2.4 PRESSURE SENSORS

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

2.4.1 PNEUMATIC BUBBLER SYSTEMS

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

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

$$P_m = Dgh + P_a$$

where

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

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

$$P_m = Dgh$$

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

(i) Pressure Point

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

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

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

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

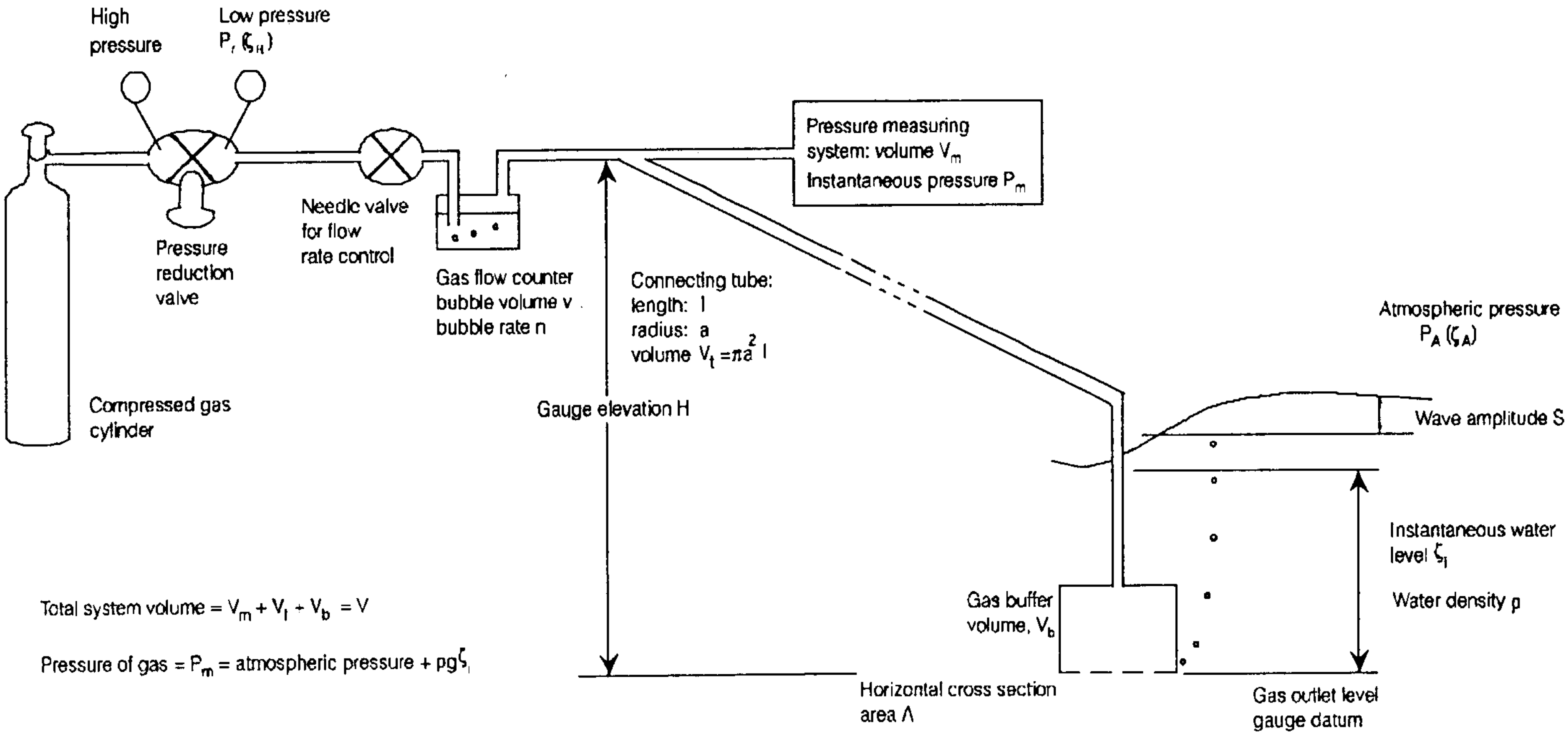


Figure 2.2

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

(ii) Air Supply Tube

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

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

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

(iii) Pneumatic Controls

