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 Bench Marks

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 **bench mark** is used as the primary reference point. A bench mark is a clearly marked point located on a stable surface such as exposed rock, a quay wall or a substantial building. When a bench mark 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 bench marks are tied into the national levelling network, and periodically checked with respect to that network. The bench marks 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 bench marks 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 Bench Mark (TGBM)

The **Tide Gauge Bench Mark (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 Bench Mark (GPSBM)

The **GPS Bench Mark (GPSBM)** is another special mark of the available set which is the reference mark for GPS measurements near to the gauge. It 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 'bench mark', 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 bench marks, 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, 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 bench mark. 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 Bench Marks

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 levellings may be necessary.

Levelling should be performed with a good quality level and staff by personnel familiar with the best practices of the technique. 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 bench mark 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 summarises 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 Coordinates 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 coordinates 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) organised 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 organising 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 coordinates 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 organised 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 organisation 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 prioritisation 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 organisational 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 organisation 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 defence 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 µgals 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 µgal/cm. In practice, for crustal deformation work, since a large area of the Earth's surface is usually displaced simultaneously, the measured gravity change is of the order of 2 µgal/cm. Thus, it can be seen that absolute gravity and 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

Technique	Distance: Accuracy
(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

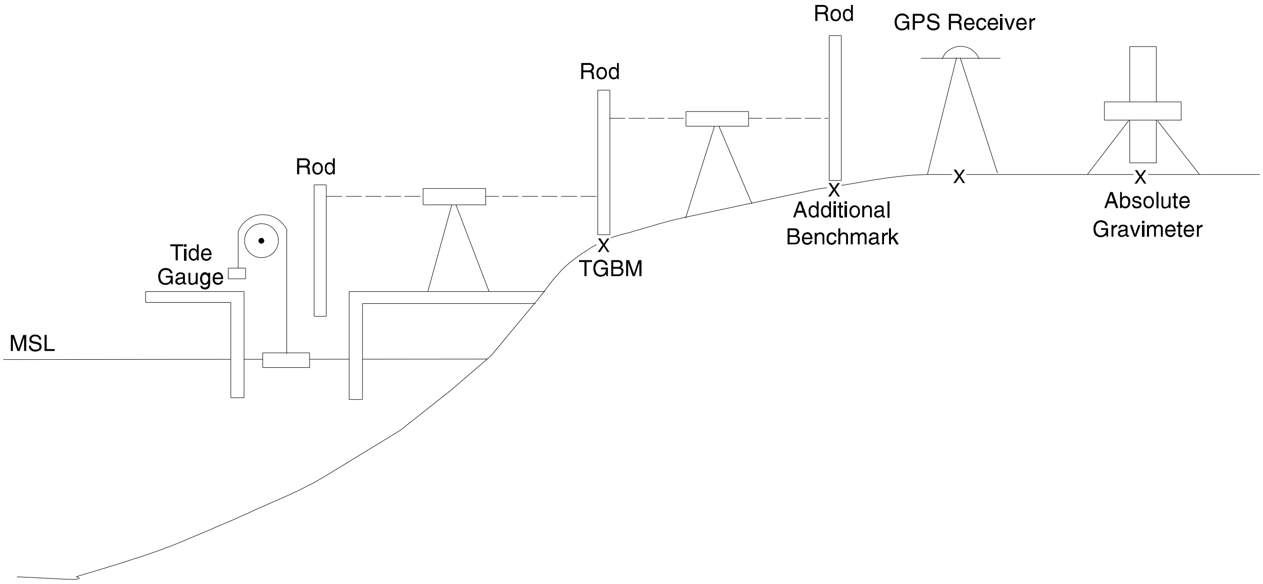

Figure 4.1 Schematic of GPS and absolute gravity at tide gauges