# A STUDY OF HIGH PRECISION GRAVIMETRY

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## DECLARATION

I hereby declare that the work presented in this thesis is my own unless otherwise stated in the text, and that the thesis has been composed by myself.

## ACKNOWLEDGEMENTS

My supervisor, Roger Hipkin has been a constant source of help and encouragement. I should like to express my considerable gratitude for his academic assistance and guidance. It has been a great pleasure for me to work with him. His sense of the aesthetic, sound logic and good humour has been greatly appreciated.

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## ABSTRACT

A study of high precision gravimetry was undertaken to assess the limits of accuracy of modern portable gravity meters. Recent interest has centred on the use of precise gravity observations preferably in conjunction with geodetic measurements (e.g. levelling, Very Long Baseline Interferometry) to determine temporal height variations associated with tectonical activity. When special procedures are followed, modern portable gravity meters can measure relative gravity differences with a standard deviation of less than 0.1 gravity units (1 g.u. = $10^{-6}$m.s.$^{-2}$). These procedures are, firstly, the accurate determination of the Earth tide at the site, secondly, the elimnination of intrinsic instrumental drift, thirdly, a correction for environmental influences on the gravity meter, and lastly, determination of the instrument's calibration factor.

Several computer programs for the prediction of the tidal potential using dissimilar methods are discussed and compared. Observations at the only known modern Scottish Earth tide station, an I.D.A. (International Deployment of Accelerometers) instrument at Eskdalemuir, are analysed. The ocean load vector is calculated for 13 main frequency groups (the magnitude , local phase and gravimetric factors for $M_2$ and $O_1$ are 0.016g.u., 128$^{o}$, 1.139 and 0.023 g.u., 111$^{o}$, 1.083 respectively. Published $O_1$ gravimmetric factors for

Europe and Britain are significantly greater than this observed value suggesting an instrument error greater than the stated maximum.

Extensive instrumental tests on the Edinburgh gravity meter (La Coste and Romberg , G-275) to study environmental effects and drift were necessary before data were collected. The method of fitting cubic spline functions by least squares was developed to eliminate instrumental drift. The instrument scale factor was evaluated on the National Calibration Line and in the laboratory using specially designed tilting apparatus. The National Calibration line results obtained using G-275 are analysed and compared with the results from several other model G meters. An ancillary platform, on to which the meter may be bolted, was constructed. The platform accommodates more sensitive levelling vials and screw feet of a finer pitch enabling the observer to level the instrument more accurately. The platform may be used in the laboratory or in the field. The platform was used as a tilt table, the angle being obtained by electronically counting laser interference fringes.

To assess the practical application of high precision gravimetry, annual measurements were made in Scotland, a tectonically quiet area and in East Central Greece, an active area. The Scottish network consists of six Ordnance Survey fundamental bench marks with gravity differences less than 10 g.u.. A unique observation procedure was followed in which the meter was allowed to attain equilibrium by observing over a long time section of the drift curve. Gravity differences are found by spline adjustment of the drift curve rather than a point value . Some of these stations were measured during a pilot study in the years 1976, 1977, and 1978, and all six stations were measured using the ancillary platform (described above) in 1980 and 1981. The average observed difference between consecutive years is 0.081 g.u. with a standard deviation of 0.073 g.u.. The Greek network consists of sixty eight stations in an area of seismic risk near Atalanti ($38^{\circ}38'$N, $23^{\circ}06'$E). The network was established using two gravimeters in ladder sequences during 1981 yeilding individual standard deviations less than 0.08g.u.. Subsequent re-measurement has revealed no gravity change at the 0.11g.u. level, and tectonic activity was undetected within this limit. It is concluded that the equilibrium observation procedure does not offer a significant increase in measurement precision.

A local engineering study to detect mining subsidence gravimetrically was also completed at Solsgirth Colliery, Fife, Scotland. Gravity observations combined with precise levelling yielded an excellent correlation between height and gravity change with a gradient of 2.17g.u.m$^{-1}$($\sigma$ = 0.097 g.u.m$^{-1}$), demonstrating that gravity can be a commercial alternative to precise levelling.

# CONTENTS

# LIST OF FIGURES

## UNITS

Despite the fundamental nature of the acceleration due to gravity there is not yet a single commonly used unit when writing about small magnitudes. I have mainly used the gravity unit (g.u.), which is in keeping with the Systeme International. One gravity unit is equal to $10^{-6}ms^{-2}$ and is sometimes denoted $\mu ms^{-2}$. The most commonly occurring units are submultiples of the c.g.s. unit, the gal ($1cm.s^{-2}$). The microgal ($10^{-8}ms^{-2}$) has a very convenient magnitude for the discussion of accuracies and amplitudes in both earth tide studies and high precision gravimetry (hence the term microgravimetry).

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

This thesis describes the measures undertaken to observe the acceleration due to gravity as accurately as possible using a convential surveying instrument. Because of the nature of the subject, a range of diverse topics are considered. These include laboratory based instrumental experiments, the prediction of earth tides, and field measurements in Scotland and Greece. High precision gravity surveys are useful in several differing contexts, itemised in Chapter Two. These applications are essentially associated with local or regional investigations of the temporal variation of gravity and form the basis for the problems addressed here. In both, the data may be directly diagnostic of subsurface activity, but in the regional case the information is best considered in conjunction with other data such as geodetic levelling or earthquake distribution.

As the use of sophisticated new technologies becomes more widespread in geodesy (eg. Very Long Baseline Interferometry (VLBI), Global Positioning System (GPS)), the need for precise gravity measurements will increase. This technology is currently being tested ( Project MERIT, sponsored by the International Union of Geodesists and Geophysicists), but ultimately geodesists would like to acheive a worldwide geodetic control point network. The 'equilibrium' measuring technique discussed in Chapters Five and Eight may be particulary useful in the direct accurate gravimetric connection of VLBI stations.

## 1.2 The Problems

The nature of the difficulties associated with precise relative gravity measurements is fully discussed in Chapter Two together with a review of the published literature. The immediate problem is one of instrumentation - the primary components of the portable gravity meter are purely mechanical and perform somewhat variably. Chapter Three discusses the constructional details of the most commonly used gravity meter and presents the environmental response curves for the Edinburgh instrument. Instrumental response can only be examined after the accurate subtraction of the force due to the Earth tides, and this is considered in Chapters Four.

After the tidal correction is applied the data is adjusted in a least squares sense to obtain the optimum solution for a particular gravity difference. Data adjustment using least squares cubic spline solutions and network analysis using specific computer programs is discussed in Chapter Five. The use of cubic splines is illustrated with data collected during a laboratory test. Chapter Six is concerned with the problem of instrument calibration and presents two approaches, the first the result of field observations, the second based on a specially designed laboratory experiment. The predicted effect of Earth tides may be altered by the local crustal deformations caused by ocean tidal loading. The magnitude of this load correction may be calculated theoretically and verified for a particular location experimentally. The data from a Scottish Earth tide station are reduced and examined in Chapter Seven

## 1.3 Field Data

The techniques explored in Chapters Two to Six were used to good effect in field studies discussed in Chapters Eight to Ten. An established Scottish gravity network was extended and strengthened on two consecutive years. The network was observed using a novel observation technique which is designed to connect widely separated stations with the maximum possible precision. This contrasts with a new network established by the author in the Atalanti region of central Greece. The Atalanti network numbered some sixty eight stations which were observed with strongly interconnected double ladder sequences. These repeated observations have not detected any gross temporal variation in gravity. A third field study, in the nature of a well controlled experiment, was carried out above a working coal mine. The extraction of the seam material caused surface subsidence in excess of one meter which was well resolved gravimetrically.

# CHAPTER TWO

# HIGH PRECISION GRAVITY

## 2.1 The Meaning of High Precision

The spatial variation of the acceleration due to gravity has been measured routinely since the 1920's to determine the density structure of subsurface rocks. These early measurements were generally made using portable pendulums which were sucessively superceded by stable and then astable spring balances. The most successful design originally appeared in 1934 (La Coste, 1934) and is still in use today.

The study of high precision gravity measurements is a diverse field covering several unrelated topics which can be loosely catagorised as follows:

(1) Global secular variations of gravity
(2) Regional deformation studies (e.g. isostatic rebound)
(3) Local temporal gravity changes associated with tectonic mechanisms.
(4) Engineering applications.
(5) A non Newtonian gravitational constant, 'G'.

Figure 2.1 is a diagrammatic representation of the amplitude spectrum of such variations.

The precision of a given point value collected during convential gravity surveying on land , undertaken by either the oil industry or a government agency, would typically be 0.5 to 1.0 g.u. (eg. NGRN73, Masson Smith et al, 1974). This is generally sufficiently accurate to resolve geological structures. Higher precision requires a further investment in both the data collection and processing judged commercially unnecessary by industry. The distinction between conventional and high precision surveying is not absolute and they may overlap in extreme cases, but a conventional survey will not attain the same degree of precision in a common area. High precision surveys involve repeated visits to all sites integrated into a carefully preplanned measuring sequence optimised to suit local conditions. All the surveys undertaken by the author required resurveying at a later date to study the temporal change of gravity and consequently each station should be permanently marked. Data reduction of the collected values includes a rigorous evaluation of earth tides and a considered representation of instrument drift.

The techniques employed in such studies are similar and comparatively recent, using for the most part relative spring balances manufactured by the La Coste and Romberg company. These meters are sufficiently small and light to

## Accuracies of absolute and relative gravimetry and related questions

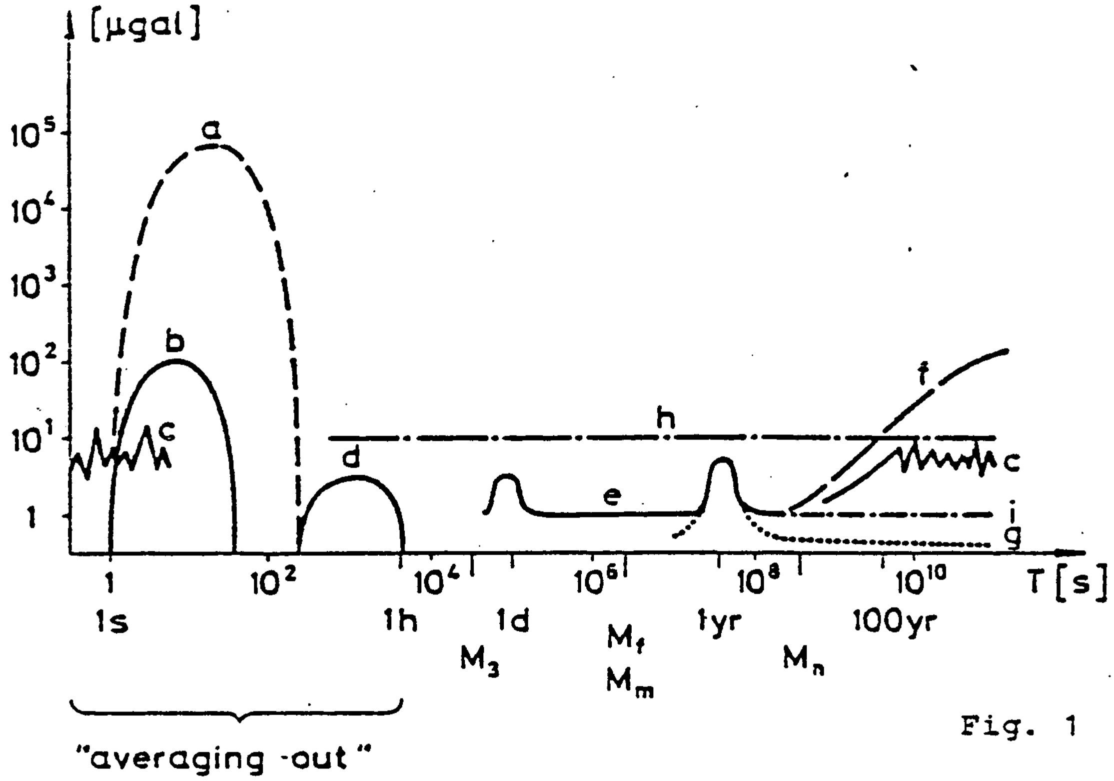



Fig. 1

tidal frequencies $(M_3, M_f, M_m, M_n)$

a = earthquake activities
b = microseismic activities
c = manmade (artificial effects) activities
d = eigen - vibrations of the earth
e = hydrological and meteorological effects
f = secular processes
g = astronomical effects (polar motion etc.)
h = present accuracy
i = special techniques (short term) ~ 1yr

Figure 2.1 The frequency spectrum of temporal gravity variations (Elstner, 1981) be carried by one person and the reading time at a site is less than five minutes. The La Coste and Romberg company manufactures several models, the most common being the land prospecting meter, model 'G', which has a worldwide range of 70,000 g.u.. The company also manufacture a modified land meter, model 'D', with a limited range of 2000 g.u. suitable for use in high precision surveys (Harrison and La Coste 1978). These instruments are discussed in some detail in a Chapter Three.