The pneumatic control panel should be designed to provide :-

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

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

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

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

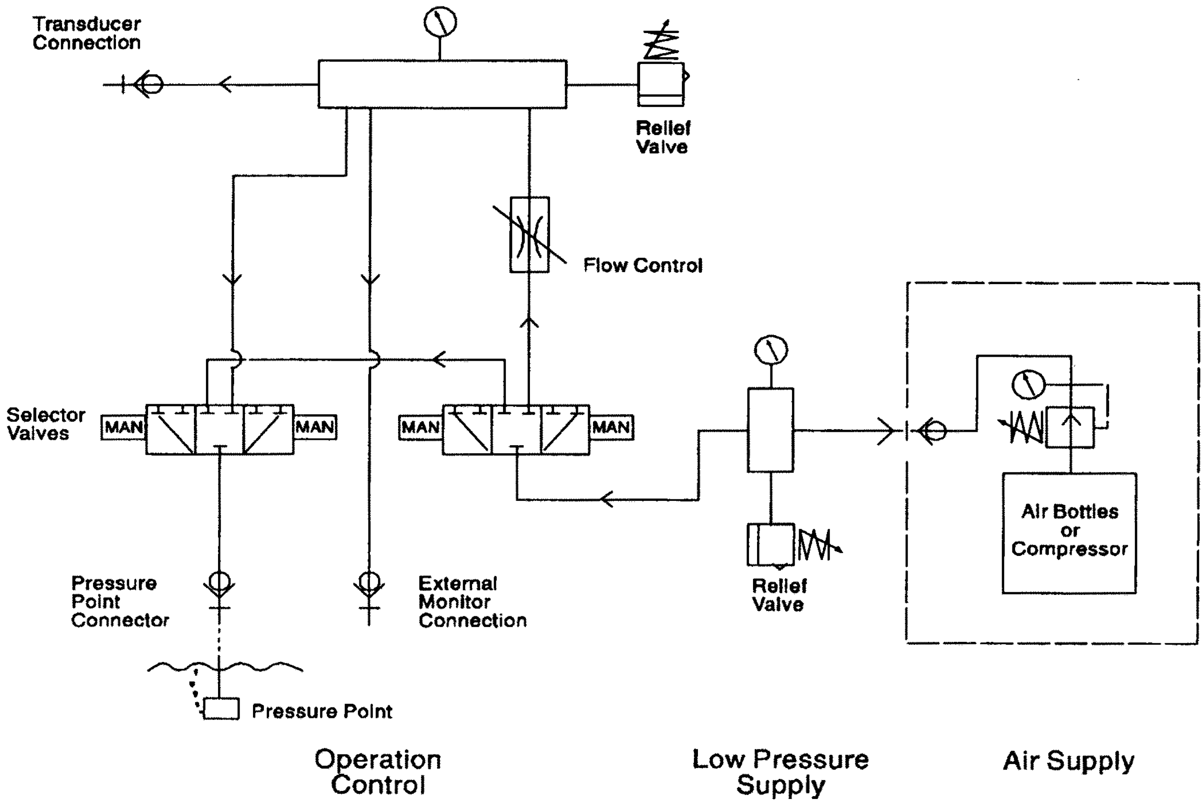


Figure 2.3

Schematic diagram of control equipment

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

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

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

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

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

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

(iv) Design Criteria for Pneumatic Bubbler Systems

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

(v) Minimum Gas Flow Rate

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

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

where f = gas flow rate

V = total volume of system (ml)

