of any tide gauge recording should be to operate a gauge which is accurate to better than 1 cm at all times i.e., in all conditions of tide, waves, currents, weather etc. This requires dedicated attention to gauge maintenance and data quality control. In brief, the major requirements for GLOSS stations are (IOC, 1997):

- (i) a sampling of sea level, averaged over a period long enough to avoid aliasing from waves, at intervals of typically 6 or 15 minutes, but in all circumstances the minimum sampling interval should be one hour;
- (ii) gauge timing be compatible with level accuracy, which means a timing accuracy better than one minute (and in practice to seconds or better with electronic gauges);
- (iii) measurements must be made relative to a fixed and permanent local Tide Gauge Benchmark (TGBM). This should be connected to a number of Auxiliary Marks to guard against its movement or destruction. Connections between the TGBM and the gauge zero should be made to an accuracy of a few millimetres at regular intervals (e.g. ,annually);
- (iv) readings of individual sea levels should be made with a target accuracy of 10 mm;
- (v) gauges should, if possible, be equipped for averaging and rapid sampling of waves, and should be also equipped for automatic data transmission to data centres in addition to recording on site;
- (vi) sea level measurements should be accompanied by observations of atmospheric pressure, and also winds and other environmental parameters, which are of direct relevance to the sea level data analysis.

Regular (e.g. daily) inspection of data will inform operators when a gauge is malfunctioning, and lead to overall better long-term data sets. Data from gauges in polar or other remote locations will inevitably be inspected less frequently, unless satellite data transmission can be installed. Similarly, data from the relatively few gauges recording only on paper charts will be slow to reach centres for quality control; these must be considered priorities for upgrading to modern standards.

Operators of gauges must always be aware of possible systematic jumps in sea level time series when one form of recording is replaced by a 'better' one. All gauges have systematic errors, but those errors will be irrelevant for time series work if the same technique is used throughout. New technology gauges are, by definition, less well understood than old ones, and they must always be operated alongside the older ones until sufficient experience has been obtained.

APPENDIX II

LIST OF ACRONYMS

ARGO	Global Array of Profiling Floats
BODC	British Oceanographic Data Centre
C-GOOS	Global Ocean Observing System – Coastal Module
CLS	Collect Localization Satellites
CMSLT	Commission on MSL and Tides of IAPSO
CNES	Centre National d'Etudes Spatiales (France)
CP	Contact Point
DATARING	Data Acquisition for Tidal Applications for the Remote Interrogation of Network Gauges
DCP	Data Collection Platform
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite (USA)
ENVISAT	Environmental Satellite
GLOSS	Global Sea Level Observing System
GMS	Geostationary Meteorological Satellite (Japan)
GOES	Geostationary Operational Environmental Satellite System
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GRGS	Groupe de Recherches de Géodésie Spatiale (France)
GTS	Global Telecommunications System
IAPSO	International Association for the Physical Sciences of the Ocean
IERS	International Earth Rotation Service
IGS	International GPS Service for Geodynamics
INMARSAT	International Maritime Satellite Organization
IOC	Intergovernmental Oceanographic Commission
IUGG	International Union of Geodesy and Geophysics
JASON	TOPEX/POSEIDON Follow-on
LAT	Lowest Astronomical Tide
LTT	Long-Term Trends
MEDALPEX	Mediterranean Sea During Alpine Experiment
METEOSAT	Geostationary Meteorological Satellite
MSL	Mean Sea Level
MTL	Mean Tide Level
NGWLMS	Next Generation Water Level Measurement System
NOAA	National Oceanic and Atmospheric Administration (USA)
NOS	National Ocean Service
NTF	National Tidal Facility (Australia)
PSMSL	Permanent Service for Mean Sea Level
POL	Proudman Oceanographic Laboratory (U.K.)
PTT	Platform Transmitter Terminal
RLR	Revised Local Reference
RTU	Remote Terminal Unit
SEAFRAME	Sea Level Fine Resolution Acoustic Measuring Equipment
SRD	Sonar Research and Development
STWS	Storm Tide Warning Service
TASK	Tidal Analysis Software Kit
TGBM	Tide Gauge Benchmark
TGZ	Tide Gauge Zero
TOGA	Tropical Ocean Global Atmosphere Programme
TOPEX	Joint US/French Ocean Topographic Experiment
VLBI	Very Long Based Interferometry
WOCE	World Ocean Circulation Experiment