In addition to the La Coste instrument several transportable absolute instruments have been manufactured and several more are currently in the design phase. These are generally based on existing laboratory absolute instruments and are 'symmetric free fall' in which a corner cube reflector is projected vertically upwards, or 'free fall' instruments, where a corner cube is released at a given height, (Alasia et al, 1981, Hammond and Iliff, 1978, Sakuma, 1971 ). Several superconducting gravimeters in which a sphere is suspended over a persistent current magnet have been designed at the University of California, San Diego (Goodkind, 1981)

These absolute instruments open up many new possiblities in geodesy and geophysics, particularly the transportable instruments which may be used in conjunction with Very Long Base Line Interferometry or laser ranging. (Transportable in this context means air freighting

1000-1500 kg. of equipment to a stable, perhaps air conditioned site and up to one week for a single measurement with root mean square errors less than $5.10^{-8}ms^{-2}$. The importance of this area of study was emphasised at the International Gravity Commission seventh session ( Res. No. 2 , Bull Geod. Vol. 115, 1975)

## 2.2 Recent Studies

It was only with the availablity of reliable accurate prospecting gravimeters within research institutes that the diverse possiblitites of gravimeters were explored. The very first gravity measurements to be undertaken to examine tectonic processes were undertaken as early as 1938 in Iceland (Schleusener, 1943) This survey, using Thyssen gravimeters, was of low accuracy by present day standards and the next repeat survey which took place in 1965 ignored the original measurements. In the same year, 1965, the International Association of Geodesists established two special study groups SS3.37 ('Special Techniques of Gravity Measurements') and SS3.40 (Secular Variation of Gravity) which have been instrumental in organising specialist meetings and publications in this field.

A high precision gravimetric profile of Scandanavia (figure 2.2) was proposed at the Symposium of Recent Crustal Movements in Aulanko, 1965 and the first measurements were carried out in Finland the following

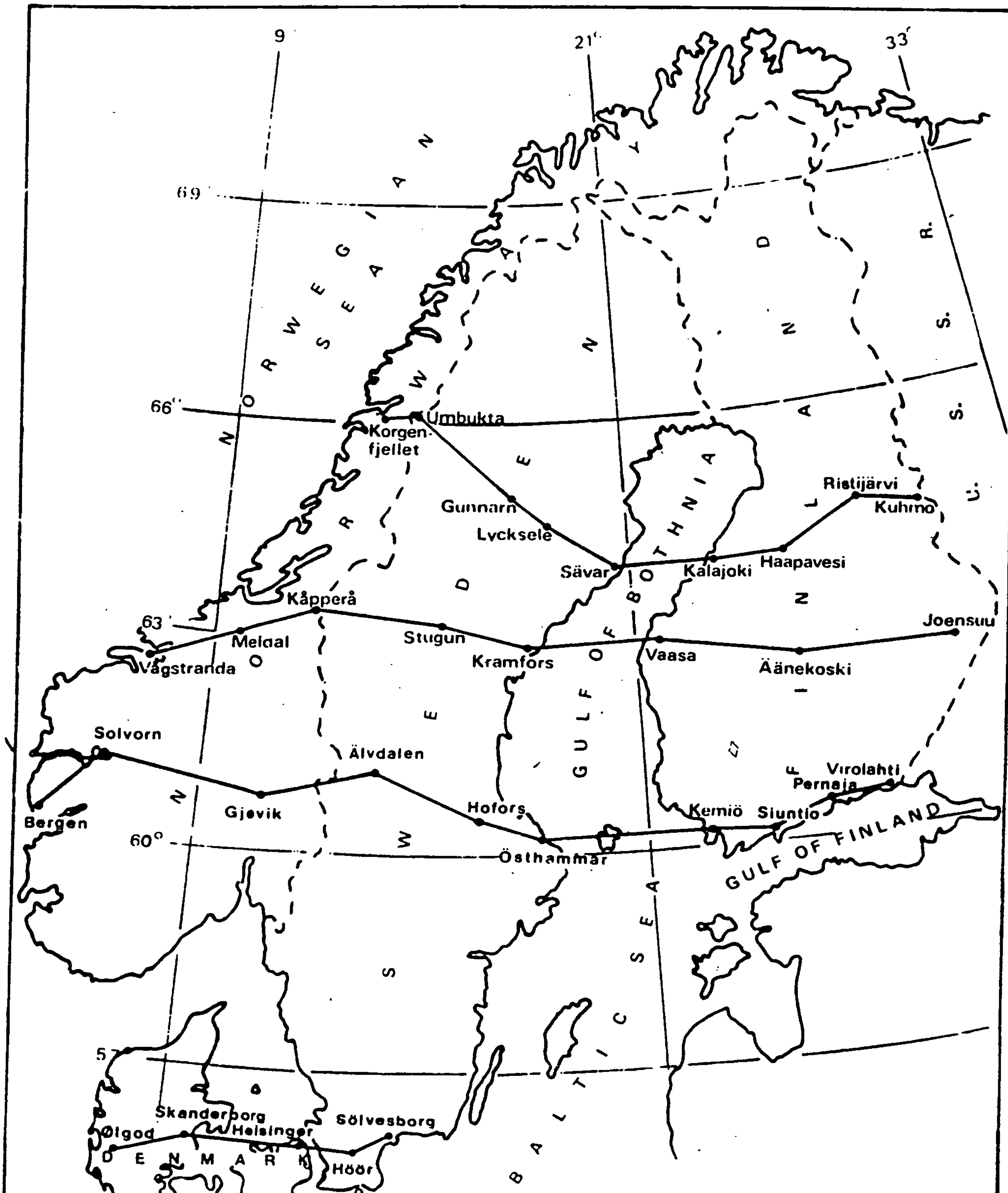



Figure 2.2 High precision gravity profiles in Scandanavia.

year. The line was subsequently extended over the Gulf of Bothnia into Sweden and Norway and is resurveyed on an annual basis. The results of these measurements are thoroughly described by Kiviniemi (1974) together with the data collection procedure. Kiviniemi obtains a standard error of 0.05 g.u. but the observed variation does not conform to the classical model of Sandanavia rebounding after the removal of the ice load. Many other institutes have collaborated with Professor Kiviniemi and the Edinburgh instrument (G-275) measured along the line during the 1978 field campaign (Hipkin, 1980). This valuable experience was utilised in the planning of network to study secular variation of gravity in Scotland. All other references to time dependent gravity variations on a regional scale have been made in tectonically active areas in an attempt to monitor either variations as a precursory phenomena or a single repeat measurement of an existing a network following an earthquake

## 2.3 Measurements in Tectonically Active Regions

There are several groups who are involved in the study of earthquake parameters and volcanology (eg. Whitcombe et al, 1980, Jachens, 1978 ) currently measuring gravity repeatedly in tectonic areas, Earthquake studies ideally involve a combined field approach with both gravity and first order levelling at common sites. Whitcomb (1976) has discussed the problems associated with geometric levelling which is density dependent as it refers to an equipotential surface and shows that the geometric elevation change may be given as

$$\varepsilon = \frac{\varepsilon'\alpha/a + \Delta G}{\alpha/a - \beta}$$

$\varepsilon$ obtained from levelling which gives the orthometric elevation to the first order

$\alpha$ the acceleration due to gravity

a radius of disc model, area within which dilatancy is occurring

$\Delta G$ measured gravity change

$\beta$ free air gradient

This expression does not depend on the density or thickness of the anomalous zone. The quantity a may be determined from the relation

$$\log l(\mathrm{km.}) = 0.26M + 0.46$$

M = earthquake magnitude,

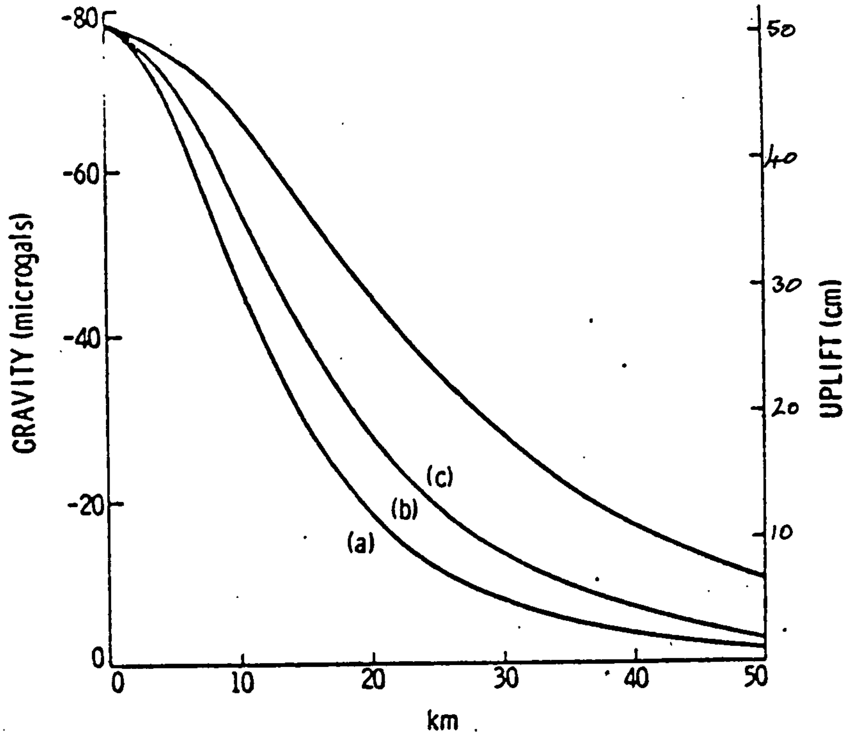
l = horizontal dimension of anomalous zone

Rikitake (1975) presents several similar numerical relations from studies attempting to relate the area of deformation to earthquake magnitude.

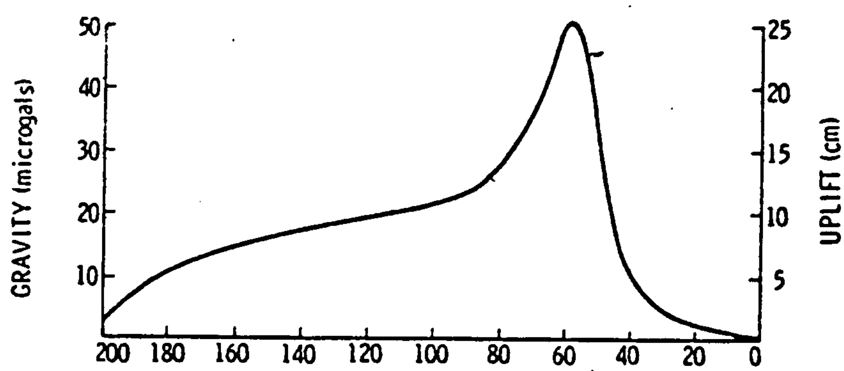
The parameter $\Delta G/\varepsilon'$ is often used by workers, this being an approximation of $\chi$ known as gravity gradient.

The vertical displacement caused by a dilating sphere of a given radius at some depth can be obtained by solving a Boussinesq problem and integrating. This is shown by Rundle (1979) who was investigating the so called 'Palmdale Bulge' of southern California. Figure 2.3 illustrates the uplift and associated gravity change from a 15km. radius dilating sphere at various depths and also the computed effect of thrust faulting. Such a sphere can cause a maximum gravity change of 0.8 g.u. for 0.25 metre uplift. Walsh(1975) has also discussed the theoretical gravity change associated with earth deformation and dilantancy.

Barnes (1966) describes gravity changes at 35 stations associated with the March 27, 1963 Alaska Earthquake (magnitude 8.4) and obtains a distortion gravity gradient of 2.0 g.u. per metre implying a Bouger relation rather than a free air gradient. Torge and Kangieser (1980) report a long term study of gravity variations in Northern Iceland. Measurements were taken in 1965, 1970 and 1975. Four La Coste and Romberg meters were used during the 1975 survey measuring at 176 stations with 1169 gravity differences yeilding an average root mean square error of 0.07 g.u.. These gravity measurements were accompanied by geodetic surveying and the authors demonstrate a positive gravity change associated with a recent volcanic area.




Uplift and gravity change from 15 km radius dilating sphere buried at depths of a) 16 km, b) 20 km, c) 30 km.




Uplift and gravity change from thrust fault: $\delta = 10°$, $\Delta U = -65$ cm, W = 200 km, h = 10 km, $\rho = 2.8$ gm/cc.

$\delta$, dip angle, h, minimum depth, W, planform width, $\Delta U$, dislocation displacement.

Figure 2.3 Theoretical gravitational effect of a thrust fault and a dilating sphere (after Rundle, 1978)

Torge (1981) presents results from a part of this profile (Narafjall) traversing an active rift which has been monitored annually. Figure 2.4 illustrates the gravity variation with time and indicates that activity was initiated in 1975 but now appears to have ceased.

Many gravity stations have been established for time dependent studies in Southern California and these have been remeasured at 1 - 2 month intervals (Whitcomb et al 1980) . Temporal gravity stations were established after Oliver et al, (1975) completed a remeasurement sequence in the area of the San Fernando earthquake , February 1971 (magnitude 6.5.) This study utilising 88 general sites with a high standard deviation (>0.6 g.u.) shows a significant gravity change over a large area (figure 2.5) with a distorting gravity gradient of 1.5g.u. per metre. In Japan, Kisslinger (1975) collated the many levelling and gravity data from the Matsushiro earthquake swarm , 1965 - 1967 and concludes that rapid dilatant expansion ocurred at the source zone accompanied by high water inflow. Following the growth of a strike slip fault the surface subsided with the explusion of water and an increase in gravity.