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

(vi) Static Pressure Head

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

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

where P_m = measured pressure

ρ = water density

P_{oa} = air density at atmospheric pressure

H = elevation of measuring point above pressure point outlet

γ_A = water level equivalent of atmospheric pressure

h = depth of water above pressure point outlet

g = gravitational acceleration

(vii) Dynamic Pressure Gradient

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

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

where ΔP = pressure drop

η = gas viscosity at system temperature

l = length of tube

a = radius of tube

f = gas flow rate

ΔP_m = incremental change in Pm in unit time

P_m = instantaneous pressure at measuring device

V_m = volume of measuring device

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

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

2.4.2 DIRECT READING SYSTEMS

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

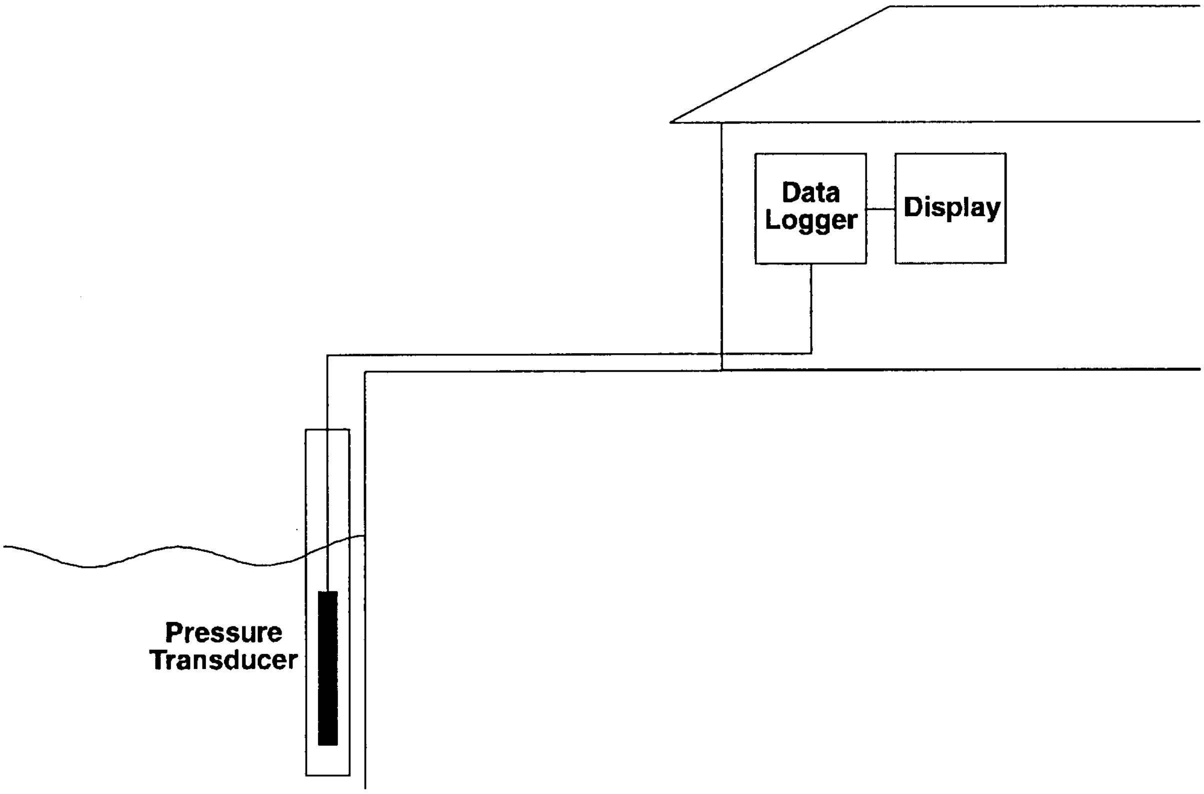


Figure 2.4

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

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

(i) Temperature Effects

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

(ii) Pressure Systems Datum

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

2.4.3 HOSTILE CONDITIONS

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

(i) Effect of Waves

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

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

where
E = error
V = total system volume
A = horizontal cross sectional area of pressure point
S = pressure amplitude of short period wave
P_o = water head pressure at outlet below trough of a wave

