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# A PERMANENT STATION FOR THE ABSOLUTE DETERMINATION OF GRAVITY APPROACHING ONE MICRO-GAL ACCURACY

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## ABSTRACT

This paper describes the first permanent station for the absolute determination of gravity at the International Bureau of Weights and Measures. The station presently consists of an absolute apparatus of a few micro-Gal accuracy based on a symmetrical free rise and fall observation of a corner reflector in vacuum. Periodic determinations of g by the apparatus permits one to monitor the small variations of g arising from the Earth tide and various geophysical causes including the secular effects. The principal sources of errors in the apparatus are discussed and it is predicted that a final accuracy of 1 μGal can be obtained by the symmetric free rise and fall principle, provided that the local Earth tide and the vertical gradient of g are measured with sufficient accuracy. A tendency of the secular variation of g of the order of 10 μGal per year is reported. An Earth tide recording gravimeter and a transportable absolute gravity apparatus, both of which have recently been completed at this station, are also described.

## 1. Introduction

Since the centre of gravity of the Earth is difficult to determine with sufficient accuracy from the terrestrial stations, the modern techniques for the absolute determination of g (presently accurate up to a few micro-Gal) (SAKUMA 1971) have been considered as the most reliable means of monitoring the variations of the physical condition of the Earth, e.g., secular change of g, sea level, tectonic motions, etc. Thus it has been proposed (LEVALLOIS 1971) and recommended by the International Association of Geodesy (IAG RESOLUTIONS 1971) that permanent stations be established for absolute gravity measurements on different sites of the Earth.

Presently there exist two stations for this purpose; the first has been in operation since 1967 (TRAVAUX IAG 1968) at the International Bureau of Weights and Measures (BIPM), Sèvres, FRANCE, while the second is being constructed at the International Latitude Observatory, Mizusawa, JAPAN. Several other future sites are also foreseen. This paper presents the present state of the BIPM Station where improvements in the accuracy of the apparatus have been continuously made in parallel with the periodical measurement of g. The aim of this work is to attain a final accuracy of one micro-Gal. When this accuracy is assured, new possibilities, such as an absolute determination of the Earth tide, crustal deformation due to air mass, polar motion effect on the variation of gravity and so on, will be open in geophysical studies.

## 2. Principle

The single principle involved in the ultimate absolute determination of g to better than 1 part in $10^8$ is the observation from an inertial reference point of free fall motion in the gravity field. In comparison with, for example, the simple free fall method, the method of symmetrical free rise and fall (VOLET 1947) is the most promising due to its inherent high precision and its relative freedom from systematic errors such as air resistance, timing errors, etc. In this symmetrical free rise and fall method, employed at the BIPM Station, an object - a corner reflector - is projected vertically upwards and crosses two defined horizontal stations : $S_1$, $S_h$ whose separation H is known. Two independent time intervals corresponding to the upward and downward passages across each station : $T_1$, $T_h$ are measured and the value of g is obtained from

$$g = \frac{8H}{T_1^2 - T_h^2} \quad (1).$$

If the vertical gradient of g is constant along the trajectory, the value of g obtained from equation 1 corresponds to that at height

$$Z = \frac{H}{6} + \frac{h}{3} \quad (2)$$

downward from the apex of the trajectory, where h is the distance between the apex and the upper station.

In spite of its principal advantages, this symmetrical method has been employed only by three standard laboratories :

- National Physical Laboratory, England ( COOK 1967);
- National Standards Laboratory, Australia (BELL 1973); and
- B I P M, France.

The main reasons preventing the use of this method are that the launching of an object in vacuum with severe limits of rotation and vertical deviation of the trajectory, is much more difficult to realize than the simple free fall, and that the mechanical shocks caused by the launching of the object are liable to produce an additional disturbance of the observation by which the advantage of the method may be cancelled out. Thus the two essential problems to be resolved for high precision absolute gravimetry are

1) how to correctly launch the projectile; and
2) how to realize an inertial reference point which is free from shocks, ground motion and other perturbing effects.

These problems become predominant at a level of accuracy of 0.1 mGal and these have been the key points for the gravimetry at BIPM on which important efforts have been made.

## 3. Description of the Apparatus

The essential part of the absolute gravity apparatus at the BIPM is a Michelson type interferometer in vacuum (figure 1). A corner reflector forming one mirror in the vertical beam of the interferometer is used as the projectile. The two horizontal stations are installed in the trajectory as the conjugate planes of two mirrors forming an end standard of 0.8 m length made of fused silica, placed in the horizontal beam of the interferometer.

The timing signals, which are white light fringes with a half width corresponding to a vertical displacement of 0.06 µm of the falling corner reflector, are detected by a photomultiplier when the optical path difference between the horizontal and the vertical is null. The frequency of the fringes is very high, about 30 MHz; in addition the effective surface of each mirror is made very small, 0.2 cm$^2$, in order to assure a highly planar surface on the mirrors and to avoid the intersection (roof) of the two orthogonal mirrors. Furthermore the solid angle of the light source seen by the interferometer is made small in order to get good parallelism of the light beam in the long trajectory. Thus an ordinary white light source is not sufficient to give a good S/N ratio (∿ 40 dB) for the fringes, and so a xenon flash lamp is synchronously triggered with each passage of the corner reflector at the two stations in upward and downward motions (SAKUMA 1963).

### 3.1 Length Measurement

The length of the end standard of 0.8 m is determined by direct comparison with the primary standard line of a Kr86 lamp in the same interferometer used for the measurement of g (figure 1). The use of the same interferometer for the two measurements eliminates several sources of the systematic errors due to the individual difference of interferometers, lack of flatness, difference of aperture, phase shifts in thin film, effects of polarization and so on. For this length measurement, the movable corner reflector in the vertical beam is fixed midway between the two stations so that the conjugate plane of the end mirror in the vertical beam is formed in the horizontal beam at the centre of the two mirrors of the end standard. Thus the length of the standard is obtained as the addition of the two distances measured by the intermediate of the conjugate plane with 0.8 m optical path difference.

For the phase determination of the standard, the horizontal optical path is finely modulated by the piezo-electric element: PZT.1 on which a corner reflector is fixed. This fine optical path length modulating device is also used for the fine adjustment of the symmetry of the white light fringe

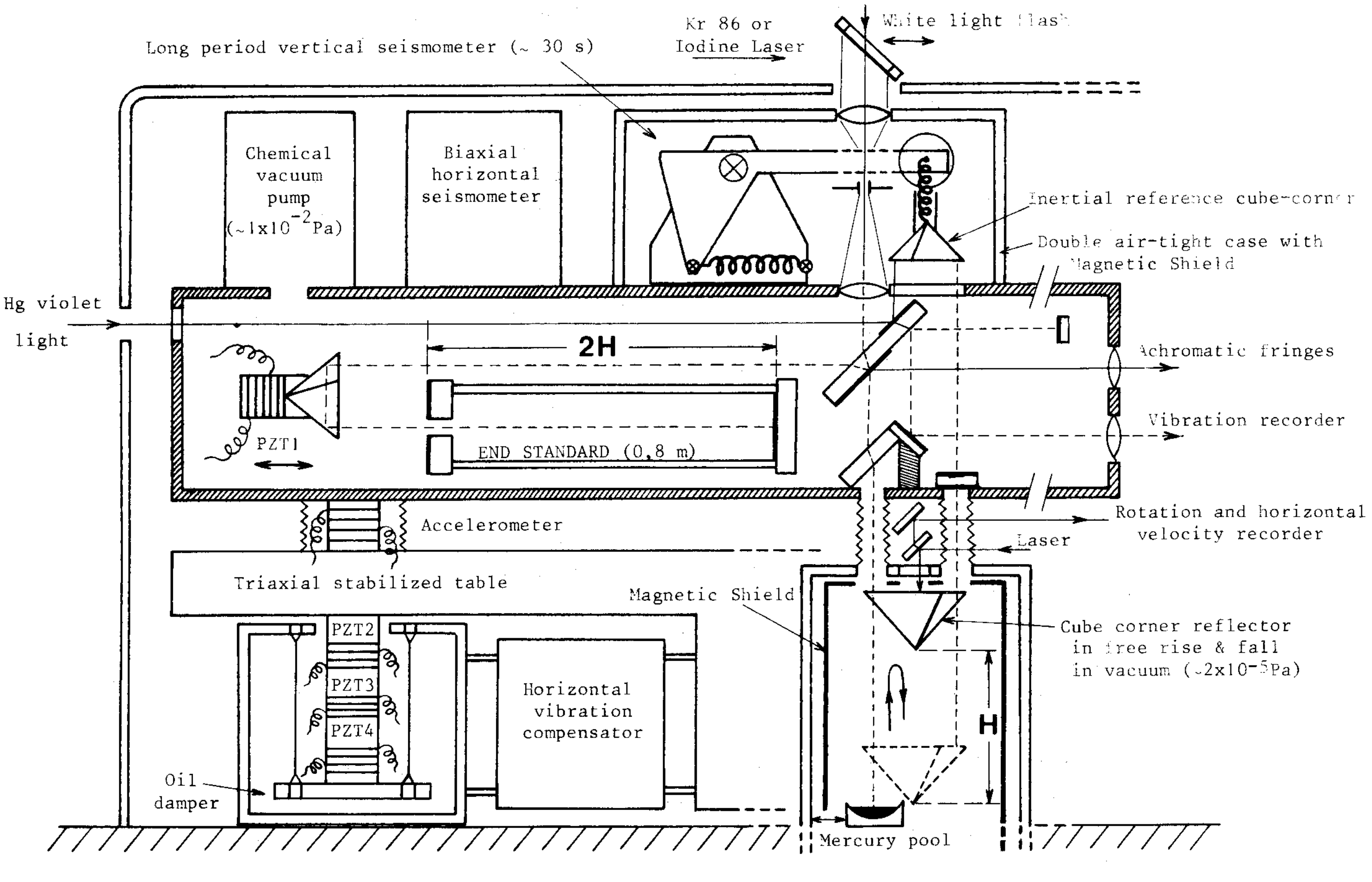

Figure 1. Schematic Diagram of the Absolute Gravimetry Apparatus at B I P M.