Repeated levelling and gravity surveys were carried out before and after the two large magnitude Chinese events of 1975, the Haicheng eathquake of February, magnitude 7.3 and the Tangshan earthquake of May , magnitude 7.8. Figure 2.6 is taken from Chen et al (1979) and illustrates

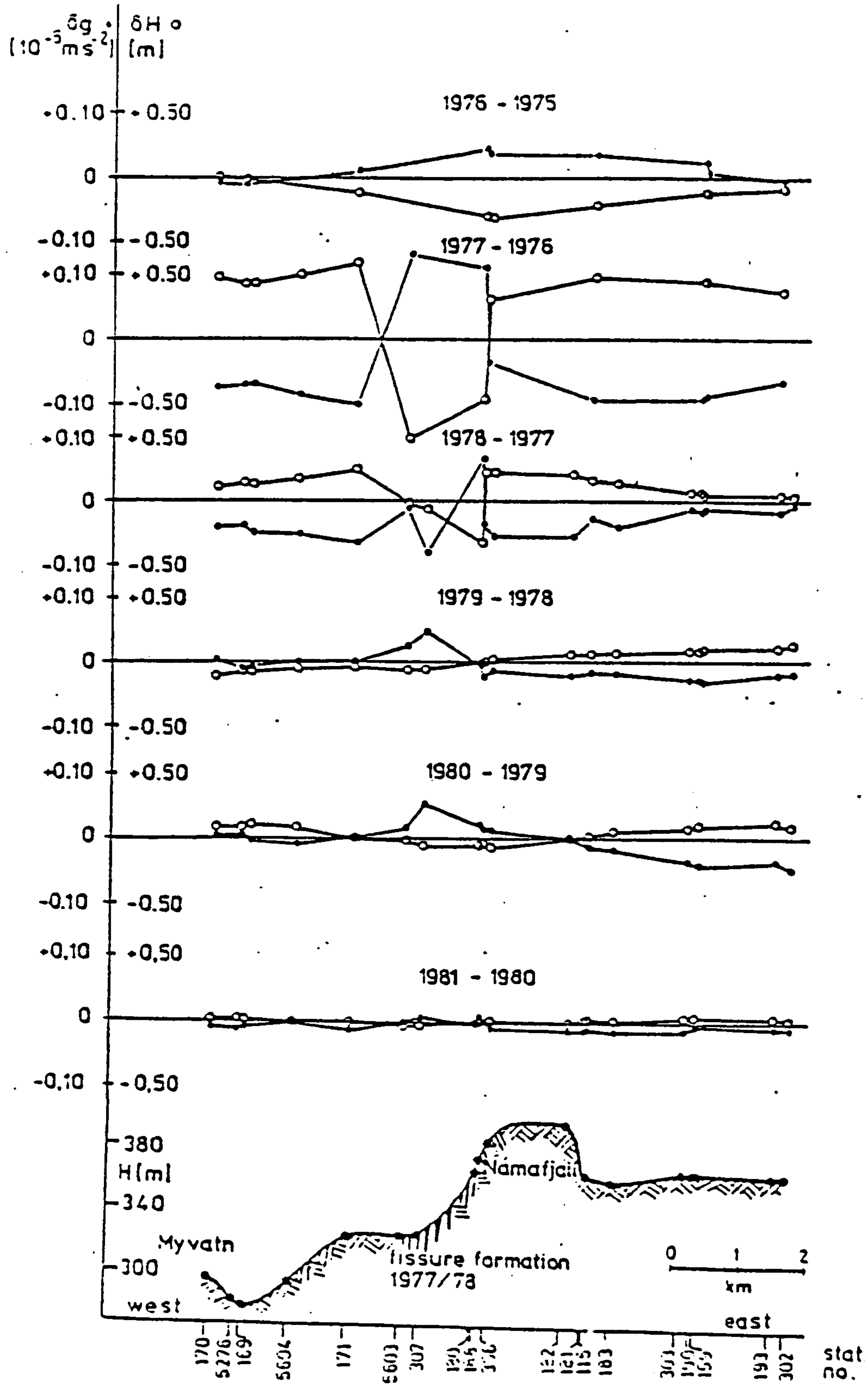



Figure 2.4 : Namafjall gravity profile :
Gravity and height variations between 1975 and 1981
(Torge, 1981)

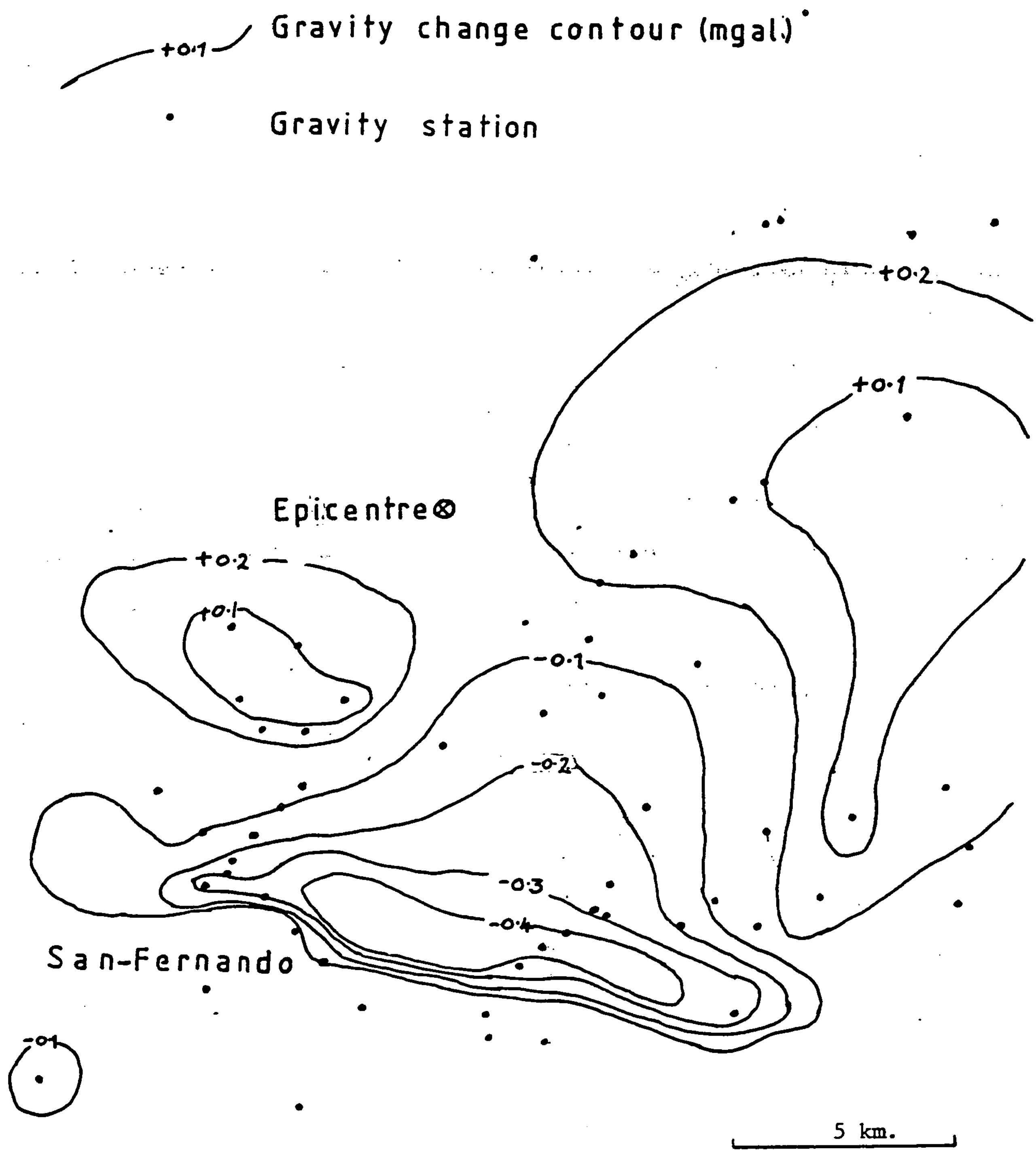
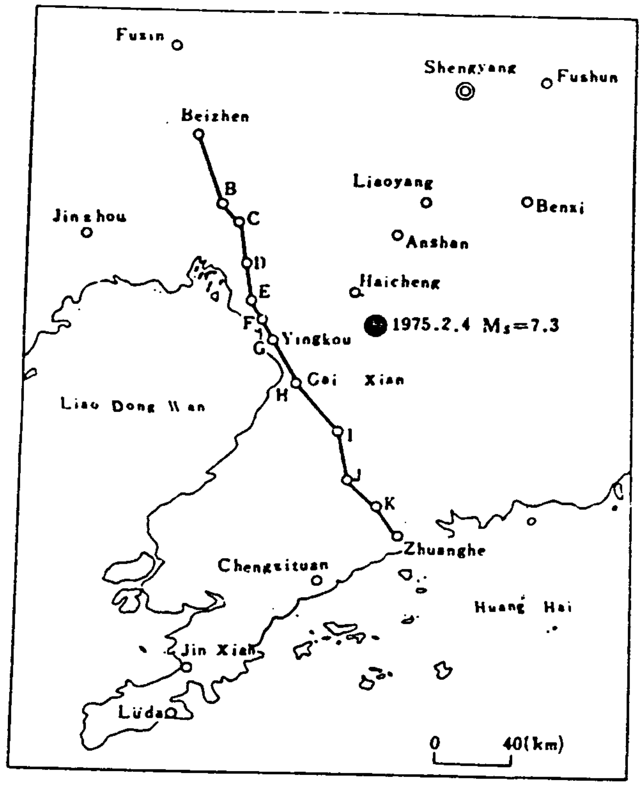
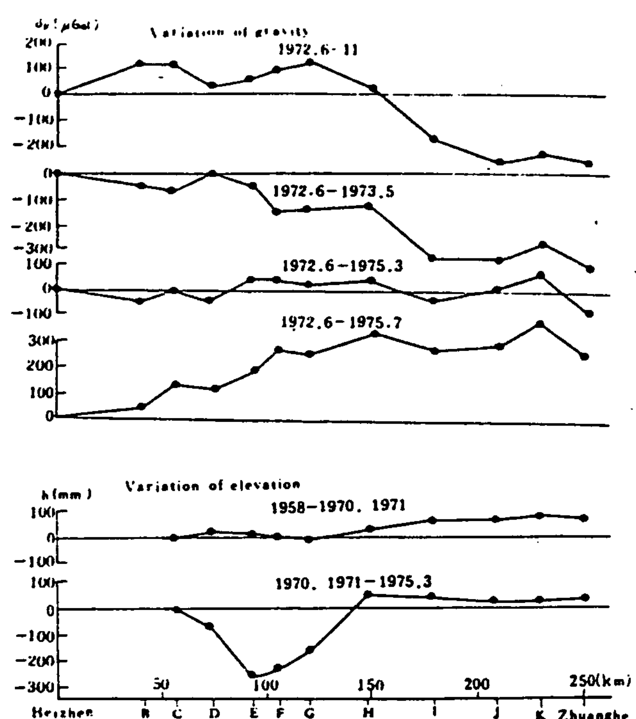



Figure 2.5 Gravity change following the San Fernando earthquake

(after Oliver et al 1975)




. Gravity traverse from Beizhen to Zhuanghe.




Changes of gravity and elevation along the Beizhen–Zhuanghe profile.

Figure 2.6 Gravity change after the Haicheng earthquake (from Chen et al., 1979) the large magnitude of measured variation. In the case of the Haicheng event the gravity value droped by a minimum of 3.52 g.u. before the shock but recovered to a slightly higher value ( 0.3 g.u.), but these measurements were made using $ZS_2$ quartz suspension gravimeters) after the shock. The subsidence attained a maximum of only 0.26 metres. The gravity change during the Tangshan region increased to a maximum of 1.65 g.u. before the earthquake followed by a slight decrease. Chen et al. proposed very large scale mass flux in these regions (up to 66km$^3$. in the case of Haicheng)

Other examples of gravity change in the region of earthquakes are available in the literature (Jachens and Eaton,1980 ; Hagiwara et al., 1980 ; Whitcomb et al., 1980 ; Boulanger, 1980 ) but it is only in the comparatively recent past that microgravimmetric networks have been established in areas of seismic risk. Generally, reported gravity changes have been associated with large magnitude events, but with the installation of specific networks Whitcomb et al. , (1980) report the precursory response of a magnitude 5.6 event at a distance of 67km. from the calculated epicentre.

## 2.4 Engineering Applications

This title refers to those areas of gravimmetric investigation which fall outside the normal regional scale surveys involving station separations of a kilometre or more. Engineering applications involve the use of much smaller station separations in the order of tens of metres to resolve highly localised structures perhaps associated with human activity. Such surveys require a high precision as well as close spacing and may involve the use of refined observation techniques to establish the gravity gradient.

the first reported use of gravimeters in such a way is the locating of a chromite (density $=_c 4400\text{kg.m}^{-3}$) ore bodies (Hammer et al 1945). Parasnis(1966) reviews gravimetric prospecting for ore bodies. A similar technique is used in the detection of voids which are difficult to detect geophysically and are often located by expensive high density drilling. Successful void detection is reported by Arzi (1975), Neumann(1966), and Blizkovsky(1979).

The earliest routine gravity exploration was undertaken using torsion balances which measure gravity gradients. This method was replaced with the use of the more rapid gravity meter. The vertical gravity gradient may be a more sensitive indicator of local structure (including oil bearing stratigraphic traps, Hammer and Anzoliga,1975) particularly voids. This is accomplished in the practically difficult operation of measuring at the top and bottom of a prefabricated tower (2-4 metres in height). Faklewicz (1976) reports rapid accurate (r.m.s.e. 15 Eotvos) detection of cavities. Attempts to measure the vertical gradient of gravity using a tower built at Edinburgh proved extremely difficult and other workers have questioned Faklewicz's reported accuracies (Arzi, 1977).

