4. LEVELLING

4.1 GEODETIC FIXING OF TIDE GAUGES

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

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

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

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

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

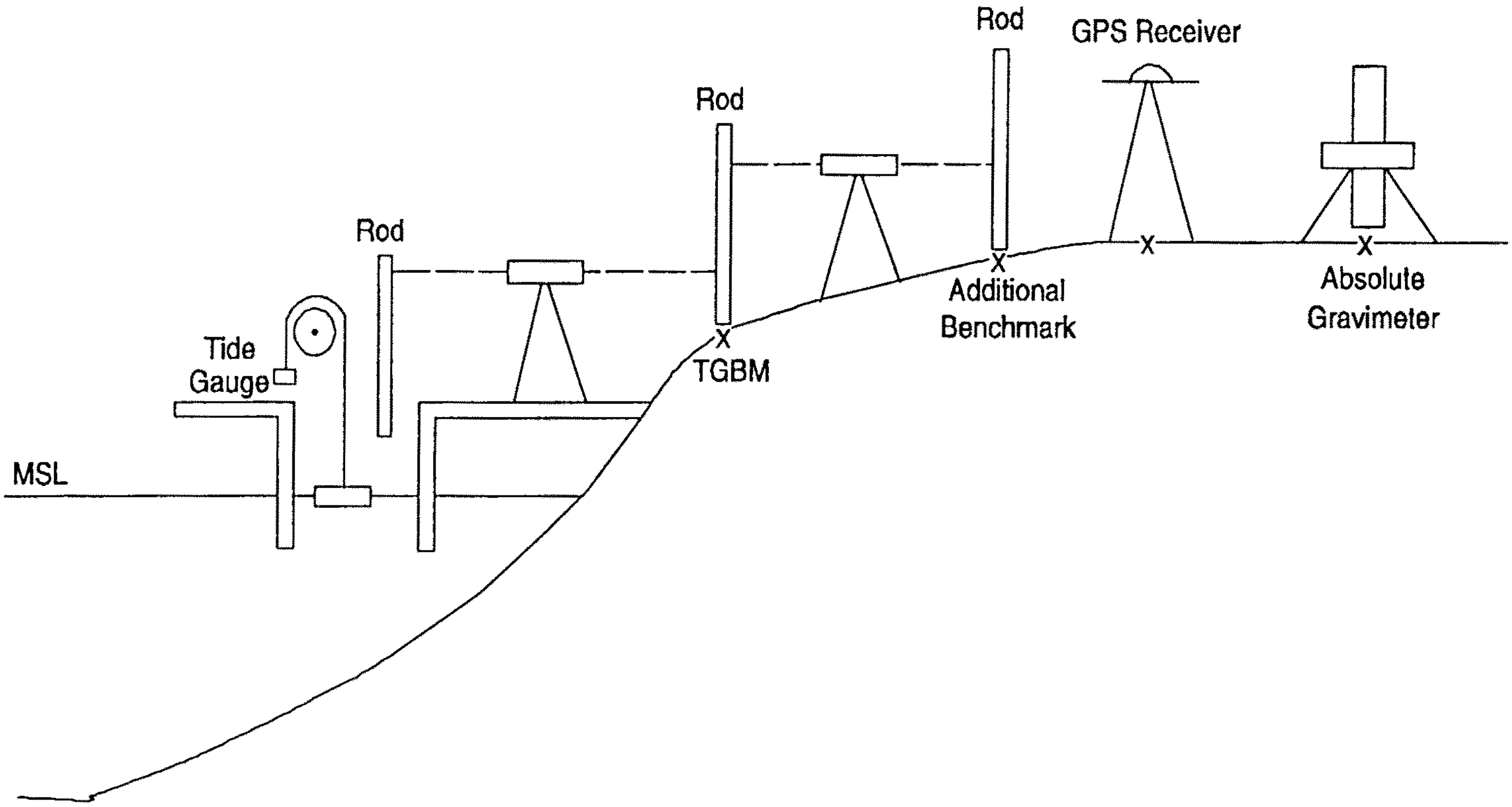

Figure 4.1

Schematic of tide gauge to measure absolute sea level

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

Table 4.1

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

4.2 GLOBAL POSITIONING SYSTEM

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

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

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

4.3 ABSOLUTE GRAVITY MEASUREMENTS

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

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

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

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

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