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

(ii) Effect of Currents

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

(iii) Density Variations

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

2.5 PRECISE DATUM CONTROL FOR PRESSURE TIDE GAUGES

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

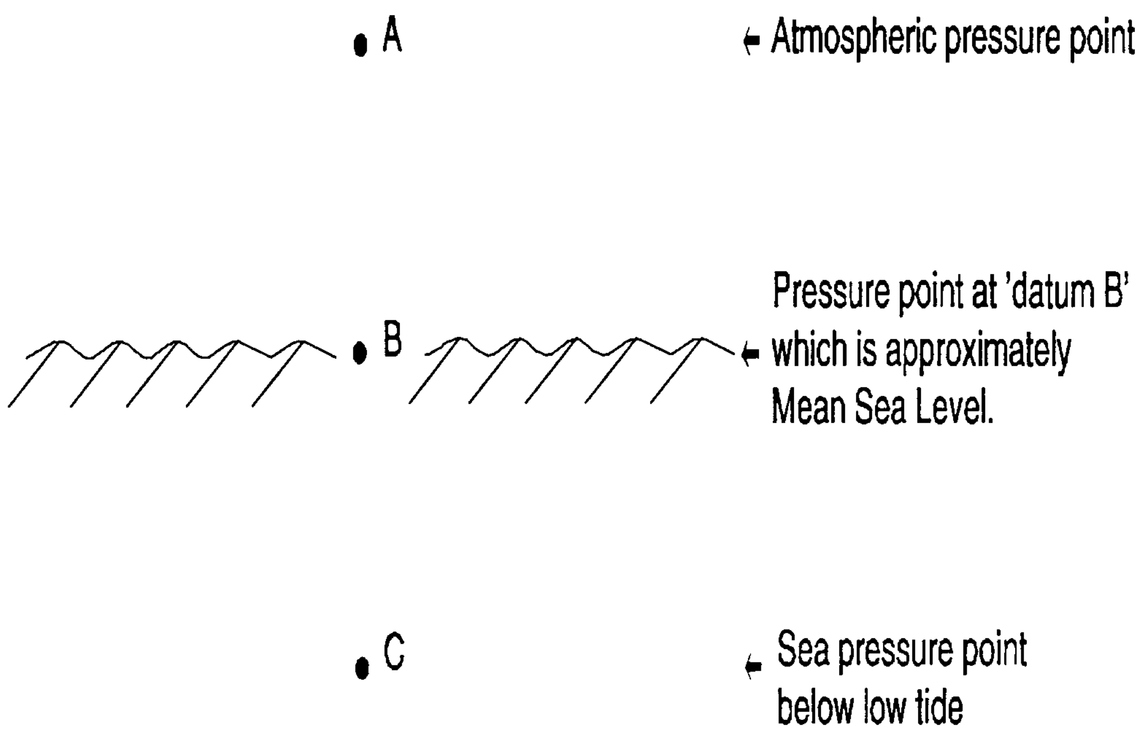
The stilling well method probably produces usable results, as long as comparisons are performed over several complete tidal cycles to remove the effect of any lag in the well. However, a stilling well will not always be present and it will have its own systematic error sources (Lennon, 1971). A tide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

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

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

2.5.1 A BRIEF DESCRIPTION OF THE METHOD

A schematic pressure gauge setup is shown in Figure 2.5 with a pressure sensor in the water ('C') and another in the atmosphere ('A'). Around the UK national tide gauge network (called the 'A Class' network), the pressure difference C-A is usually recorded in a single channel of a differential transducer connected to a bubbler gauge (Pugh, 1972). At the South Atlantic sites of POL's ACCLAIM (Antarctic Circumpolar Current Levels by Altimetry and Island Measurements) network, C and A are separate absolute transducer channels (Spencer et al., 1993). In both cases, Paroscientific digiquartz sensors are employed (Banaszek, 1985). It is the difference C-A which gives sea level, after sea water density correction, and which must be constrained to a land datum. In practice, both C and A, or their difference, may measure pressure changes extremely well, but it would be common for their data to contain uncalibrated offset pressures and small low-frequency drifts specific to each individual pressure transducer. In addition, other parts of the apparatus may also introduce biases and drifts (e.g. through insufficient gas flow in a bubbler gauge) or the ocean itself may drift (i.e. through density changes).



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

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

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

Figure 2.5

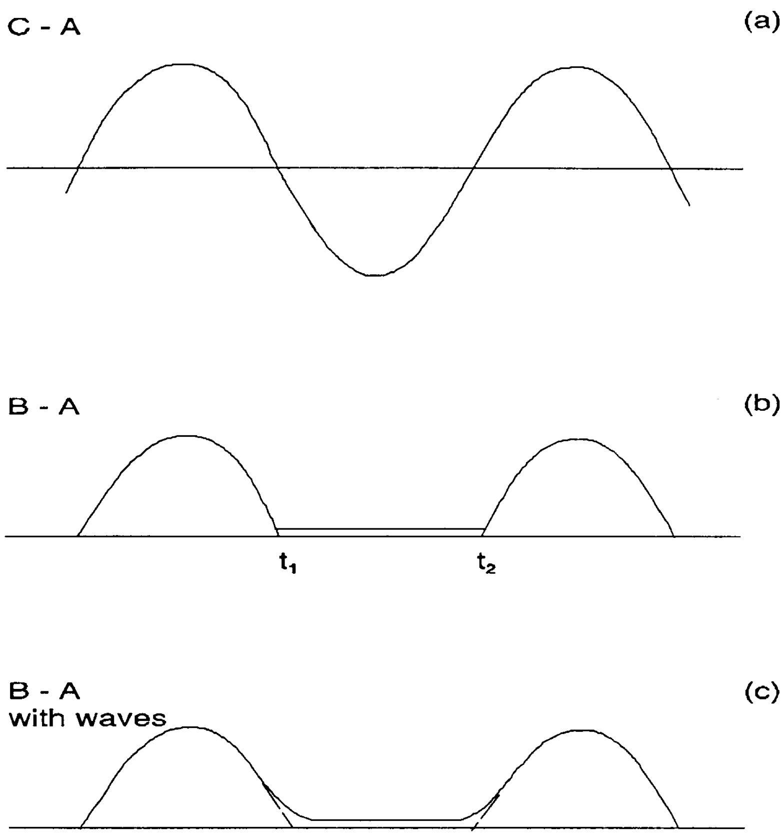
Schematic illustration of a pressure gauge setup containing three pressure transducers