## 2.5 Underground Gravity Measurements

The very first undergound measurements were conducted using pendulums as early as 1854 in an attempt to determine the Newtonian gravitational consant (Airy, 1856). Subsequent underground measurements using modern gravimeters have largely been concerned with density determinations (Hammer, 1955 ; Hussain and Walach, 1980) and assumed the laboratory determined value of 'G'. Recent theoretical work has proposed that non-Newtonian attractive short range forces may exist and the attractive potential may be written

$$V(r) = -G_{\infty}m/r\ (1 + \alpha a e^{-\mu r})$$

$$\alpha = 1/3,\ \mu^{-1} = 10 - 1000\ \mathrm{m}$$

Stacey et al. (1981) review all the reported subsurface gravity measurements but fail to demonstrate a significant difference from the convential value of 'G'

# CHAPTER THREE

# THE MEASURING INSTRUMENT

## 3.1 The La Coste and Romberg Gravity Meter

The only commercially available relative gravity meter suitable for use in high precision work is manufactured by the La Coste and Romberg company of Austin, Texas. The La Coste and Romberg meter is in fact a modified long period vertical seismometer, the theory of which is well discussed in the literature (eg. Melton, 1971). A schematic diagram of the basic elements is shown in figure 3.1. An essential component of the instrument is the use of a 'zero length' spring . A zero length spring is defined a one in which the tension is proportional to the actual length of the spring (ie $l_o = 0$ in figure 3.2). This is accomplished by winding the spring under tension opposing the helix such that the spring is in compression when free.

Considering figure 3.1 the sensitivity may be stated as

$$S = x\ ( l_o + x )^2 / \ l_o a.b.\sin\ (\beta)$$

where x is the extension

Thus the sensitivity increases as $l_o$ approaches zero

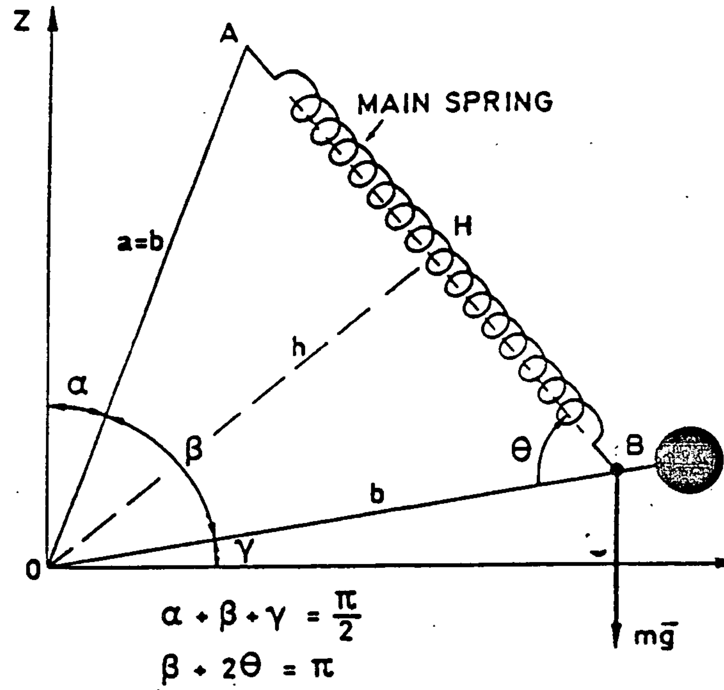



Figure 3.1 Spring arrangement of a typical gravimeter

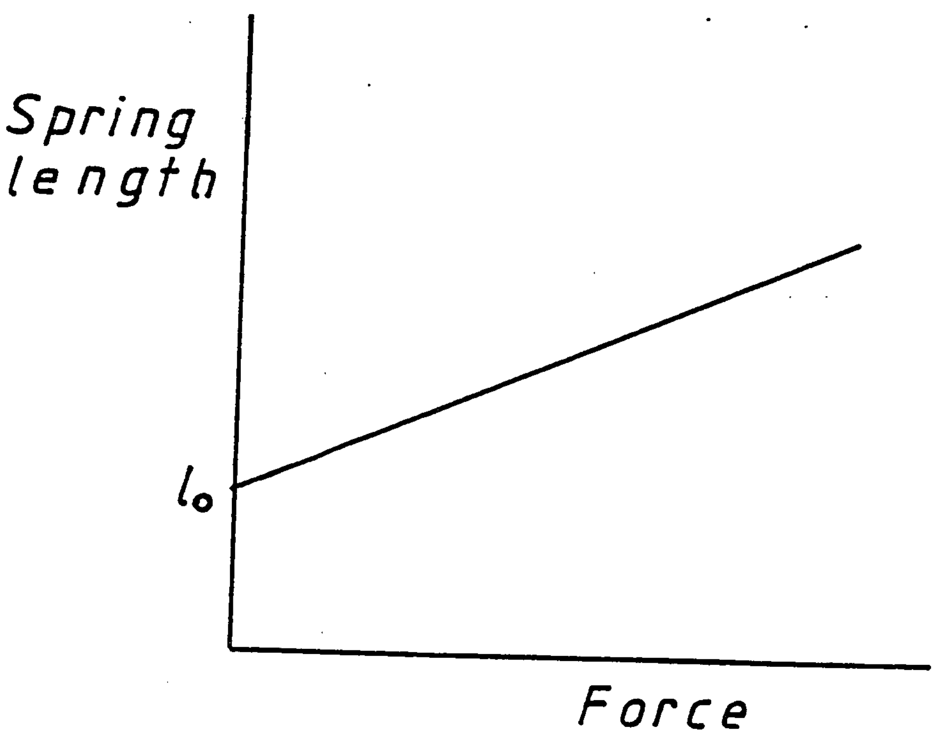



Figure 3.2 Spring extension curve.

Meters are individually produced by hand machining and for this reason it must be stressed that each meter posesses highly individual characteristics which become more apparent when the meter is taken to the limits of it's precision. Exact information about the internal workings are scant and the best source of information was found to be the original patents. A diagram taken from the original patent (U.S. 2,377,889 , 1945) is shown in figure 3.3 and the design has changed only trivally (Harrison and La Coste , 1978) since that time. A negative length spring (4), with wire added to bring it to the zero length condition supports the beam (3). The beam pivots about the line joining the points of attachment of the springs (5) to the support rods (6) and theory (La Coste, 1935) shows that for equilibrium of the beam in a horizontal position the distance, A, of the upper support (35) of the zero length spring above this pivot line is proportional to g.. The meter is read by moving the support 35 vertically to bring the beam into position The change dA in A required to do this as the meter is read first in one place and then another is proportional to gravity difference dg by the relation $dA/A = dg/g$. The meters are built with A = 2.5 cm. so that the 70,000 g.u. range of the G meter requires moving the support 0.115 mm. and 0.01 g.u. accuracy means positoning the support to within $2.5 \times 10^{-11}$m.. The La Coste company has recently introduced the model 'D' meter which has many refinements to the basic design. These include improved levels which the manufacturers claim

June 12, 1945. L. J. B. LA COSTE ET AL 2,377,889

FORCE MEASURING INSTRUMENT

Filed Aug. 12, 1939 2 Sheets-Sheet 1

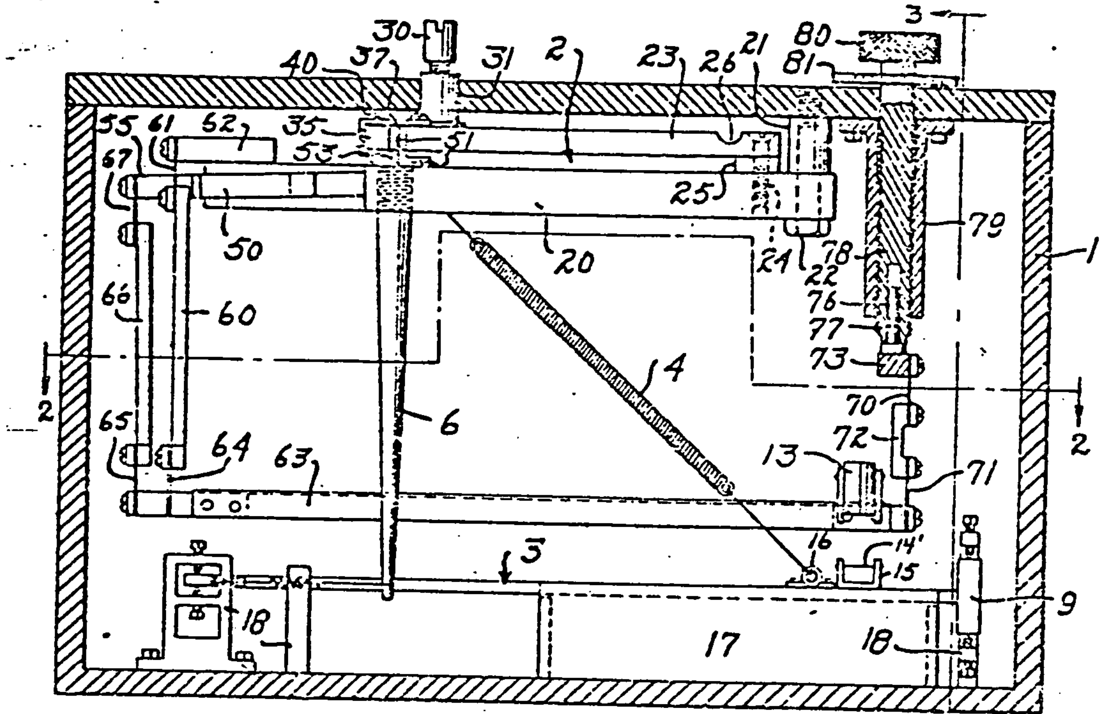


Fig. 1.

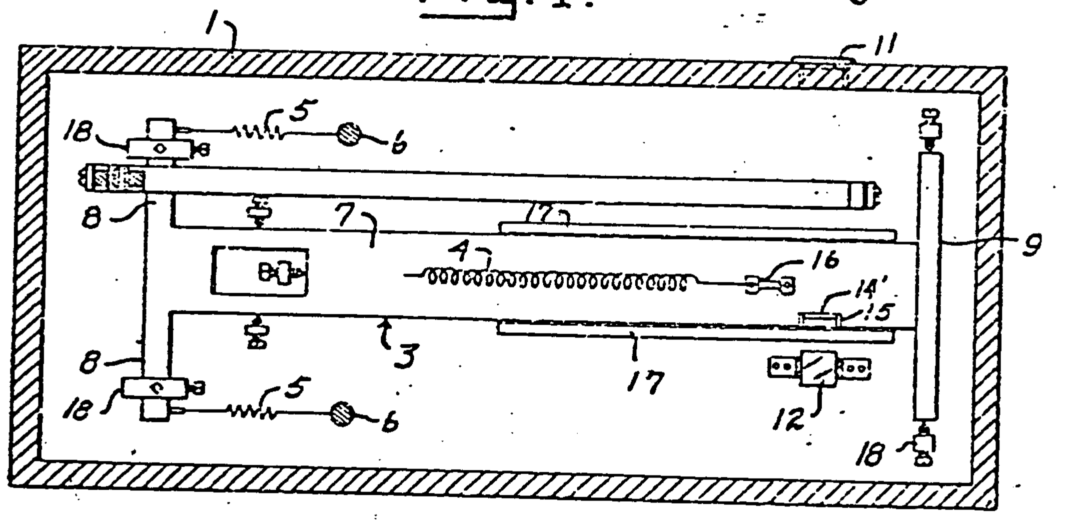


Fig. 2.

LUCIEN J. B. LACOSTE
ARNOLD ROMBERG
INVENTORS.

BY Jesse R. Stone
Lester B. Clark
ATTORNEYS.

Figure 3.3 Extract from the 1945 La Coste and Romberg patent.

improve the accuracy of the meter and more importantly changes in the gearing system. This improvement is undoubtedly the case in some cirumstances but for surveys including large gravity differences ( the D model range, without resetting is 2000 g.u.) or much transportation the intrinsic accuracies of the G and D models are similar (McConnell et al, 1975; Grannel et al. , 1982, summarise the relevant differences)

## 3.2 Instrumental Modifications

Certain external modifications were made in an effort to improve reading accuracy. The only alteration affecting the meter directly was the addition of a small vernier scale to replace the dial pointer. To improve the levelling precision it was necessary to bolt the meter on to a large secondary base plate which also incorporated improved screw feet. The meter was simply bolted to this plate using the convential feet screw holes, thus it could be easily removed for other use. The base plate design criteria also included.

(1) Accommodation of two nickel cadmium batteries for prolonged observation sequences

(2) Mounting hooks for suspending the base plate during transportation to eliminate shocks and vibrations

(3) Finely threaded screw feet at right angles , parallel and perpendicular to the direction of the meter beam ('long axis')

(4) Mounting for improved levelling bubbles

(5) Easy use with a sturdy tripod suitable for use on Ordnance Survey fundamental bench marks.

(6) Use as a laboratory tilting table

The level bubbles of the standard La Coste and Romberg instrument suffer from several disadvantages. (a) They are not adequatly sensitive: one scribed division on the glass vial corresponding to 30 seconds of arc. (b) The bubbles are illuminated by festoon bulbs situated directly beneath the glass vials. When illuminated for a period of time both the fluid and the vial are heated causing bubble drift. (c) The bubbles are simply viewed from above and consequently there is a parallex error. This problem is further accentuated by uneven illumination of the bubbles from beneath.