pattern and for checking the alignment of the interferometer. Because of the large optical path difference of 0.8 m, the visibility of the interference of the Kr86 primary standard line decreases to only 5%. Nevertheless, by using a low-noise photomultiplier cooled to -50°C, the length of the standard can be measured with $1 \times 10^{-9}$ precision. This high precision length measurement was the first experimental proof that the present metre definition by Kr86 has a reproducibility of one part in $10^9$. This proof was reconfirmed (CCDM 1973) recently by several standard laboratories when the new wavelength standard became available. This improved standard which uses saturated molecular absorption lasers ($^{127}I_2$ laser for example), gives a precision of $1 \times 10^{-10}$. A determination of the wavelength of an iodine stabilized laser made recently by the g apparatus gave

$$\lambda(^{127}I_2,\text{"g"}) = 632\ 991\ 231.1 \pm 0.6 \text{ fm}.$$

The uncertainty in the wavelength ( $1 \times 10^{-9}$) comes from the uncertainty of the Kr86 standard. This value is in good agreement with the value:

$$\lambda(^{127}I_2,\text{"g"}) = 632\ 991\ 231.0 \text{ fm}$$

recommended by the 5th Consultative Committee for the Definition of the Metre (June 1973 at BIPM). Thus this good agreement of the wavelength shows that the length measurements made in the gravity apparatus at BIPM did not contain a systematic errors exceeding $1 \times 10^{-9}$. (Moreover the use of this new wavelength standard greatly facilitates the length measurement in the apparatus, in addition to increasing the absolute stability of the unit of length up to $1 \times 10^{-10}$.)

The obliquity correction must be applied for the length measurement by the interferometric method. This correction is due to the curvature of the interference wave caused by a finite dimension of the light source and in the present apparatus, the theoretical correction attains 2.8 parts in $10^8$ of the length standard. This correction agrees with the experimental result obtained by the extrapolation to null dimension of the light source with 2% accuracy. The resulting uncertainty of the length standard is $\pm 6 \times 10^{-10}$.

The inhomogeneity of illumination in the interferometer, combined with the lack of flatness of the mirrors also causes a systematic error in the length measurement but this effect can be verified experimentally and reduced to below $1 \times 10^{-9}$ in the standard. Thus it is presently possible to determine a length standard of around 1 m with an accuracy of 1 part in $10^{-9}$.

## 3.2 Projectile and Catapult

Figure 2 shows schematically the composition of the projectile and the catapult. The projectile (figure 2.1 and figure 3) is composed of a pair of corner reflectors, 10 cm high, weighing 430 g, arranged back to back with their apices at the same point so that the optical centre of a corner reflector coincides with the centre of gravity to within 10 µm. The three mirrors of each corner reflector are fixed on a duralumin support in which the six holes are made every sixty degrees around its vertical centre axis to let pass freely the light beams of the interferometer. This duralumin support also has a central hole in the vertical direction and the top of the hole is slightly tapered. This tapered top of the projectile rests before launching on a conical piece (4) attached at its top to the elastic cord (3) of the catapult and at its bottom to a cylindrical piece (6) by means of the nylon wire (5). The piece (6) is also attached to a weak elastic cord (7) so that (6) moves always in the vertical direction. Before launching, the projectile sits on an elevator table (8) and is turned around its vertical axis so that the light beam (2) falls correctly in a specified hole.

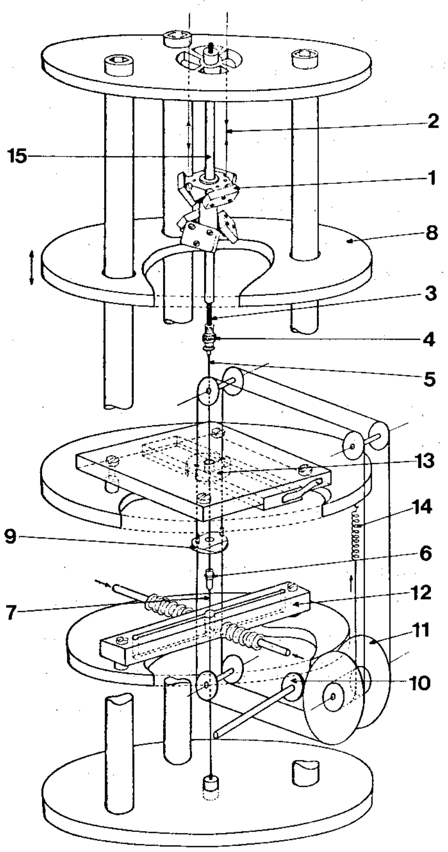

Figure 2. Schematic Drawing of the Catapult with the Corner Reflector in Flight

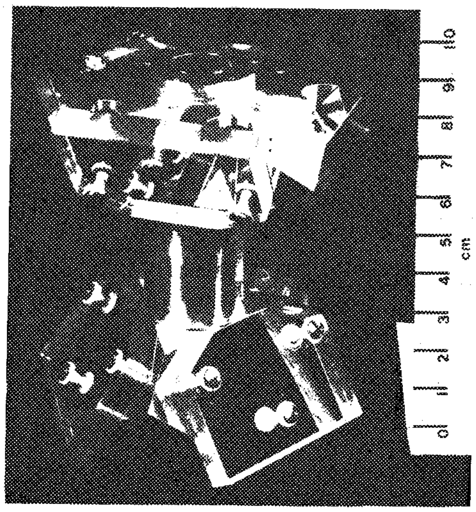

Figure 3. Projectile: Double Cube Corner Reflector for Absolute Measurement of Gravity
430 g. right angle $\pm 5\ \mu$rad
flatness: $\sim \lambda/50$ on $\phi = 12$ mm

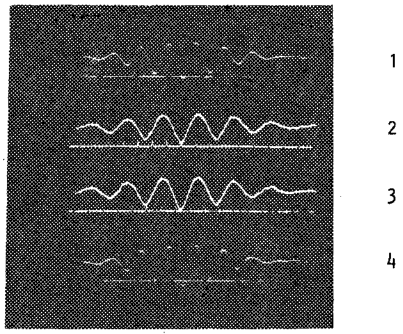

Figure 4. Four White Light Fringes with 20 MHz Time Base
1 & 4: Rise and Fall at Lower Station with increased sweep speed
2 & 3: Rise and Fall at Upper Station with Normal Sweep Speed

Then the table (8) goes down slowly and leaves the projectile hanging on the conical piece (4). An annular piece (9) placed co-axially with the wire (5) can be displaced vertically by rotating a shaft with clutch (10) and by a pulley (11). By these mechanisms the piece (6), guided by the ring (9), is engaged into a hole of the release (12) by the pressure of compressed air. Then the ring (9) goes up to be locked into a fixed stage (13) and the shaft (10) is declutched. When the piece (6) is released, the projectile is accelerated by the traction of the elastic cord (3). After an accelerated rise of about 0.3 m, the piece (6) touches and is stopped by the fixed stage (13). Likewise the conical piece (4) is also stopped so that the projectile enters in its free rise. By the shocks given by the piece (6) to the fixed stage (13), the locked ring (9) is liberated and it sits on the piece (6) by the downward traction of the spring (14). After the free rise and fall, the projectile (1) falls on the piece (4) and the elastic cord (3) is stretched. During this braked fall, the two pieces (6) and (9) follow this downward motion of the projectile by means of the traction of the spring (14). During this motion, one friction disc in the pulley (11) absorbs the kinetic energy so the projectile is stopped smoothly without rebouncing.

This catapult throws the projectile while giving it a rotation of less than 0.01 rad per sec, and with a horizontal velocity of $\sim$ 0.2 mm per sec. The mass of the moving part of the catapult is only 20 g and there is no moving element during the free rise and fall of the projectile. Moreover the whole of the catapult is mounted on a vibration absorber. Therefore the mechanical vibration due to the operation of the catapult is much smaller than the ground motion. At the beginning of the free rise, the projectile is observed to oscillate longitudinally with 18 kHz and 0.04 μm amplitude, but this oscillation decays rapidly with a 6 ms time constant. Therefore a free rise time of 50 ms (18 cm rise) is allowed before entering the lower station of the g measurement. After this decay time, the free oscillation is less than 0.1 nm amplitude. The catapult is adjusted so that at the apex of the normalized trajectory, the optical centre of the corner reflector rises vertically 5 cm above the upper station (45 cm from the lower station). In this normalized flight the four white light fringes appear every 0.2 s and this periodicity is convenient to change uniformly the capacitances of the xenon flash tube. The elastic cord (3) produces some electrostatic charge by its contraction. This effect on the projectile (1) is avoided by a metallic tube (15) placed around the elastic cord. This electrostatic shield by the tube (15) maintains a constant capacitance of $\sim$ 20 pF of the projectile against the Earth during the flight. Due to this constancy of the capacitance, the effect of electrostatic force on the projectile in flight is confirmed to be negligible, even though the projectile is charged artificially up to several hundred volts.

### 3.3 Stabilized Table and Inertial Reference

The anti-vibrating devices employed for the gravity measurement are shown in figure 1.