In the present experiment, another pressure gauge 'B' is placed at 'datum B' (Figure 2.5) which is a datum approximately at mean sea level. Datum B would be geodetically connected to the local levelling network (Carter et al., 1989) and, it will be seen, will supply a sort of Tide Gauge Zero. The essential feature is that, while any pressure measured by a sensor at B will also contain an offset, and maybe a drift, the vertical height of its effective pressure point can be positioned at datum B very accurately. So, although it is not known absolutely *how much* it is measuring to within perhaps a few millibars (i.e. to within a few centimetres), it is known *where* it is measuring it to millimetric precision.

Figure 2.6(a) shows schematically the C-A record while Figure 2.6(b) shows the B-A record with the assumption of no waves. Initially, the datum of each record will be unknown. Of course, the latter is the same shape as the former, except that as the still water level drops below datum B the curve of Figure 2.6(b) bottoms out generating an inflexion point at the steepest part of the tidal curve at times 't1' etc. The flat part of B-A and its inflexion points will provide an extremely precisely defined shape which will be immune to any problems with datum offsets and low-frequency instrumental drifts. Our computation now involves overlaying the full curve of Figure 2.6(a) on to 2.6(b) using the top parts of the tidal cycles. Then the intersection of the flat line with the full curve can easily be computed, and the corresponding C-A values redefined to be at datum B. In other words, the datum has been transferred.

What about a more realistic situation with waves? Figure 2.6(c) shows that the sharp inflexion points might become rounded by waves, and it will not be until the wave crests have fallen with the tide below datum B that the curve will bottom out properly. However, this should not be a problem, provided that the waves are not too large, as Figure 2.6(c) can still be matched with 2.6(a) with the flat bit extrapolated on to the full curve. In practice, the matching can easily be done by least squares fit with a software algorithm designed to leave the area of the rounded inflexion points out of the computation.

This procedure is analogous to the function of the mechanical and acoustic water level switches used by the UK TGI. However, a switch acts at an instant and may go off prematurely with waves around. The 'software switch' here is the several hours of the bottom-out of B-A and is, in effect, a time-averaged discrimination of C-A. The rounding of the inflexion points due to waves will not bother the method in general but, as we are interested here in using B to establish a datum at regular intervals, rather than obtaining a continuous time series, the data of high wave days can simply be ignored. (Obviously we want a continuous record from C-A). High wave conditions might be identified from the degree of rounding at the inflexion points, or the digiquartz of C could be made to record at 1 Hz or higher frequency to measure them. 'B recording' may be intermittent at some sites owing to environmental or operational restrictions, and recording could be a feature of visits to remote



(a) the tidal curve produced from the C-A pressure time series;

(b) the ideal B-A time series showing inflexion points 't1' and 't2';

(c) the B-A time series possibly distorted by the presence of waves.

Figure 2.6

Schematic illustrations of time series comparisons islands or summer stays at polar bases. In our experience, such a procedure might be adequate to provide long term datum control to a continuous C-A record, as long as good (i.e. previously tested, relatively stable) transducers were used and the visits were at least once every year. However, where possible, it would be desirable to have the B sensor installed permanently as there is great appeal in being able to check the datum with every low tide (i.e. twice a day in most places).

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

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

To summarise, the most important feature of the method is its ability to impose a datum as a function of time and its ability to handle slow drifts in any, or all, of the A, B and C transducers. As any drifts will manifest themselves as changes in the vertical conversion factor to impose the curve of Figure 2.6(b) on to that of Figure 2.6(a), they can be continuously adjusted for by constant constraint of C-A to the B datum imposed by the least squares adjustment.

2.5.2 EXPERIMENTAL RESULTS

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

Since the 1991 Holyhead experiments, purpose built equipment based on the same principle has been constructed for the digiquartz-in-the-sea technique for use at South Atlantic sites where the mean range is typically 1 metre. It is intended that these will be operating at least two sites in the second half of 1992. Some of the 'A Class' bubblers around the UK will also be modified along these lines. POL would be interested in working with any group which might be interested in jointly developing this technique.

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