The zeiss coincident viewing system overcomes these disadvantages and is the method used on many one second theodilites. Both ends of the bubble are view separately via a prism system and 'level' is found when the two images are coincident and appear as a single smooth curve (Bomford, 1981). Suitable levels, manufactured for use on a Cook ,Trout and Simms geodetic theodilites were obtained for use on the secondary plate. The fitted coincident veiwing levels had the disadvantage that the instrument cannot be levelled at night , but high precsion surveys should not include night time readings because of the change in the relative illumination of the beam marker image..

The secondary plate was milled from twelve millimetre aluminium plate, the plan and elevation are shown in figure 3.4. A large aluminium block, machined to a right angle , accommodates the coincident levels at right angles. The screw feet are manufactured from stainless steel with a pitch of 0.025 inches and two screw feet are mounted on brass pillars. The third support consists of a ball bearing forced into a brass pillar and is of fixed length. The screw feet are mounted eccentrically and rotation of the brass pillar causes lateral movement of the point of support. The level mounting block may also be rotated and after securing the gravity meter a series of iterative adjustments ensures that the levels and feet are parallel to the principle axis of the meter The tilt of the coincident veiwing levels may be adjusted by means of two allen screws.These were adjusted in a manner similar to that described in the La Coste and Romberg manual for the levelling of the internal levels.

A tripod was constructed with adjustable hardwood legs and a top frame of three millimetre angle aluminium (figure 3.5). The screw feet of the secondary platform rest on the

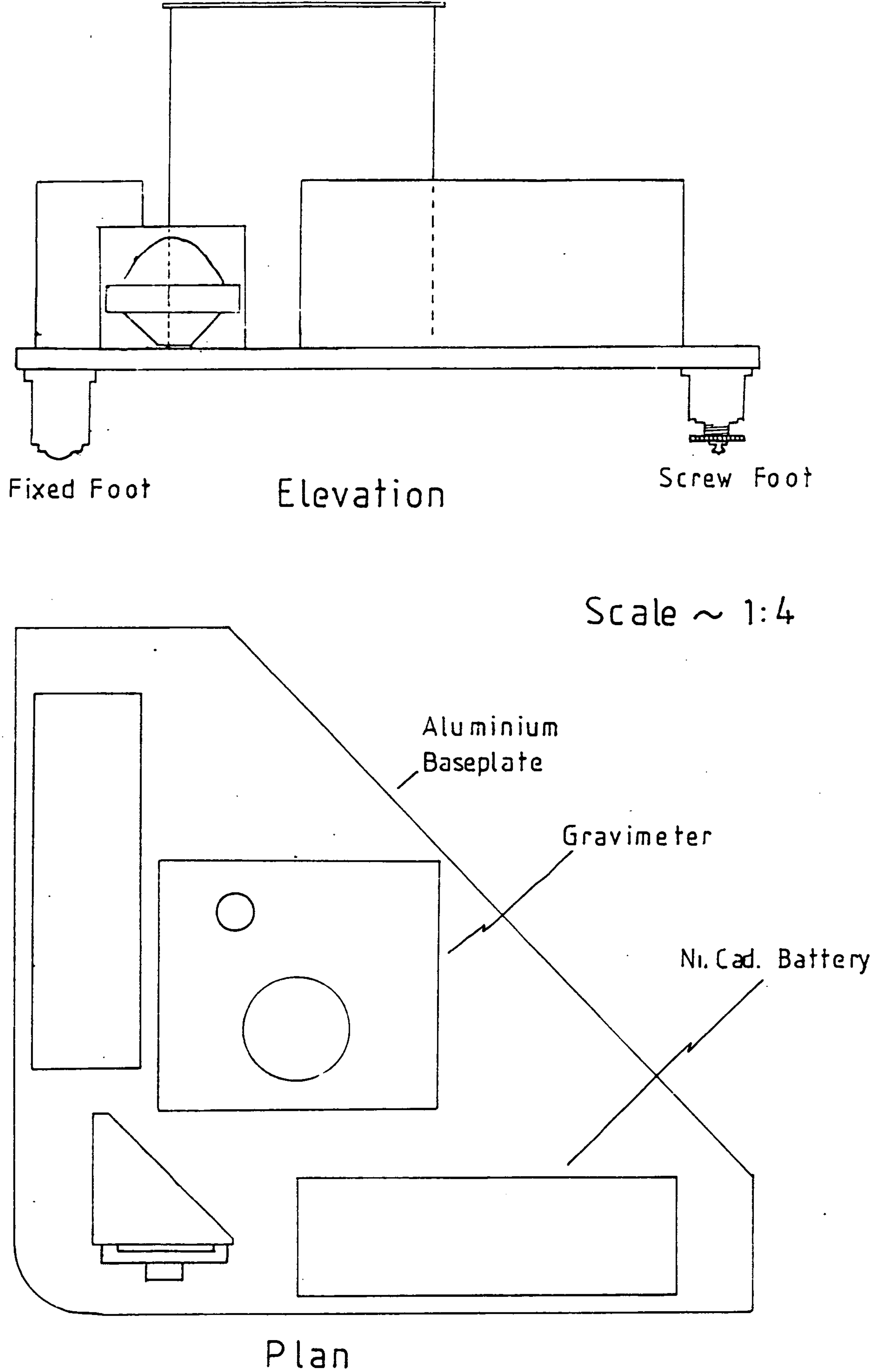



Figure (3.4) Instrumental Modifications

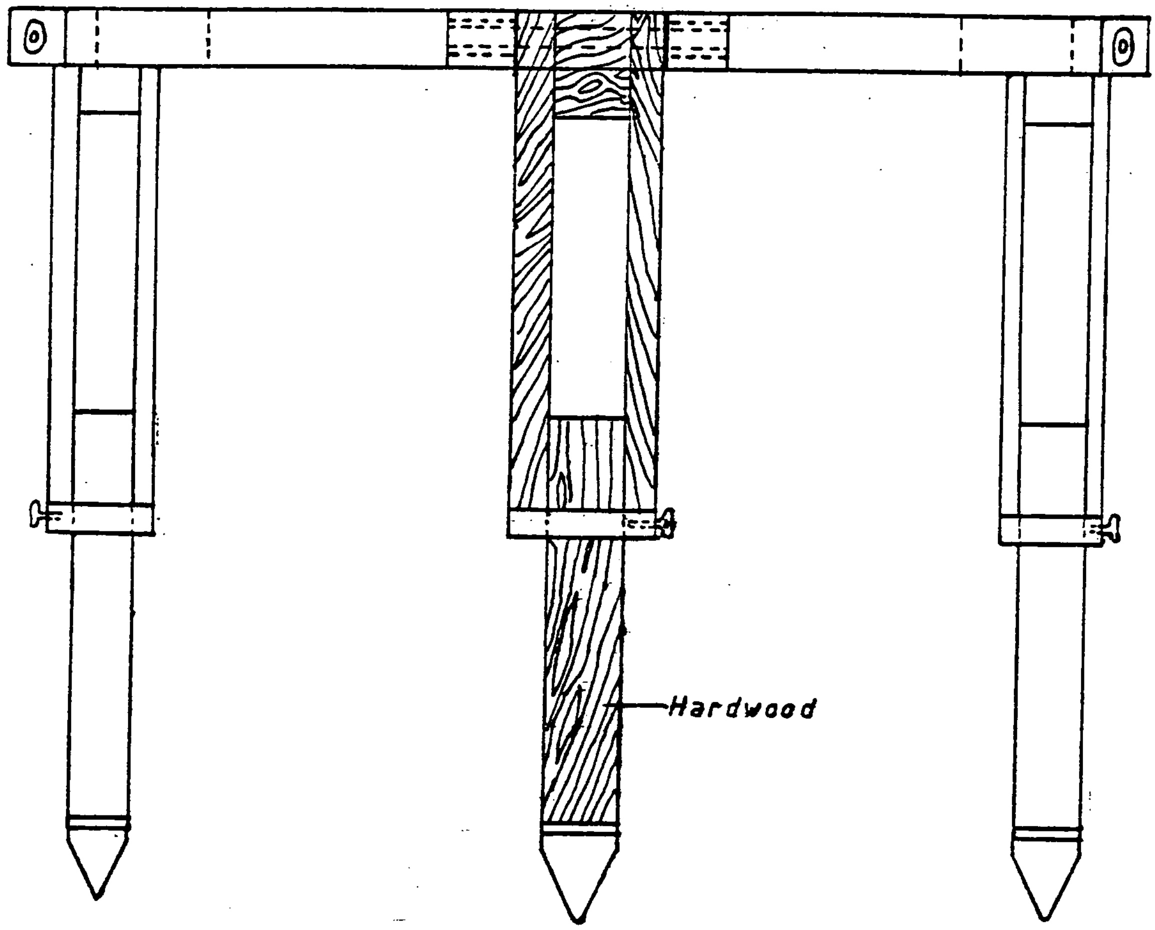
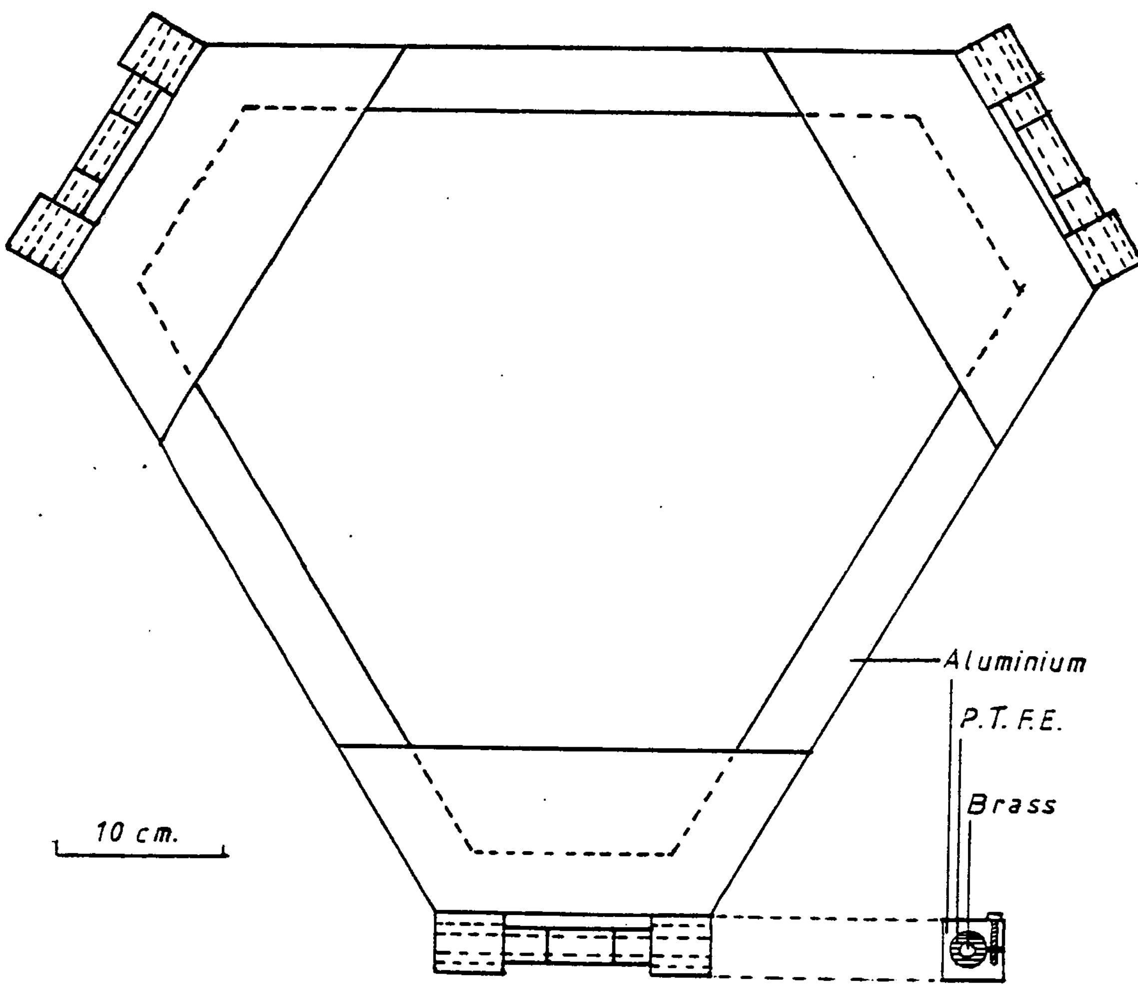



Figure 3.5 Plan and elevation of tripod



the trapezoidal corner plates. The tripod can be rapidly dissassembled for storage and transportation. The tripod may be used in conjunction with a fundamental bench mark used as a third leg to provide an extremely stable measuring base. In this case one tripod leg is removed and replaced by a plate with a triangular hole cut out directly beneath the static foot, providing a three point contact with the hemispherical dome of the bench mark. Two views of the tripod in use at a fundamental bench mark (Tummel Bridge) are shown in Plates 3.1 and 3.2.

## 3.3 Instrumental Investigations

As stated above, each instrument is an individual and before high precision measurements can be undertaken it is necessary to quantify intrinsic characteristics and the instrument response to external factors.