The Michelson interferometer in the horizontal vacuum chamber is mounted on the suspended table by metallic wires. This wire suspension with oil damping attenuates the horizontal acceleration due to the rapid ground motion (> 5 Hz) over thirty times. Thus the relative vibrations of mirrors in the interferometer become negligible (< 0.1 nm). For vibration control in the vertical direction, an electronic feed-back device is used between the vertical accelerometer and the piezo-electric driver PZT-2, so that the output of the accelerometer tends to null. By means of this device the rapid ground motion (5 Hz $\sim$ 50 Hz) is attenuated over ten times without using a soft suspension (spring) which is liable to derange the vertical and the horizontal position of the interferometer. The other piezo-element PZT-3 is driven by an auxiliary long-period vertical seismometer to compensate the long period microseisms due to the ocean waves (0.15 $\sim$ 0.3 Hz). Another piezo-element PZT-4 is used for the fine adjustment of the horizontal of the table against the instability of the concrete piers. The residual vibration of the interferometer with respect to the corner reflector suspended by a long period seismometer is measured and recorded during the gravity measurements. This seismometer is carefully protected from the variation of the terrestrial magnetic field due to traffic, microbarometric pressure change and the temperature drift. The horizontal acceleration due to the ocean waves also excites this vertical seismometer because of weak coupling between the two directions, so that a horizontal compensator is presently being made.

The residual acceleration of the inertial reference corner reflector is presently ∿ 2 μGal (1 second average) and 0.5 μGal is expected in the near future.

### 3.4 Time Measurements

The time intervals of the flight, 0.6 s at the lower station and 0.2 s at the upper station, are measured in two steps. First, 50 ns resolution is obtained with 20 MHz counters. Next, 0.1 ns resolution is achieved by means of a photographic record of an oscilloscope display of the white light fringes with a 20 MHz time base (figure 4).

In order to assure sub-nanosecond accuracy, careful checks of the chronographs are required. These checks test the perturbation due to the gate operation, the effects of standing waves due to impedance mismatching, non-linearity of the oscilloscope sweep, fluctuation of the electron transit in the photomultiplier, parallax in the photographic record, time base jitter, and so on. Presently, the time measurements are accurate to 0.2 ns to 0.6 ns for a corresponding uncertainty of 1 μGal in g. This is due principally to the noise of the white light fringes. This uncertainty will be improved in the future by a factor of two (0.5 μGal). Practically, the chronographs are designed for three successive time measurements: $T_r$, rise time in crossing the two stations; $T_h$, up and down crossing at the upper station; and $T_f$, fall time crossing the two stations. By comparing the two times $T_r$ and $T_f$, the coefficient of the residual air resistance on the projectile can be determined as a function of the pressure in vacuum chamber. By virtue of the symmetrical free fall, the air resistance effect on the value of g was negligible up to 1 Pa (CIPM 1970). On higher vacuum, < 0.05 Pa, the time difference

$$\Delta T = T_f - T_r$$

was found to be proportional to the pressure with a coefficient of +16 μs per Pa. Therefore the pressure variation should exceed no more than $1 \times 10^{-5}$ Pa during the free rise and fall of the projectile to ensure that the influence of air resistance on g is less than 1 μGal. Fortunately, the pressure variation due to outgassing because of the operation of the catapult in a vacuum of $2 \times 10^{-5}$ Pa was within the limit of the sensitivity of a vacuum gauge; that is $\leqq 2 \times 10^{-6}$ Pa. Thus the effect of air resistance is negligible (< 0.2 μGal) for the measurements of g when the symmetrical free fall is employed. The time difference for an ideal vacuum was obtained by an extrapolation to be

$$\Delta T_{po} = +5.3 \pm 0.5 \text{ ns.}$$

This residual time is explained by the velocity of the light c. The white light fringes at the lower station arrive at the photodetector after travelling an additional distance of

$$2H = 0.8 \text{ m} \quad (2.67 \text{ ns times c})$$

compared with the white light fringes at the upper station. So the measured rise time is decreased by 2.67 ns, and the measured fall time is increased by the same quantity, resulting in a measured time difference of +5.34 ns. This time delay has no influence on the value of g in the case of the symmetrical free fall method, but in the case of simple free fall, this correction due to the finite velocity of light must be applied.

The observation of this time difference of +5.3 ns confirms the accuracy of the time measurements. In addition, the comparison of this time difference obtained in each measurement of g permits the detection of accidental perturbations which may occur during the experiment.

## 3.5 Earth Tide Recording Gravimeter

The gravimetric Earth tide perturbs the mean value of g by as much as +110 μGal and - 160 μGal, with a maximum gradient of ±0.8 μGal per minute at the BIPM station.

Therefore it is necessary to know the correction for the Earth tide with 0.5% accuracy in amplitude and 1 minute accuracy in phase (0.5 degree phase accuracy for the semi-diurnal waves) in order to compare the mean value of g from day to day with 1 μGal accuracy. On the other hand, a systematic phase delay of several minutes has been identified in the theoretical Earth tide by comparison with the absolute determination data. For these reasons, a new Earth tide station has been completed in October 1973 at an underground site 40 m north of the absolute station of the BIPM and the existence of the phase delay of the theoretical tide has been confirmed by this apparatus. The principal part of the apparatus is an old gravity meter, type Western (< 1956), modified at the BIPM so that the Earth tide can be measured with a short response time (∿ 20 s) by a null method using a symmetrical electrostatic compensation of the tidal force. This apparatus has been installed on a stabilized table in a constant pressure well with an optimum temperature control (∿ 0.01 mK). The instrumental drift is presently found to be +3 μGal per day. This combination of the two types of gravity apparatus, absolute and relative, is of mutual benefit; the real correction of the Earth tide now becomes available for the absolute apparatus, and the absolute apparatus gives the possibility to study and calibrate the long term drift of the relative apparatus.

## 4. Experimental Results

All experimental results of the absolute determination of g since October 1966 are shown in figure 5. The significant discrepancies of 20 ∿ 40 μGal are noted, especially that between the data of 1969 and that of 1972-1973. These differences in g are still unexplained.

In spite of careful verifications of the absolute apparatus, no instrumental drifts of such magnitude have been identified up till now. The variation of the underground water table was surveyed for this period with the collaboration of the Bureau of Geological and Mining Research (BRGM), Paris, but no correlation was found.

Several more years will be necessary to clarify the observations in figure 5, but when the data prior to 1969 are taken into account, the minimum value of g appears around 1969. In the same year, the tidal wave of 18.61 year period due to the Moon's nodal regression also passed its minimum value. The calculated variation of g due to this wave is only 4 μGal peak-to-peak at this station and the correction due to this wave is already applied to the data of figure 5. On the other hand, it is said that the response of the Earth to this long period (18.61 years) wave is not yet well understood (MICHELSON 1973). Furthermore, in view of the fact that geyser activity and polar motion observations also indicate 19 year periodicity (NOAA 1972; OKUDA 1968), this tidal wave motion probably affects the Earth much more strongly than classical tidal theory indicates.

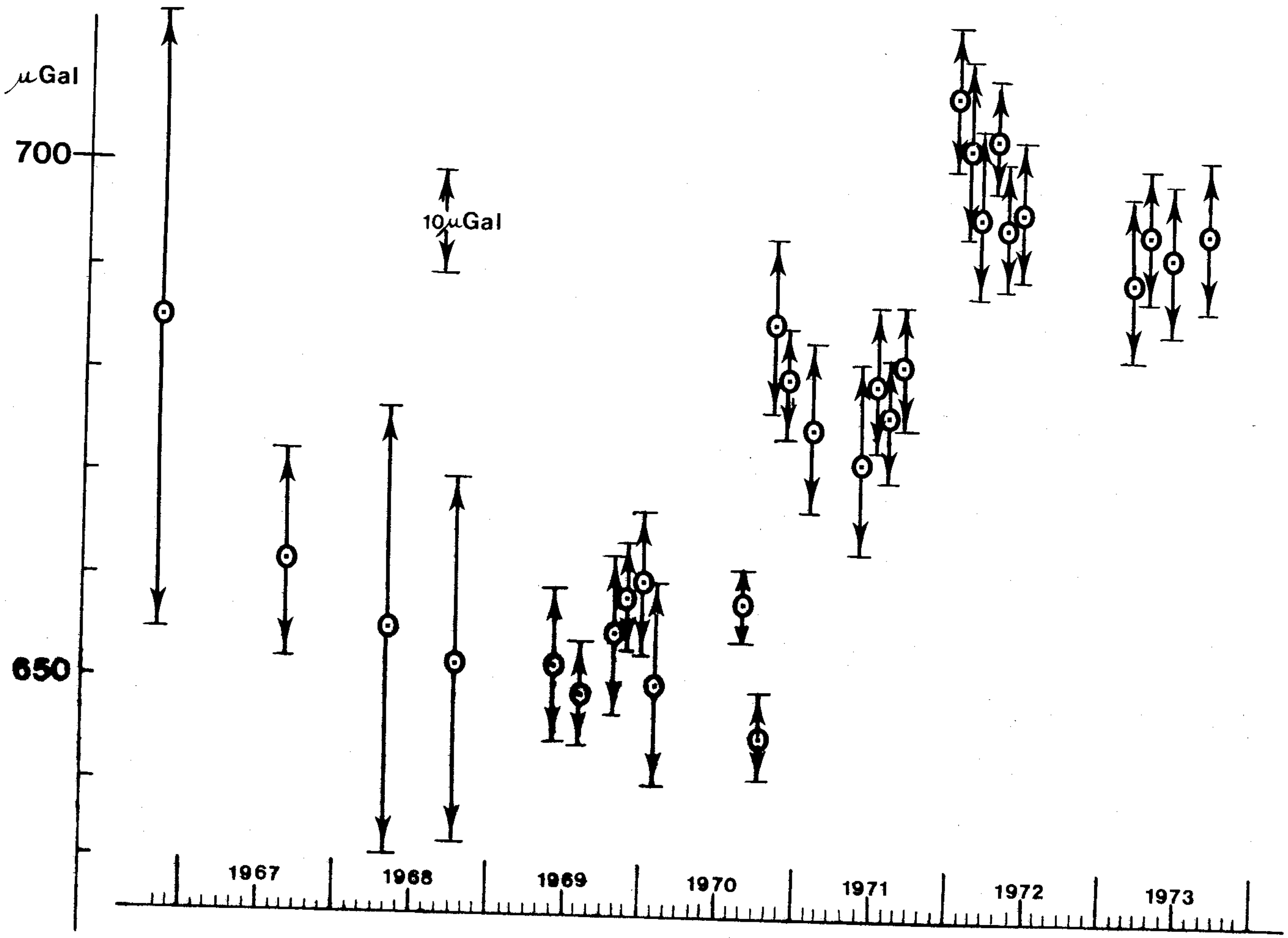

Figure 5. Monthly Mean of Absolute Value of Gravity with Scatter of Single Measurement at SEVRES POINT A2 (Apparatus Site).

B I P M : $g_{A2}$ = 980 925 000 μGal + Values on Graph

## 5. Transportable Absolute Gravity Apparatus

This apparatus, constructed by the National Institute of Metrology (IMGC), Torino, Italy, with the technical assistance of the BIPM, also employs the principle of symmetrical free rise and fall. The instrumental details of this apparatus are very similar to those of the fixed apparatus at the BIPM. Nevertheless, it is worth noting three differences which facilitate the transportation of the instrument and the calculation of g, namely:

1) The determination of g is made in a low vacuum of about 0.1 Pa for which the secondary vacuum pump is not required;
2) Instead of the end standard of length, a stabilized laser is employed with a reversible interferometric fringe counting method; and
3) The vibration effect is compensated automatically by an inertial reference corner reflector forming itself the end mirror of the horizontal beam.

This apparatus, 1.4 m high and with a 0.5 × 0.5 m section, consists of two separable main parts; a Michelson interferometer in a pressure tight case weighing ∿ 40 kg, and a catapult in a vacuum cylinder weighing ∿ 60 kg. This apparatus can be transported in a small truck.

A first preliminary result was recently obtained by this apparatus, transported to the BIPM and installed on a pier where the value of g is already known. The mean value of 25 measurements of g (about one hour) was in agreement to within ±0.02 mGal with the value obtained by the fixed apparatus.

A final precision of 0.01 mGal will be obtained by this transportable apparatus and its accuracy and repeatability will be checked by the fixed apparatus of the BIPM.

This apparatus has been of interest to several geophysical and standards laboratories for their studies. So a project for its industrial production by a French firm is presently in progress. This kind of apparatus will be useful not only for the creation of absolute stations and for the calibration of the gravity net, but also, by means of periodical gravity ties by the apparatus, for the study of the global evolution of the gravity field of the Earth.

## 6. Conclusion

The accuracy of the absolute determination of gravity is now steadily approaching one μGal and there are no further essential metrological difficulties preventing the realization of this goal. The results obtained at the absolute station of the BIPM have been significantly improved by the direct observation of the Earth tides and they no longer rely upon the theoretical calculation for the correction of this effect. Also, new observations of the underground water level will be started at the BIPM. Such activities lie in the domain of geophysical studies, but it is nevertheless the responsibility and interest of metrological laboratories such as the BIPM to confirm that the apparatus functions correctly. With such an apparatus to provide accurate data, geophysicists can then make the interpretations necessary to arrive at a better understanding of the Earth.

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## 8. Discussion

HOPKINS: It seems to me that in the measurement of absolute gravity, we are using length standards and time standards using hyperfine transitions which themselves use the value of g. Aren't we involving something we are looking for in the search?

MARKOWITZ: The value of g does not enter directly into the present quantum definitions of the units of either length or time. The possible variations in **g** are too small to have any significant effect.

(For a "conversation" by **D.** ECKHARDT on developments in absolute gravimetry at the Air Force Cambridge Research Laboratories, Bedford Mass., see p.716)

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# DEVELOPMENT AND USE OF A TEST FACILITY FOR COMPARING LONG-LENGTH STANDARDS

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## ABSTRACT

Secular variations in the Earth's shape can be measured by a number of ways of which direct length changes are the most obvious. A long-term program aims at the provision of basic knowledge about the stability of long-length (decametres) standards especially over ultra-long periods. To date, two generations of 10m test-base have been built and the stability o Invar and quartz standards tested to parts in $10^{12}$ per hour drift. A superior facility, currently under construction, enables both temperature and pressure to be controlled for 5m length devices. It is situated 300 m underground to make use of natural environmental control. Strainmeters, tested on these bases, have been installed to monitor rock strain: they have provided long-term data on the secular relative ground movement to parts in $10^{12}$ per hour uncertainty. The contribution of the program in its relation to surface geodetic survey are that improved techniques seem feasible to raise the accuracy of short bases beyond current EDM capability.

## 1. Metrological consideration of strainmeters

For a variety of reasons it is desirable to measure relative ground movements - continental drift, expanding earth, tidal studies and global shape changes come to mind. There exists many means by which this can be performed - EDM, taping, Viasala interference multiplication, VLBI, satellite triangulation, lunar ranging, strain and creep-meters, tilt and gravity variations and even visual inspection. Each has its own field of useful application in the study of the Earth.

Common to all is a necessary hierarchy of metrological requirements. Firstly, the process must possess adequate stability (or repeatibility, depending whether it is a continuous or discrete measurement process). The more stable the process the more that can be learnt within a given time-scale. Next, and only next, comes the need for accuracy of either the absolute interval length or of the differences in length.

The research reported here relates to the measurement of both relative and absolute values of intervals in the region of 1-100m. This includes earth strainmeters, metrological length standards for industrial and surveying practice and scientific strain meters for use in basic research such as gravity wave detection.

To date the emphasis of this program, conducted in the Cooney Observatory near Armidale in NSW, Australia, has been on the stability and installation problems of nanostrain extensometers. Here accuracy is needed to only a few percent compared with required stabilities of parts in $10^{10}$ or better.

## 2. The Need for a Stabilised Test Base

The easiest way to test the stability of a length standard is to mount it on a base-line that is more stable by an order of magnitude. This approach works well in the standards laboratory-to-industrial relationship but not so well in the standards situation where the ultimate standard is being improved - the new device could well be superior to the existing authority. An approach used to avoid this dilemma is to build two devices and compare them against each other. Provided systematic secondary effects are eliminated it is reasonable (but never totally certain) to suggest that one device alone exhibits no greater than the total drift observed. It is like the scientific basis - all is right until proven wrong. When identical devices agree there is room for some doubt as each could be systematically effected. A slightly better process is to use two different systems where possible, leaping from one to the other as the foundation for the next stage of development.

At present the international standard of length uses krypton radiation and provides knowledge of absolute length to within parts in $10^9$. It requires sophisticated equipment and demanding technique. Molecular absorption stabilisation of laser radiation is almost certainly about to replace krypton giving length reproduceability to parts in $10^{10}$. It is however, one thing to have basic stable radiation available and another to apply it to practical measurement: usually some basic accuracy is lost in the process.

Recent research has developed ways to apply mechanical length standards (quartz tube and tensioned-catenary) to rockstrain measurement with stabilities of parts in $10^{10}$ per hour drift. Theoretical considerations show that both mechanical and optical standards, given a controlled environment, exhibit similar practical and theoretical limits (three or four orders of magnitude difference at present) so which is the ultimate is really a matter of the point in time of development that the question is asked. In strainmeter designs, it is the relative stability that is vital, not the absolute length; this enables their performance to be pushed further in some respects than absolute standards.

The obvious way to research strainmeters is to set them up on a stable baseline - the Earth, for instance, or a geodetic-tape base. These suffice to parts in $10^7$ over short-time periods but this is totally inadequate for state-of-the-art nanostrainmeter research. Beyond this a new approach is needed. This program (the only of its kind) uses substantial steel structures that are length stabilised by controlling their temperature to fine limits. These bases are supported to be free of the influence of rock-strains.

## 3. Thermally-controlled Bases

In 1968 the need arose, in connection with an industrial 10m length measuring device, to provide a stable base of 12m length (SYDENHAM 1969) that could be used to determine the repeatibility of a wire-on-drum length measuring transducer to parts in $10^6$ over several months. The first design of base used (a cross-section is given in figure 1) internally-circulated water that was temperature controlled to 0.01K. It realised stability of parts in $10^7$ per day and parts in $10^6$ per annum being measured relative to tensioned Invar wires. This work indirectly led to a new form of earth-strain meter - the tensioned catenary design.

In 1971 the chance arose (in connection with the earth-strain program started in the Cooney Observatory at that time) to build an improved version of the 1968 measuring base, placing it deep underground (SYDENHAM 1972a).

Naturally improved thermal background stability and hanging arrangements realised milliKelvin control and for a while stability measurements were found to be limited (by inherent creep in Invar) to parts in $10^8$ per hour even after many months of waiting.

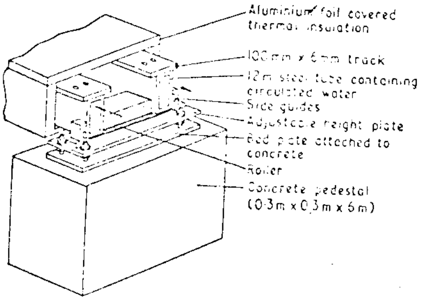

Figure 1. The first measuring base.

In 1972 the control system was improved (SYDENHAM 1973a) by distributing the heating throughout the 10m base, as shown in figure 2. At the same time the use of tensioned-quartz canes was made practicable and the combined result were several periods (of 100-200 hr duration) when the stability of quartz relative to the steel base held constant to within parts in $10^{11}$ per hour. Long term relative stability was also studied (IBID).