The La Coste and Romberg meter is designed to minimise instrument drift. The mechanism is maintained at a constant temperature and typical hourly drift rates are about 0.02 $g.u.hr.^{-1}$. This long term drift is approximately linear and regional surveys using a La Coste and Romberg instrument usually visit a single base only twice a day. In addition to the long term drift pattern meters drift when unclamped. This effect appears to be particularly large for G -275 though other workers have not investigated the

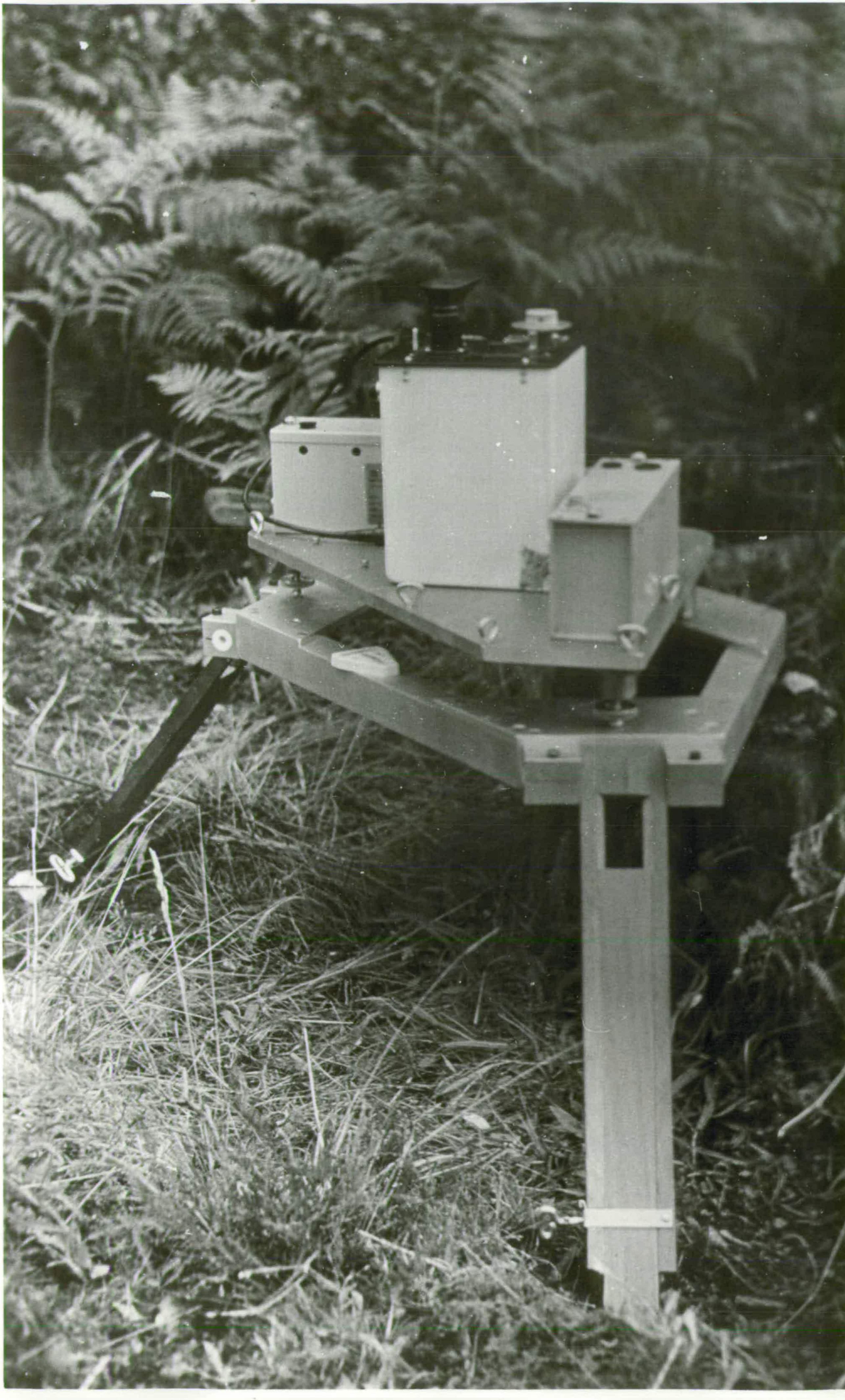
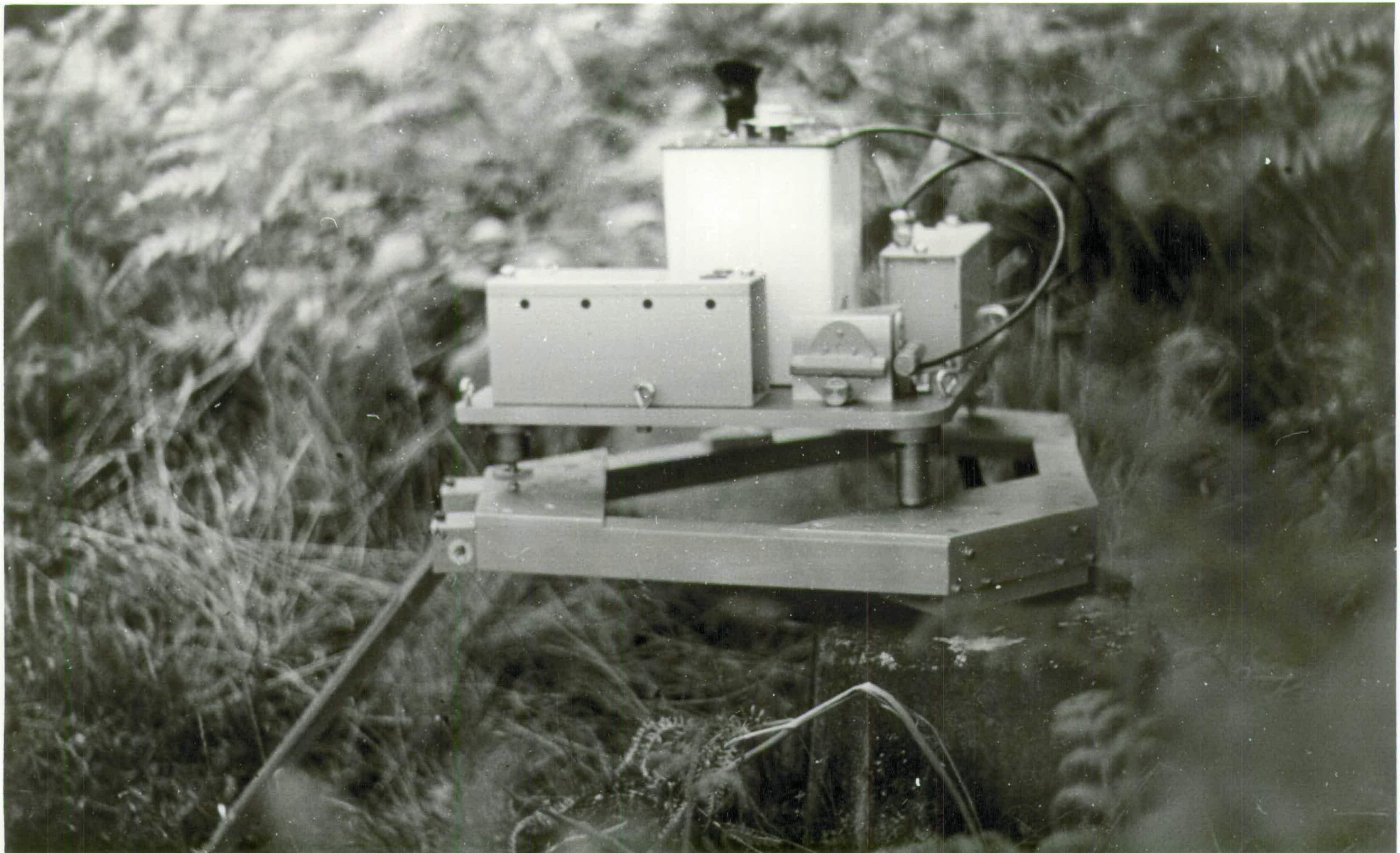
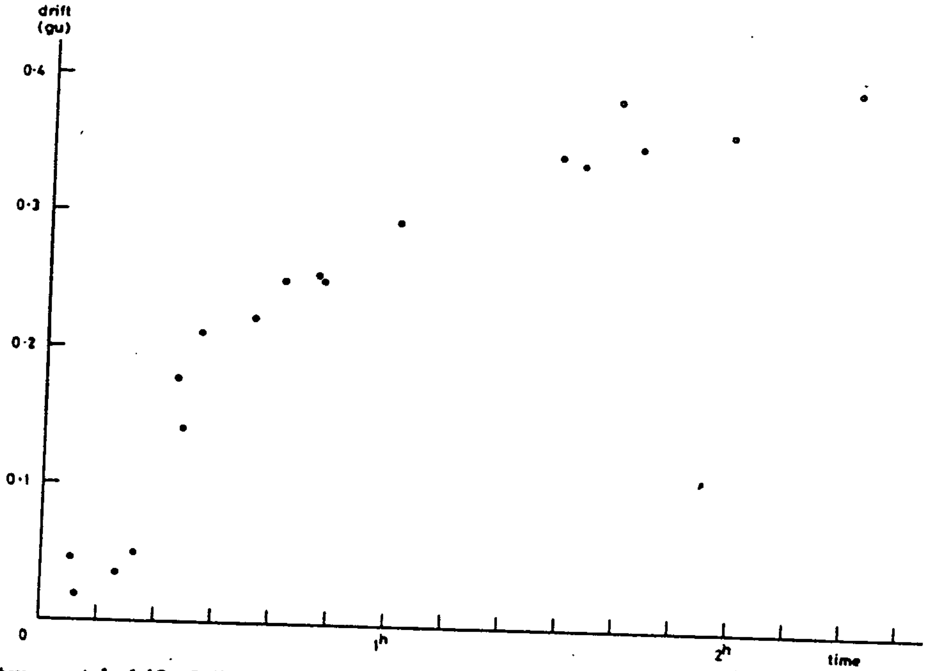


Plate 3.2: An illustration of field use of the tripod.



effect thoroughly. The Edinburgh instrument had previously undergone some testing which established a recognisable, repeatable drift curve at any site, probably associated with unclamping of the beam (Hipkin, 1980). A typical drift curve, obtained by repeated reading of the meter with the lamps continuously on and the beam unclamped, is shown in figure 3.6 . The two observation sequences illustrated in figure 3.6 differ by seven years demonstrating this is long term feature of this instrument. The readings display a rapid initial positive drift over the first thirty minutes, levelling out to an 'equilibrium' value after eighty to one hundred minutes. Such drift is not explicitly described by other workers but sharp initial drift is a recognised phenomena and is is common practise to take site readings as rapidly as possible (Peterson, 1978). Indeed Sanderson (1982) illustrates a mean drift curve obtained from a set of thirty readings for G-90 , reproduced in figure 3.7, which is remarkably similar to figure 3.6. The author attributes this effect to mechanical hysterisis associated with the removal of tension from the pivotal shock eliminating springs ((5) in figure 3.3) and the main spring. It is the experience of the author that a high precision reading can not be taken very rapidly and that the time to obtain a satisfactory reading is somewhat variable.

Since field measurements are necessarily taken in uncontrolled environments it is necessary to evaluate the effec ts of external agents such as (1) Temperature, (2) Air




Instrumental drift following unclamping for the LaCoste and Romberg gravity meter G-275. The zero of time is $15^h 03^m$ on 23/2/76 (○) or $15^h 39^m$ on 3/3/76 (•).

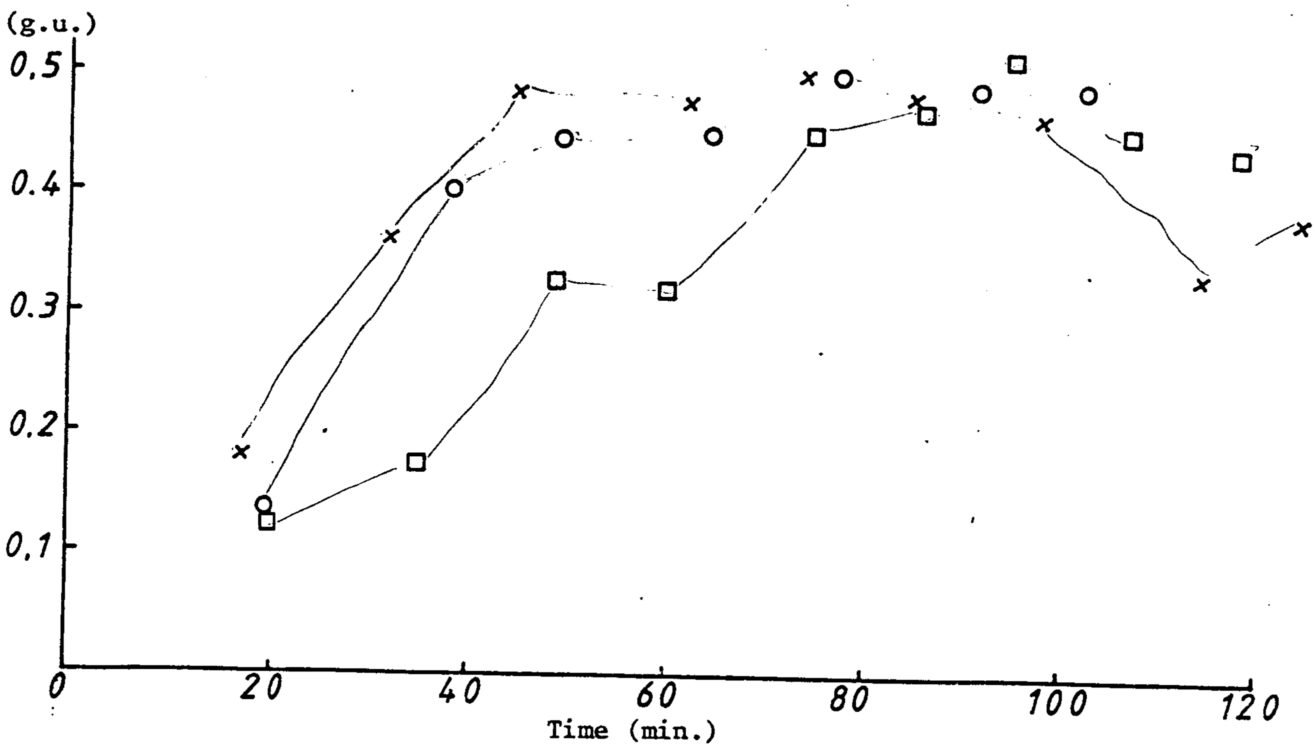



Figure 3.6 Representative drift curves for La Coste and Romberg gravimeter G-275. The upper figure is taken from Hipkin (1978), the lower set of observations (three independent sets) were observed by the author .

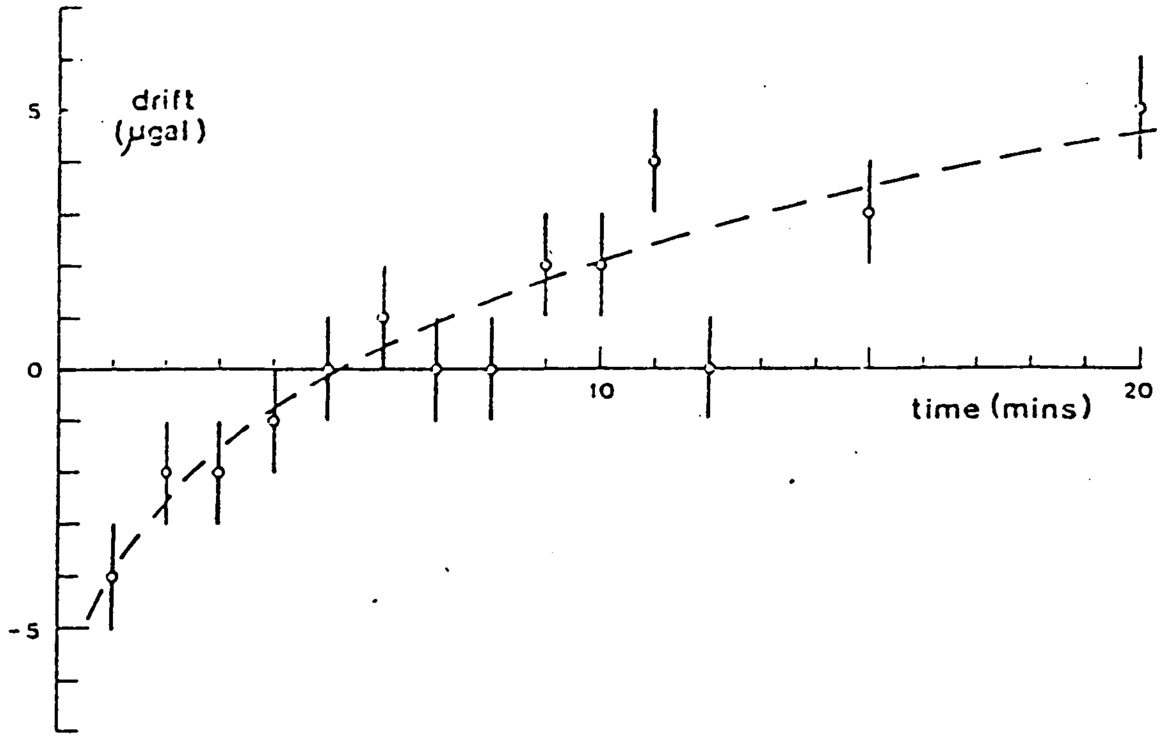



Figure 3.7 Composite drift curve taken from Sanderson (1982) for La Coste and Romberg Gravity Meter G-90. Mean of 30 independent determinations.

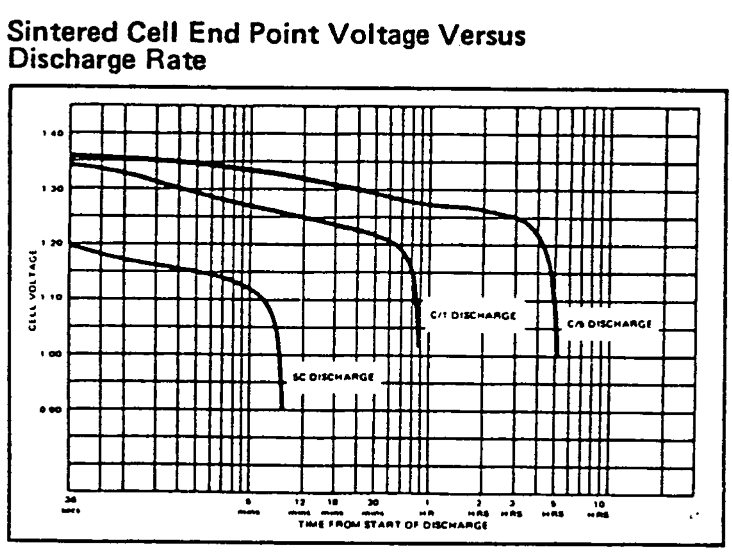



Figure 3.9 Typical Nickel-Cadmium cell discharge curves.
C is the cell capacity in Ampere-hours.

Pressure, (3) Voltage Supply, (4) Magnetic Field.

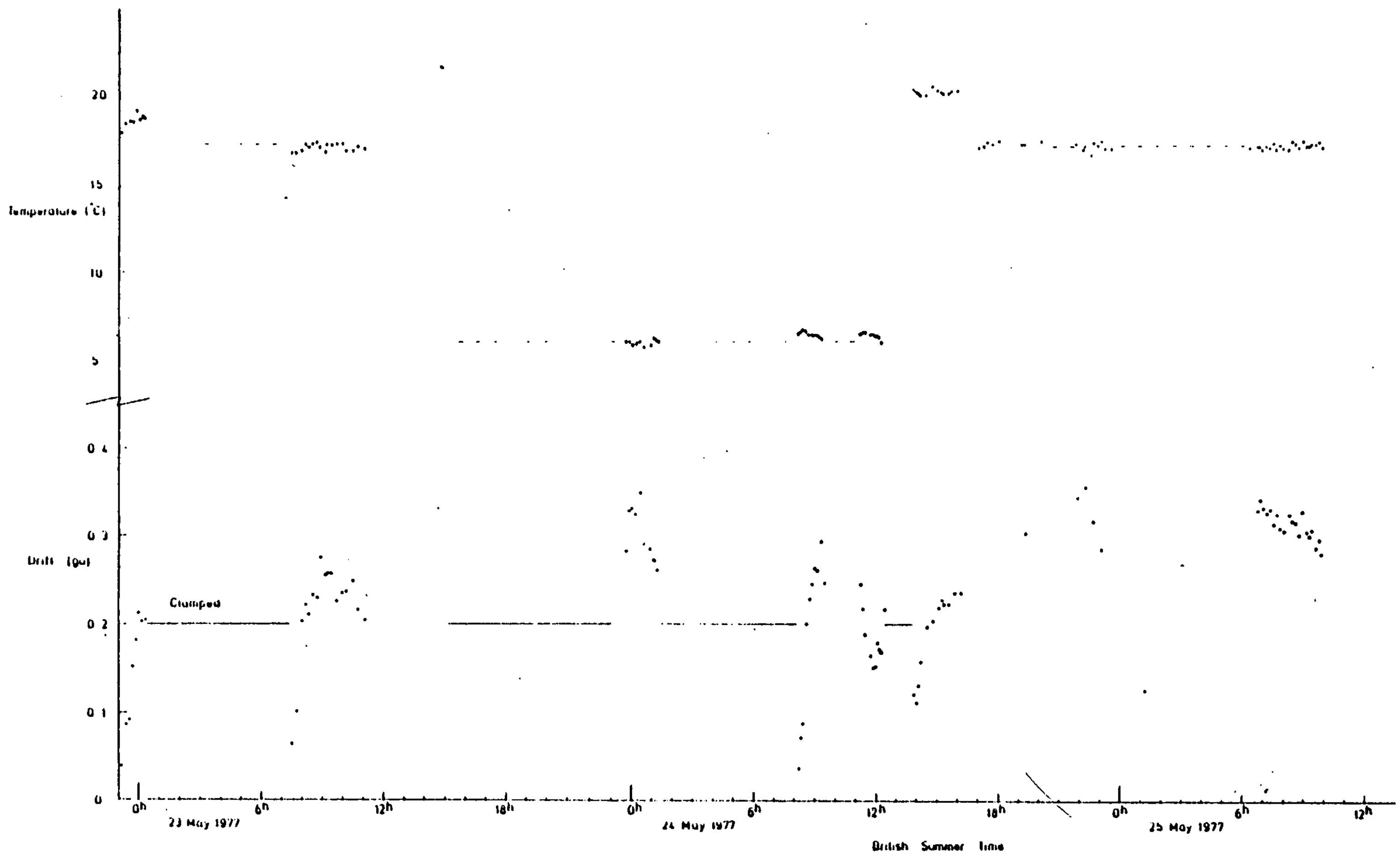
**(1) Temperature**

It was initially postulated that the drift curve illustrated in figure 3.6 was a response to a temperature change associated with the removal of the instrument from it's insulated carrying case. Hipkin (1978) describes elaborate tests on G-275 which disprove this and indicate there is no recognisable gravity change associated with a temperature variation of $17^{\circ}C$. (see figure 3.8 taken from Hipkin, 1978).

Table (3.1) illustrates the results presented in the literature. It can be seen that the effect is varaiable from meter to meter and generally small. Many observers note that the effect is indeed variable in form on a given instrument depending on the rapidity of the temperature change. Boedecker (1981) noted that it is almost impossible to model under field conditions. The effect may be particulary small for G-275 because the meter has been obtained at the working temperature of $49.1^{\circ}C$ since it's purchase in 1972.

**(2) Air Pressure**

Variations in air pressure at a station will cause a gravity change associated with the changing Newtonian




The effect of ambient temperature on instrumental drift for the LaCoste and Romberg gravity meter G-275.
Note: (i) a voltage reduction, not affecting the gravimeter thermometer but slightly dimming the lights, occurred between $11^h$ $28^m$ and $11^h$ $46^m$ on 24/5/77. Readings between $11^h$ $17^m$ and $12^h$ $25^m$ are considered unreliable;

Figure 3.8 Effect of temperature variation on G-275 (from Hipkin, 1978)

Table 3.1

Gravimetric Effect of Air Temperature Changes

| Author | No. of Meters | Temperature Change | Observed 'Gravity Change' g.u./$10^{o}C$ |
|---|---|---|---|
| Brein et al., 1977 | | | |
| GL | 5 | $8^{o}C \rightarrow 30^{o}C$ | $-0.16 \pm 0.037$ to $+0.058 \pm 0.040$ |
| | 4 | $14^{o}C \rightarrow -10^{o}C$ | $-0.012 \pm 0.002$ to $-0.002 \pm 0.002$ |
| | | | Rate dependent |
| IFAG | ? | $\Delta T = 10^{o}C$ | $-0.02$ max |
| THD | ? | $\Delta T = 20^{o}C$ (fast) | 0.4 max (irregular |
| Boedecker, 1981 | 4 | $0 \rightarrow 30^{o}C$ slow | $-0.23$, $-0.02$, $+0.0$ $+0.08$ and $+0.1$ |
| Nakagawa, 1975 | 8 | $20^{o}C \rightarrow -10^{o}C$ | c $-0.05 \rightarrow +0.1$ |
| Gerstenecker, 1978 | 1 | $\Delta T = +12^{o}$ in 3 min | $\Delta G = 0.08$ g.u. |
| Williams, 1983 | 7 | $\pm 20^{o}C$ | Optical readout av $0.2 \pm 0.03$ Electronic readout $0.1 \pm 0.08$ |

GL Geodettinen Laitos, Helsinki (Kiviniemi)

IFAG Institut fur Angewandte Geodäsie, Frankfurt am Main (Brein)

THD Technische Hochschule, Darmstadt (Gerstenecker) attraction of that mass of air. Theoretically this effect is $-4.2\times10^{-3}$ g.u./mbar but deformation of the crust and lateral pressure variations reduce this factor. A correction of $-3\ \times10^{-3}$ g.u./mbar is applied to observations in the program PBAS (Section 4.5)

In addition to the direct Newtonian attraction, the changing air pressure exerts a mechanical effect on the delicate balance of the instrument. Figure 3.3 shows a damping chamber attached to the main beam to minimise the effect of rapid pressure variations. Furthermore the mechanism is enclosed in a sealed chamber which though not perfect, lessens the effect of external pressure variations (Harrison and La Coste, 1978).

No facilities for controlling the air pressure in a chamber containing both the meter and an observer were available to the author. Table 3.2 presents all the published values for the mechanical effect of pressure variations located by the author.