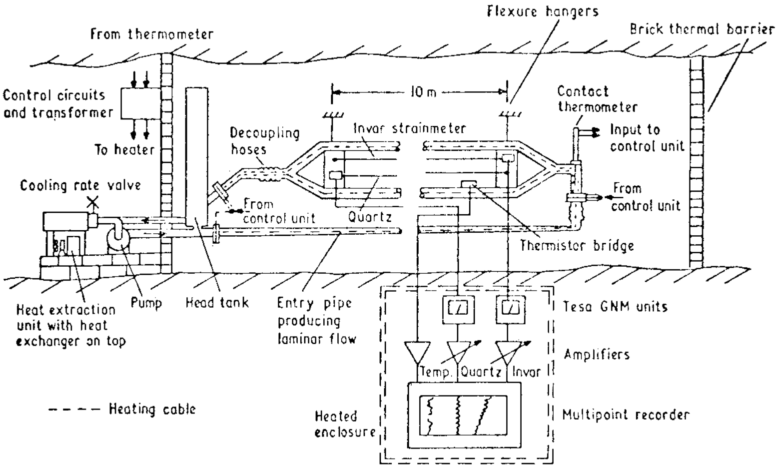

Figure 2. Cooney Observatory open-sided measuring base.

In early 1973 it was established that the random drift normally observed in the records was mainly caused by set-point instability in the contact-thermometer controller. The design was subsequently changed to use a micro-Kelvin sensitivity thermistor sensor as the proportional input to an industrial SCR controller; this greatly reduced the thermal fluctuations giving continuous average thermal stability to within ±2μK per hour drift. It is apparent that this can still be improved by an order of magnitude as the servo control system is not, as yet, tuned.

To date, it seems that instability in controlled temperature quartz and steel is still undetectable. This is discussed further, later in this paper. Figure 3 shows the drift of Invar and quartz.

In the middle of 1972 it became obvious that the control and design of the first base was inadequate - pressure on the standard could not be controlled and ambient thermals were not isolated sufficiently.

To overcome these disadvantages, and to provide a superior test base where both optical and mechanical methods could be intercompared to parts in $10^{12}$ or better, a new design was implemented.

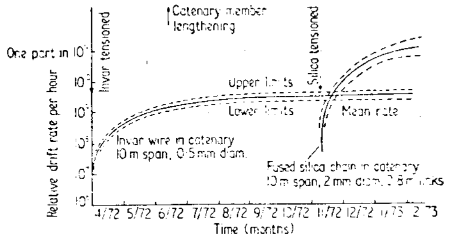

Figure 3. Drift of Invar and quartz relative to steel

The second design, designated the coaxial base, uses concentric cylinders of water to provide better shielding and has a double level, piggy-back, control, coarse on the outer, fine control in the inner jacket. The inner measurement chamber is supported on flexure diaphragms and by flotation.

The whole unit hangs from a single-point support with vibration isolation between the unit and the ground. It has been situated in a deeper underground chamber than the earlier version. It is envisaged that stability, down to natural Brownian limits, will be reached (parts in $10^{15}$). Figure 4 shows the side view.

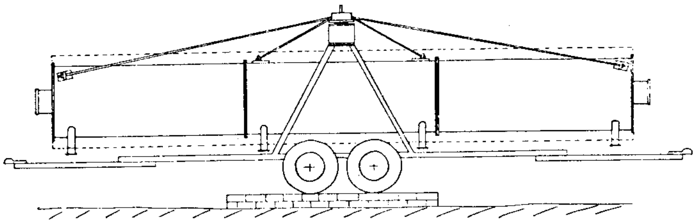

Figure 4. Side view of 5m, double-jacketed, coaxial measuring base

At the time of writing the coaxial unit was close to initial testing, but due to delay in the iodine absorption stabilised laser development it has not yet been used for intercomparison.

## 4. On Secular Earth Movement Measurement

The research program is designed to be integrated with earth-strain measurements. One long-term aim is to produce a strainmeter that can be used with the ease of a gravity meter (but for less expense). One example of this spinoff from the stabilised-base research was the logical deployment of a 10m quartz catenary strainmeter (sectioned in figure 5) alongside an existing 10m quartz-tube design (SYDENHAM 1972b). During 1973 they have both produced visually identical strain records (SYDENHAM 1973b) drifting relative to each other only 5 parts in $10^{12}$ per hour for a 500h period. The high fidelity enables the recorded secular drifts of the observatory area to be accepted with a high degree of confidence. It has been shown, in this way (figure 6) that the area undergoes quite large secular strain variations and that any harmonic analysis of tides should be carried out on carefully chosen records obtained during quiet background periods.

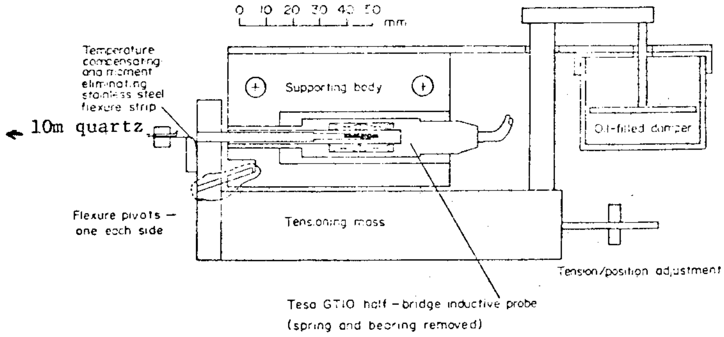

Figure 5. Tensioning and measuring head of quartz catenary strainmeter.

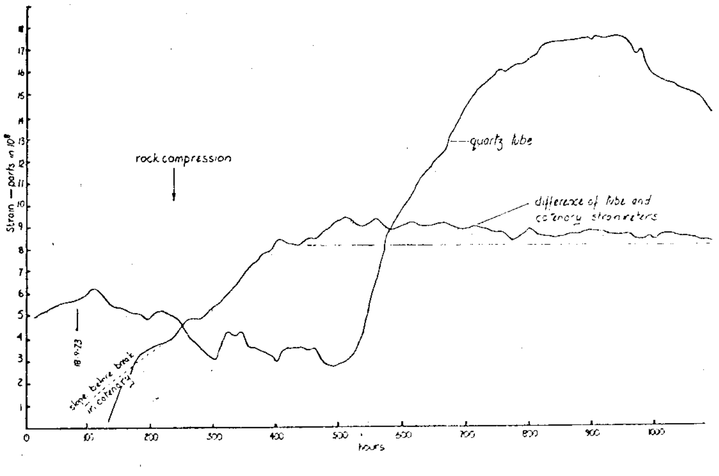

Figure 6. Secular drift in Cooney Observatory region

## 5. The Future

The past two years of research by the Cooney group have realised gradual improvement in strainmeter designs. Quality nanostrain data is now being obtained with a very simple 1m long mechanical design (PETERS & SYDENHAM 1973). Much has been learned about the drift of the instruments and their installation. Mounting instability has also been studied (JEFFREY & SYDENHAM 1973) showing that this part of the strainmeter loop is the significant source of creep during the first few months of a new installation.

Two laser components (SYDENHAM & BLAIR 1973), forming part of a multi-coordinate array, are about to be completed. By 1974, these, plus other strainmeters, will provide data for strain tensor investigation.

If the coaxial measuring base does realise stabilities of parts in $10^{15}$ it could become routine to look for gravity wave reception - a currently unsolved new area of gravity phenomena.

The information produced so far on the stability of mechanical instruments now enables a new path to be developed (manpower allowing). This is to find ways to use the stable lengths for defining highly precise baselines on the surface. Tides and secular movements produce surface changes, maximising around parts in $10^7$ so there is still room for improvement in surface surveying. Although this suggests a return to a kind of relatively slow taping procedure or Colby-bar approach, on order of magnitude gain over EDM could prove useful in many areas of geodetic survey, especially in ground settlement monitoring.

At present this is being pursued (on a less precise scale) with the development and appraisal of a 50-100m range automated wire-drum transducer (SYDENHAM 1970) for the Melbourne Underground Loop Railway Authority. It is hoped this unit will enable trilateration of streets to be made with an accuracy of 0.1mm, filling the gap below EDM equipment capability.

## 6. Acknowledgment

Research is supported by a continuing Australian Research Grants Committee Award (providing for laser strainmeter, stabilised-laser and general research needs); by a two-year Nuffield Foundation Award (to build and test the coaxial measuring base); and from various University funds. The Bureau of Mineral Resources, Canberra, and the University jointly operate the tiltmeter installation.

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# TIDAL DEVIATIONS OF THE VERTICAL AT ARMIDALE, AUSTRALIA

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## ABSTRACT

Deviations of the vertical are being recorded at the Cooney Geophysical Observatory near Armidale, New South Wales, using a pair of Verbaandert-Melchior horizontal pendulums. Problems associated with the installation and operation of the apparatus have been largely overcome. Since the pendulums were installed in 1971 only two periods of reliable records longer than 29 days have been obtained. These data have been scaled and will now be forwarded to the International Centre for the Earth Tides for detailed analysis. Various non-tidal effects still appear on the current records and are probably due to site defects.

## 1. Introduction

Since 1961 the International Association of Geodesy has repeatedly recommended that Earth tides should be recorded in the southern hemisphere, and particularly in Australia at the antipodes of Europe.

Although more than 300 stations are now observing Earth tides, the stations are not uniformly distributed internationally. Central Europe is comparatively well-served with stations which have records extending over many years. Significant data have been obtained from a number of stations across the USSR, in Japan, and in North America. It is known that various groups in Australia, New Zealand, South America and Antarctica are attempting to record reliable Earth tide signals, but, as far as the authors are aware, no Earth tide data from the southern hemisphere have yet been published.

This paper describes the installation and operation of a pair of Verbaandert-Melchior horizontal pendulums in the Cooney Geophysical Observatory near Armidale, New South Wales. This is a co-operative project by the Bureau of Mineral Resources, Geology and Geophysics (BMR) and the Department of Geophysics, University of New England (UNE) to measure tidal deviations of the vertical.

It was expected that analysis of recent data would be completed in time for presentation at this conference, but unavoidable delays have made this impossible. Nevertheless, continuous recordings from both pendulums have been obtained over two periods of more than 29 days, and the data have now been scaled and are being checked before transmittal to the International Centre for the Earth Tides for detailed analysis.

In common with other groups seeking to obtain reliable observations of the tidal variations in tilt we have experienced considerable difficulty in the installation and operation of apparatus. It is clear that the present site is not ideal, and non-tidal effects continually appear in the records.

Preliminary analysis of the data showed that the principal components of the tides can be separated, but that it may be difficult to determine their amplitudes and phases to the desired accuracy.

## 2. Installation of the Pendulums

The Verbaandert-Melchior horizontal pendulums ORB 53 and ORB 54 were obtained by BMR from Professor Paul Melchior in 1963. Because of difficulties in obtaining a suitable site and because of the unavailability of staff for this project the pendulums remained unused for some years. In 1970 UNE established the Cooney Geophysical Observatory in an abandoned mine in the Hillgrove area 28 km east of Armidale (see figure 1). BMR and UNE agreed to install and operate the pendulums as a co-operative project at that site.

The Cooney Observatory has been described in several earlier papers (e.g., GREEN & SYDENHAM 1971) and is shown in figures 2, 3 & 4. The pendulums are installed at the innermost end of the Upper Cooney tunnel about 170 m from the tunnel mouth so that the rock cover exceeds 100 m. The pendulums are isolated from the main part of the tunnel and the cross-cut by three brick partitions with sealing doors, so that the occasional ventilation of other parts of Upper Cooney do not produce significant temperature variations in the pendulum observation chamber.

As far as possible the installation follows the procedures laid down by MELCHIOR (1966). A niche measuring 0.4 by 0.4 by 0.8 m was cut into the end face of the tunnel without the use of explosives. The rock is a garnetiferous carbonaceous slate and is extremely hard. Sets of fracture planes in three directions are clearly seen in the rock floor of the niche. Water weeps into the niche through various fractures, and has caused considerable difficulty. The pendulums are mounted on stainless steel pins glued with Araldite into holes drilled into the floor of the niche. As recommended by Melchior great care was taken to ensure that each pin is a close fit in its hole and that the shape of the bottom of the pin matches the shape of the bottom of the hole. The ceiling, back and side walls of the niche were sheathed with galvanised iron to catch and divert water entering the niche. The floor of the niche was sealed with a layer of Readibond (epoxy-resin plastic). A hinged glass door closes the front of the niche.

Moisture has been a persistent problem; fogging of the glass door of the niche was finally cured by blowing freeze-dried air on to those portions of the glass that transmit the light rays to and from the pendulum mirrors. A small amount of this dried air is allowed to weep into the niche to prevent entry of moist air from the observation chamber.

Imperfections in the pendulum mirrors, particularly that mounted on ORB 54, made sharp focusing of the traces impossible and it was necessary to re-silver these mirrors.

Automatic calibration apparatus was obtained from Melchior and installed in the observation chamber. Two of the stainless steel pins have oversized heads and support the crapaudines (expandable bearing plates) under the drift leg of each of the pendulums. The apparatus which automatically changes the height of the mercury bottle was installed close to the tunnel ceiling in order to obtain a pressure head of 1.5 m between the mercury bottle and the crapaudines.

The recorders and the light sources are mounted on a brick and concrete table 5 m from the niche. It was necessary to widen the tunnel at this place in order to allow access past the table to the niche. A pair of timing lights, mounted close to the niche and at the same height as the mirrors on the pendulums, provide a flash of light each hour in response to a signal from a Bulova Accutron clock.

To improve ventilation in the chamber when it is occupied for extended periods, air is sucked from the ceiling of the chamber and evacuated into the main part of the tunnel by a domestic vacuum cleaner.

The portion of the tunnel immediately before the observation chamber serves as a light trap and workroom. Ambient pressure is recorded in this workroom; other apparatus is being installed to record other parameters in the observation chamber, including temperatures of chamber air, niche air, rock floor of the niche, and interstitial water.

The installation commenced in August 1971 and several of the features were not installed until much later.

The records are changed weekly by UNE staff, who also make adjustments for drift as required.

## 3. Azimuths and Co-ordinates

The true bearing of the Upper Cooney Tunnel is 53° 13' 11". The narrowness of the observation chamber prevents the mounting of the pendulums with the preferred N-S and E-W orientations. Tilt is measured in the mean azimuths 54° 59' and 142° 05'; this limits the accuracy of determination of amplitudes and phases of the various components. The co-ordinates of the observation site are :-

| | |
|---|---|
| Latitude (Australian National Spheroid) | 30° 34' 43" S |
| Longitude (Australian National Spheroid) | 151° 53' 36" E |
| Elevation (Australian Height Datum - mean sea level) | 649.9 m |

The acceleration due to gravity referred to absolute datum (IGSN 71) is 9 791 662 $\mu m\ s^{-2}$ (BMR gravity station number 7291-0646).

## 4. Records Obtained

During the period August 1971 to July 1972 and August 1972 to June 1973 the records obtained were unsatisfactory for scaling and analysis for one or more of the following reasons:

(a) Problems due to moisture in the niche, condensation on optics, etc.

(b) Extremely high drift of one or both pendulums for several months following initial installation and following later work necessary to eliminate moisture problems.

(c) Slipping clutches in the drive mechanism of the recorder drums.

(d) Inadequate resetting of light spots during periods of medium drift.

(e) Failures of timing mechanism due to clock and relay faults.

(f) Disturbance from experimental heating rings on lenses.

(g) Failure of small refrigerator used to freeze-dry air.

During July and August 1972, a 29-day continuous set of recordings was obtained on both pendulums. No resets were made during this period as the drift rates of both pendulums were small. The records are usable but have the following defects:

(a) Poorly focused traces, particularly from ORB 54.

(b) Timing problems necessitating the use of earthquake arrival times to verify universal time datum.

(c) Incorrect setting of the calibrator arm and hence poor calibration of amplitudes.

These data were partly scaled and analysed, the principal tidal components being resolved in the records from one pendulum. The azimuths of the pendulums were not available until March 1973. By then the behaviour of the pendulums suggested that the scaled data were suspect and should be confirmed by a second set if possible.

During June and July 1973 a 37-day continuous set of recordings was obtained on both pendulums. These records are usable but have the following defects:

(a) Poorly focused traces, particularly from ORB 54.

(b) Minor problems causing intermittent faults in the drum drives and timing apparatus.

(c) High drift on ORB 53 necessitating resets about every ten days.

(d) Several periods of noise continuous over several hours or several days.

(e) Small tares, usually without recovery but occasionally with recovery over several hours.

The first two are instrumental faults, corrected by re-silvering the mirrors and other repairs. The remaining faults have continued since that time. Both the noise and the tares have become more frequent, so that the June-July period data remain the best obtained to date. These records have been scaled and are being analysed at present.

The data from both sets of continuous records are being checked and re-formatted before transmittal to Brussels for detailed analysis.

## 5. Non-Tidal Effects in the Records

Records from the pendulums show a number of interesting non-tidal effects during the 27-month recording period:

1. Drift.
2. Small tares.
3. Bays, both large and small.
4. Teleseismic and microseismic noise.
5. Discordant noise.

### *1. Drift*

When the pendulums were first installed, both had drift rates of several hundred milliseconds of arc (mseca) per day. These drift rates fluctuated and even reversed during the first three months. Since then the measured drift rates have always been less than 70 and generally less than 30 mseca/day. Each pendulum has shown drift rates less than 5 mseca/day for periods of about 2 months. The drift rates of both pendulums are acceptable , although not as small as those quoted by MELCHIOR (1966) and others.

MELCHIOR (IBID) lists several instrumental, geophysical and tectonic effects as probable causes of drift. Movement in one of the pendulum supports, or in the fractures in the floor of the niche, was initially suspected at Cooney. The pendulums were interchanged on their supports in May 1972 in an attempt to improve focus, and were changed back again in August 1973. Thus half the recording period to date has been made with the pendulums interchanged, but the drift data do not suggest any particular effect as the probable cause of drift.

2. *Small Tares*

Small offsets or tares in the trace of one pendulum occur several times each week (figures 6 and 7). They range from 1-10 mm on the record (4-40 mseca) and recovery is rarely seen to occur. Almost without exception, these tares occur in the trace of only one pendulum and are in the direction of the apparent drift. It follows that their cause is instrumental and lies in the pendulum apparatus or in the support pins. It is possible that the observed drift is mainly or totally due to the accumulated effect of such tares.

3. *Bays, Both Large and Small*

Large bays, during which the trace is displaced 20-400 mm, are rare. Both pendulums are affected and recovery appears to be complete. The shape of the trace is similar to that recorded after the environment has been thermally disturbed, the displacement occurring over 5-20 hours. These bays are thought to be due to thermal effects. Smaller bays of 5-20 mm amplitude and lasting ½ - 2 hours occur every few months. These bays are also thought to be of thermal origin (figure 5)

4. *Teleseismic and Microseismic Noise*

Distant earthquakes, local tremors, rock-bursts, and man-made explosions contribute noise to the records (figures 5, 6 & 7). Individual arrivals of energy occur simultaneously on the traces of both pendulums. The noise level is frequently high during normal working hours, even though the observatory itself is unattended. It is likely that this daytime noise is generated by mining activity in the area. Although no mines are worked within 1 km of the site, ore is treated in a plant on the hill above the observatory. Several periods of unexplained noise have continued without break for periods of 2-6 days.

5. *Discordant Noise*

Discordant noise affects one pendulum only, or affects both pendulums over a period with different arrival times for individual energy packets. Time differences of 10-40 minutes are observed. No explanation for this noise has been found.

## 6. Need for Further Work

Several recent papers have indicated that a niche excavated in the end wall of a tunnel is not an ideal site for the recording of tidal tilt because of unequal stress relief parallel and transverse to the axis of the tunnel. Moreover the present site does not permit the pendulums to be oriented north-south and east-west. A better site may be found in the centre of one of the large chambers of Lower Cooney, but is likely to have the same noise level as the present site. LENNON & BAKER (1973) discuss the discrepancies in the tilt attenuation factors and phases reported by various Earth tide stations in central Europe. Tilt records from a number of stations yet to be established throughout Australia are required, but there is so little activity in this field (SYDENHAM 1973) that it is impossible to forecast when these data will be available.

The analysis of tilt data from the present site will be of interest because it will be first data from this part of the globe. Nevertheless it should be treated with reserve until joined by data from other sites. It is impossible to distinguish between regional and global influences in the data from only one site.

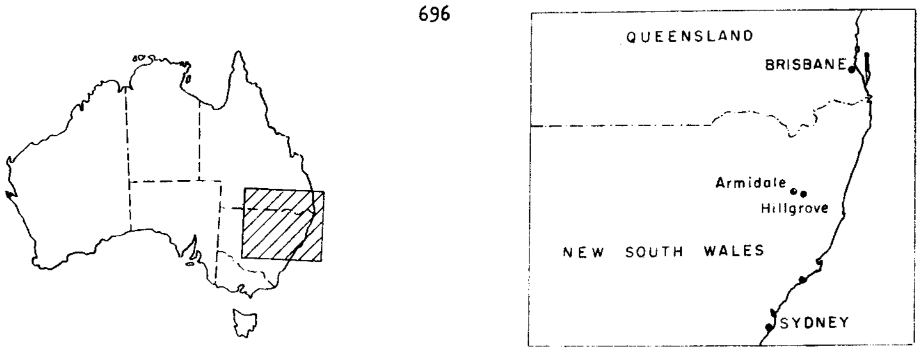


**Figure** 1

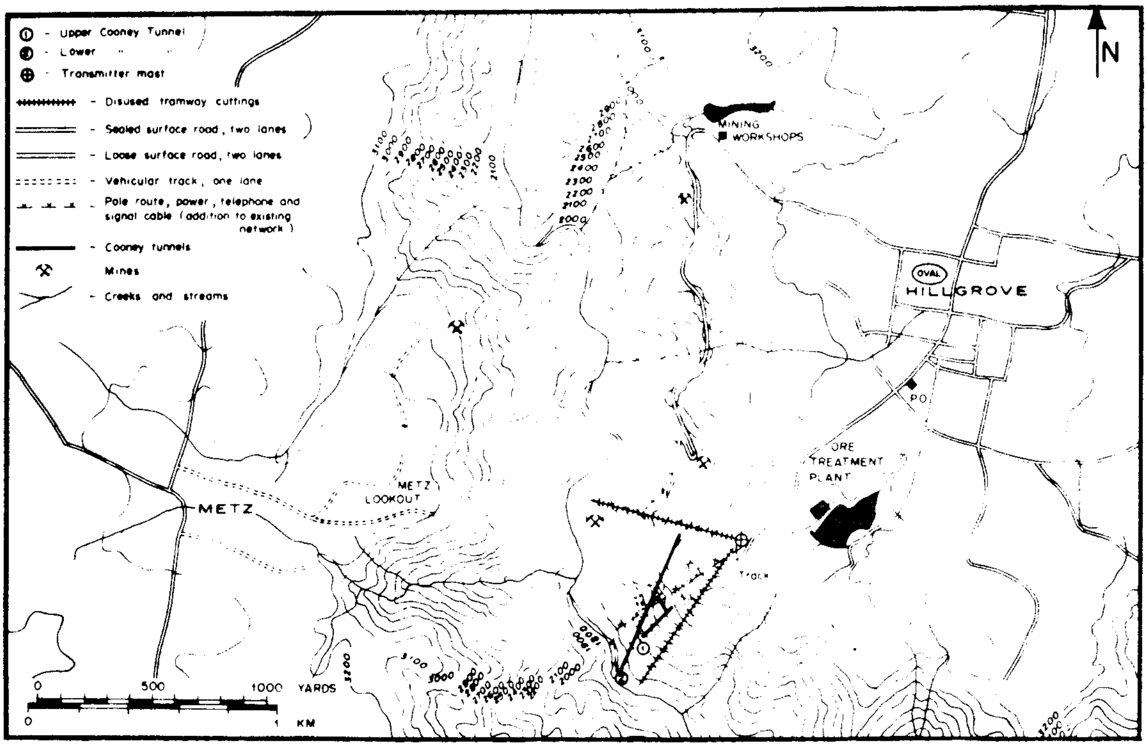


**Figure 2**

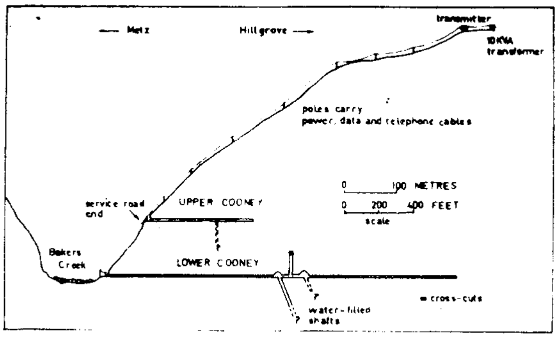


**Figure 3**

## COONEY GEOPHYSICAL OBSERVATORY SITE, HILLGROVE, NSW.

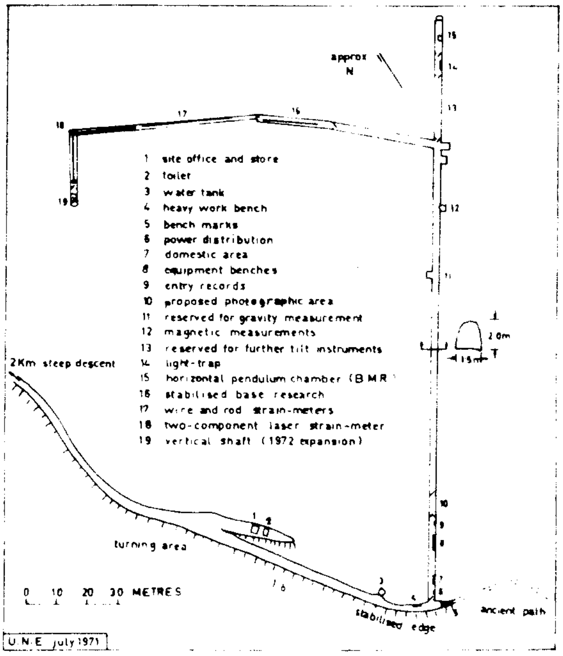
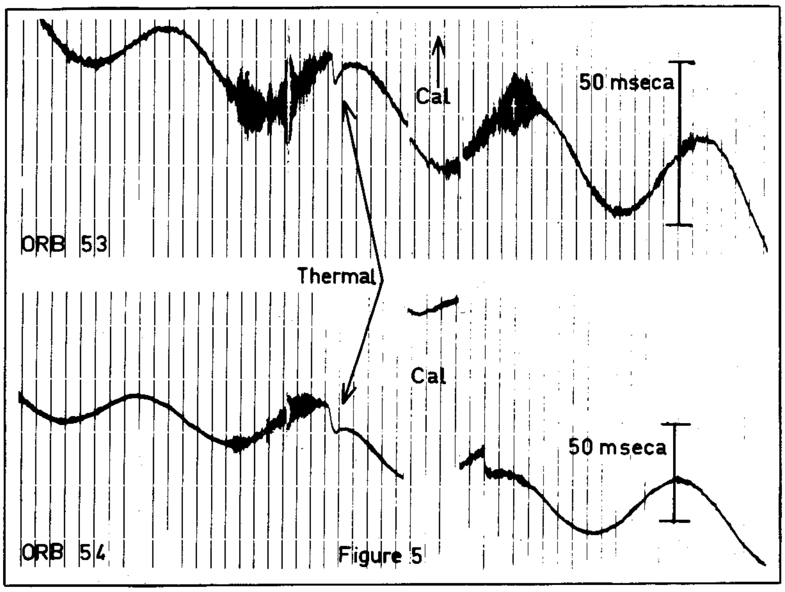
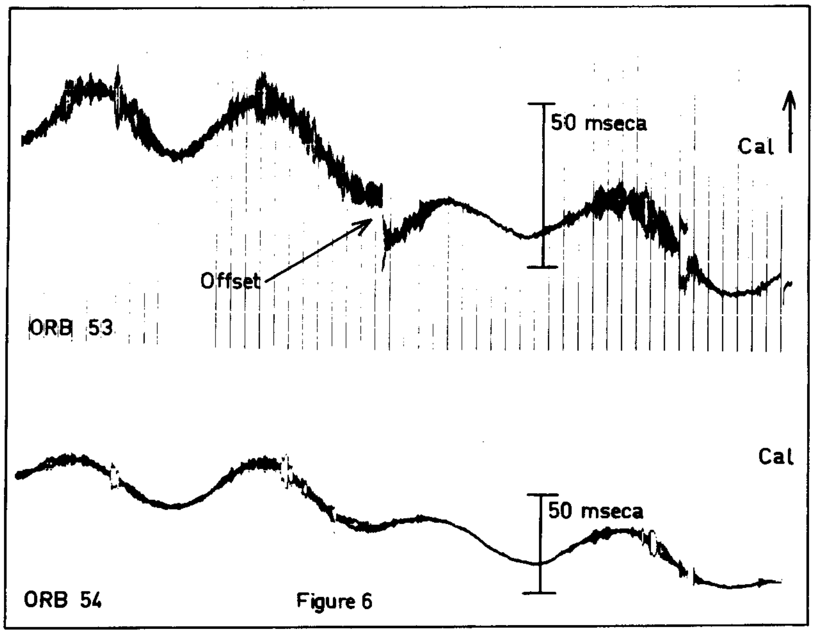


**Figure 4**



*Explanatory notes for figures 5, 6 and 7*

1. Each figure is a half scale reproduction of simultaneous photographic records produced by the two horizontal pendulums ORB 53 and ORB 54.
2. Vertical lines are hourly time marks produced photographically.
3. The 50 mseca bar shown against each trace indicates the response of the pendulum to a tilt of 0.050 seconds of arc. During these periods of recording ORB 53 is more sensitive than ORB 54 because it is operating with a longer period.
4. Each trace includes one example of the offset produced by the auto-calibrator and crapaudine system. This offset corresponds to about 90 mseca.
5. The various figures show examples of non-tidal effects in the recent records.



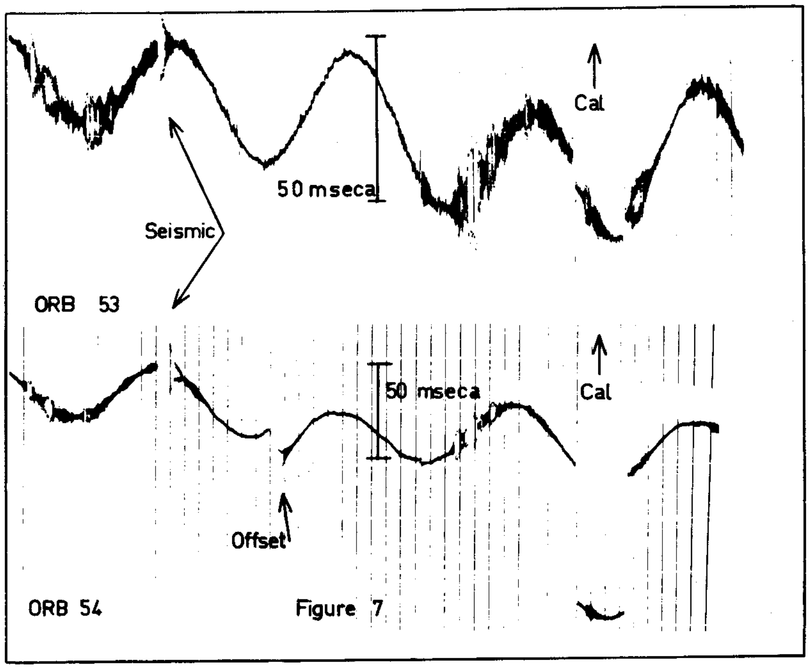


Figure 7

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# INTERNATIONAL UNITS (S.I. UNITS) IN GRAVIMETRY

## ABSTRACT

It is attempted to show that it would be beneficial for geodesists to follow practising geophysicists in introducing S.I. Units and ISO proposals for uniform mathematical notation (ISO 1961).

## 1. Introduction

International bodies such as the International Standards Organization (ISO)* and related commissions have recommended the use of S.I. Units. Governments are preparing new Weights and Measures Acts which will recognise S.I. Units; among these are France (1977), Germany (1978) and, surprisingly, the United States.

Appropriate standards of S.I. Units have been published in many countries. The draft proposal ISO/DIS 31/1, February 1973, Part 1, for "Quantities and Units in Space and Time" reads, among other items:

1.10.2 acceleration due to gravity, acceleration of free fall $g_m = 9.806\ 65\ \mathrm{m/s^2}$,

1.10.b Gal = 1 $\mathrm{cm/s^2}$, conversion factor 1 Gal = 0.01 $\mathrm{m/s^2}$.

This proposal means that there is no word for the unit of *standard gravity* other than that used so far. 980.665 Gal are simply written as shown above. Rules for multiples and sub-multiples are that tertiary powers of ten should be used. Table 1 shows acomparison of Old, acceptable but not S.I., and proper S.I. Units proposed in this paper.

## 2. The Argument

Articles preceded by a legend of notation and definitions or clear references to national standards reveal a degree of individual style of notation and inconsistent use of units and dimensions which make understanding unnecessarily difficult. Naturally authors follow a well established tradition and the majority of geodesists may not have concerned themselves with aspects of international standardization other than that effected through their respective organizations such as the IAG, the IUGG or the FIG. There is also the strong feeling that the *Gal* is an unassailable term because it has found recognition by the ISO (ISO DIS 31/1). This is a misinterpretation of the intention of that body. Some terms are considered "tolerable" but their use is discouraged, simply because their definition defies the first fundamental rule that all units must be derived from the six basic units,

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* I.S.O. - also called the International Organization for Standardization

Table 1

| OLD | ACCEPTABLE BUT NOT S.I. | PROPOSED PROPER S.I. |
|---|---|---|
| *GRAVITY* | | |
| 1 Gal = 1 cm/s$^2$ | 1 Gal = 0.01 m/s$^2$ | $10^{-2}$m kg s$^{-2}$kg$^{-1}$ = $10^{-2}$N kg$^{-1}$ |
| 1 milliGal | 1 mGal = $10^{-5}$ m/s$^2$ | $10^{-5}$N kg$^{-1}$ |
| 1 microGal | 1 µGal = $10^{-8}$ m/s$^2$ | $10^{-8}$N kg$^{-1}$ |
| 1 gravity unit | $10^{-1}$ mGal = $10^{-6}$ m/s$^2$ | µN kg$^{-1}$ |
| | | (Note that the convenience of the old expression is retained) |
| *POTENTIAL* | | |
| (Generally)<br>W = g cm$^2$s$^{-2}$ | (newton.metre = joule)<br>N m = J | As ISO |
| *GRAVITATIONAL POTENTIAL* = Work per unit mass = force • length per unit mass | | |
| W = cm$^2$s$^{-2}$ | Not considered by ISO | |
| (implying | (Could be written thus - | |
| W = g cm$^2$s$^{-2}$g$^{-1}$ | W = $10^{-4}$m$^2$s$^{-2}$ = $10^{-2}$Gal m s$^{-2}$) | N m kg$^{-1}$ = J kg$^{-1}$ |
| *GEOPOTENTIAL NUMBER* | | |
| kiloGal.metre | Not considered by ISO | $10^5$J kg$^{-1}$ |
| *DYNAMIC HEIGHT* | | |
| metre | Not considered by ISO | m |

of which the kg, m and second of time are of interest to us here. The second fundamental rule states that all units should be expressed with the aid of prescribed prefixes and multiples of the tertiary powers of ten. Obviously the *Gal* being 0.01 m/s$^2$, does not obey this rule and cannot therefore be expected to be accepted as a S.I. derived unit.

However, this is not the central argument. The need for serious consideration of changing from the *Gal* and the *kiloGal.metre* to the N kg$^{-1}$ and the J kg$^{-1}$ is seen to be derived from the following considerations which are divided into:

a. administrative reasons; and
b. technical reasons.

*a. Adminstrative Reasons*

1. All educational institutions have or are about to change to S.I.
2. Editors could control the selection and checking, etc. of papers and thus have some influence on reducing the publication explosion.
3. Information scientists could efficiently assess and catalogue specialist papers. This is a most important aspect because non-specialists would have a better grasp of the scope of numerical results.
4. Practising geophysicists have begun to work in S.I.

*b. Technical Reasons*

1. Newton spoke of *the force of gravity*; therefore the S.I. Unit for force is the *Newton* or N m kg s$^{-2}$. Geodesists naturally prefer to think and compute in terms of what they can measure, e.g., the metre, the second of time and the Gal. One could even leave the Gal as a word and it would

still be clearly understood to represent 0.01 m $s^{-2}$ or $10^{-2}$N $kg^{-1}$. Mass, force and acceleration are taught in that order and the degree of difficulty of understanding increases with each term in that order; metre per second squared conveys acceleration but says nothing of its reason; Newton per kilogram reveals the reason but loses the elegance of appearing as an acceleration. A derived S.I. Unit must show its basic components (in this case m, kg, s or N and kg) unless it is given a new name. It is interesting to note that the Oxford Dictionary (CONCISE,4th ed. 1959) defines gravity as a force - "degree of intensity of this measured by acceleration", while MUELLER & ROCKIE (1966) define *gravity* as "centrifugal force" or "gradient of the geopotential".

2. If one accepts the definition of gravity as "gradient of the geopotential" and that in itself is clearly understood to be "work per unit mass" in gravimetry, i.e., joule per kilogram, then it is reasonable to retain that approach for the derivations of the geopotential and to think of acceleration in terms of *force per unit mass*. If one speaks of force it should be seen as such by its dimensions of Newton.

## 3. Conclusion

It seems that it would be more appropriate to think of *force per unit mass* for the non-S.I. Unit of the *Gal*; likewise the geopotential can be expressed in units of *joule per kilogram* instead of the kiloGal metre which is a term conveying very little meaning to those trained in S.I. Units.
The computations of corrections to gravity would become consistent and not fraught with the present danger inherent in having centimetres and metres side by side. If the *Gal* is seen as 0.01 m $s^{-2}$, certain dimensional difficulties arise when computing corrections. No good author will write solely for the initiated.

The gravitational constant, being $6.67 \times 10^{-8} cm^3 g^{-1} s^{-2}$ would read

$$k = 6.67 \times 10^{-11} m^3 kg^{-1} s^{-2}$$

in S.I. Units.

## 4. References

ISO 1961. *Mathematical Signs and Symbols for use in Physical Sciences and Technology.* Recommendation R 31 ,Part XI (1st ed.). International Standards Organization.

MUELLER, I.I. & ROCKIE, J.D. 1966. *Gravimetric and Celestial Geodesy.* Ungar,New York.