(3) Voltage Supply

The meter is supplied with Nickel Cadmium cells, which can supply the meter for one day under typical field conditions. The voltage of nickel cadmium cells under load drops gradually from 1.35 to 1.25 volts before the onset of very rapid loss of capacity (figure 3.9). The measurements

Table 3.2

Gravimetric Effect of Air Pressure Variations

| Author | No. of Meters | Pressure Change | Observed 'Gravity Change' g.u. per 100 mbar |
|---|---|---|---|
| Brein et al., 1977 | | | |
| IFAG | ? | 65 mbar | 0 |
| THD | ? | Fast > 20 mbar/min | $3.5 \times 10^{-4}$ |
| GL | 5 | ? | −0.027 0.021 to<br>+0.021 0.6 |
| LMV | 2 | ? | −0.027 and −0.024 |
| Williams, 1983 | 2 | 300 mbar | $-3 \times 10^{-4}$ and 4 x 1 |
| Boedecker, 1981 | 4 | 400 mbar | −0.0006, −0.0014<br>−0.0014, −0.0016 |

IFAG Institut fur Angewandte Geodäsie, Frankfurt am Main (Brein)

THD Technische Hochschule, Darmstadt (Gerstenecker)

GL Geodeettinen Laitos, Helsinki (Kiviniemi)

LMV Statens Lantmäteriverk, Gävle (Pettersson) carried out by the author in Scotland (see Chapter Eight) required prolonged use of the cursor illuminating lights and field battery life was less than one day. The auxiliary platform accommodates two batteries which is sufficient for a twelve hour field day with repeated use of lights. In addition to these measures, an in line connector was attached to the supply cable so that a car battery could be inserted into the circuit. This alternative (a 36 ampere hour sealed lead acid battery) was used whilst the gravimeter was in the vehicle.

Laboratory tests using a stabilised power supply failed to demonstrate any gross effect caused by varying the input voltage of G-275. The results of these tests are shown in figure 3.10. In the upper caser the supply voltage has been varied rapidly between converging extremes whilst in the lower case the voltage has been held at an anomalous voltage for about sixty minutes. The characteristic drift pattern discussed above is evident but no voltage effect at these extreme voltages is apparent. Table 3.3 summarises the results of several published studies.

**(4) Magnetic field**

Precise details of the materials used in the construction of the La Coste and Romberg gravimeter are not available but it is known that the main spring is

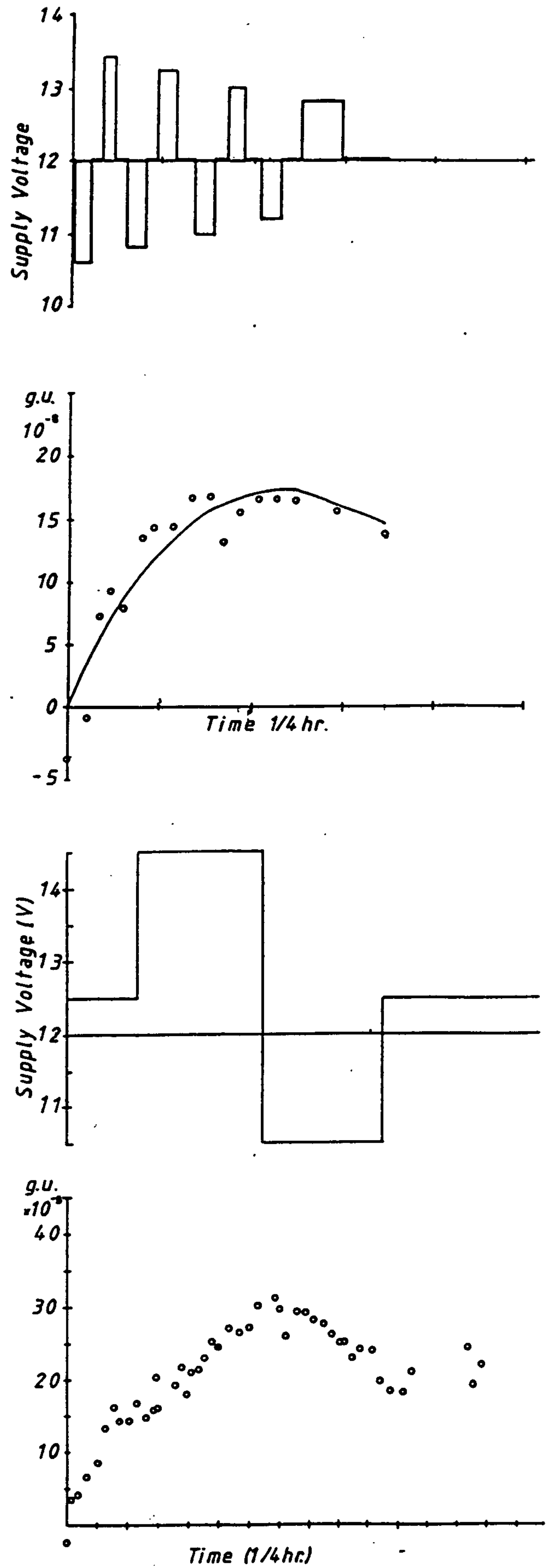



Figure 3.10 Effect of varying voltage on G-275 reading

Table 3.3

The Effect of Supply Voltage Change on Gravity Meter Reading

| Author | Number of meters | Voltage variation | Observed gravity change g.u. per volt |
|---|---|---|---|
| Boedecker 1978 | 1 | 10 V → 12.5 V | - 0.04 |
| Williams 1983 | 7 | 10 V → 14 V | maximum of<br>+ 0.04 ± 0.01 optical<br>- 0.01 ± 0.005 electronic |
| (Nickel Cadmium cells recommended ΔV = 0.3 V) | | | |
| Nakogawa 1975 | 4 | 10 V → 14 V | - 0.02, - 0.05, - 0.05, - 0.05 |

magnetic (Harrison and La Coste, 1978). The spring is demagnetised before assembly and the sealed chamber provides magnetic sheilding.

The meter was tested by placing it in the centre of a large, 2x2x2 meters, set of Helmholtz coils (figure 3.11) with the long axis of the instrument aligned east west. The magnetic field was altered by by varying the current in each set of coils independently and measured using a hand held field strength meter. The meter was read continuously, during which time the magnetic field underwent three transitions between the field states illustrated in figure 3.11. Initially the coil currents were adjusted to null the ambient field to within a few nano Tesla. The meter was then read continuously (i.e. about every four minutes, temperature and pressure were also noted) for a period before the vertical and north coil currents were switched off. Hence the earth's field was again ambient in those directions (referred to as 'H'). After a period of observation, the zeroing current was turned on again but reversed so the magnetic field of the vertical north-south plane was twice that of the Earth (referred to as '2H'). The third transition was accomplished by finally returning to zero field ('O').

Five observation sequences were undertaken and the results of four are shown in figure 3.12. These graphs clearly illustrate a correlation between magnetic field

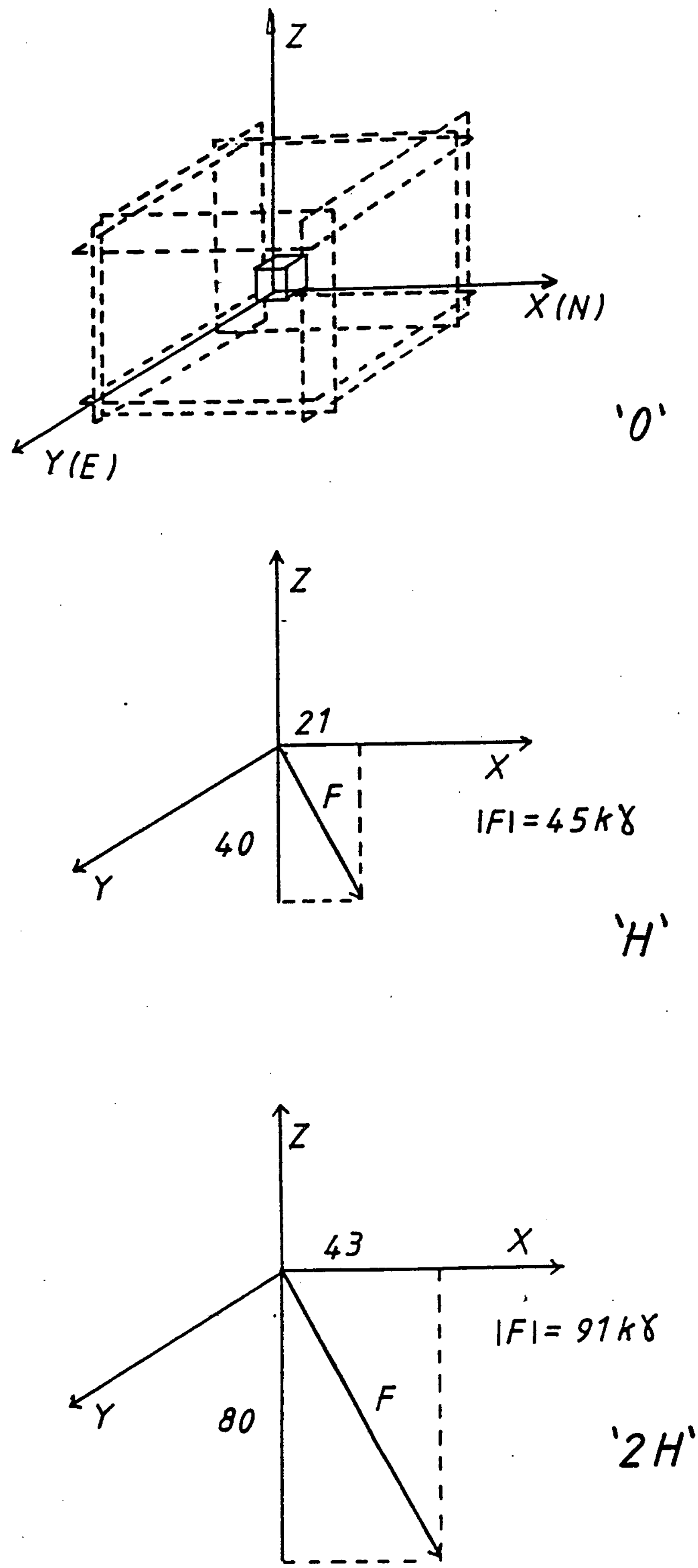



Figure 3.11 Schematic diagram of magnetic field vector

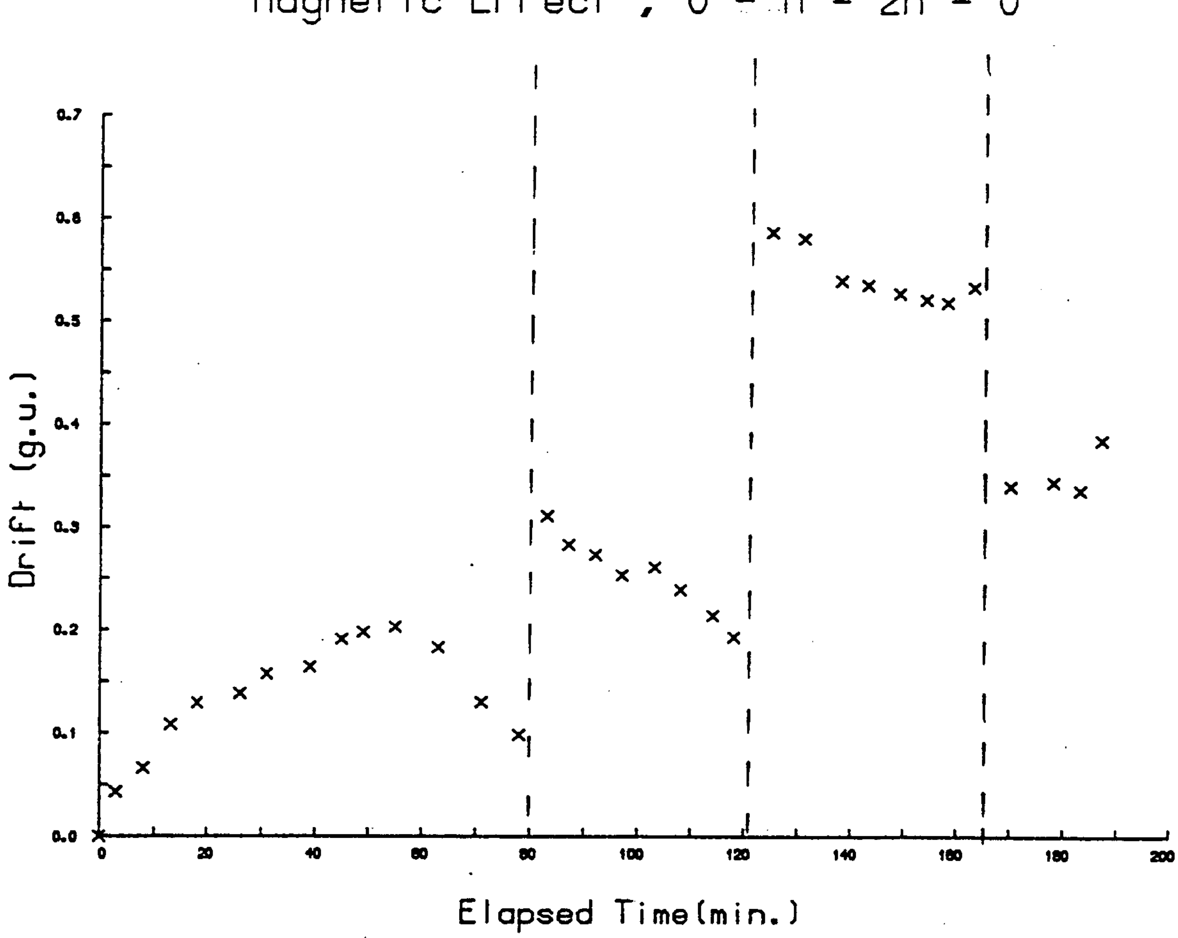



Figure 3.12(a)  MAGA Observations

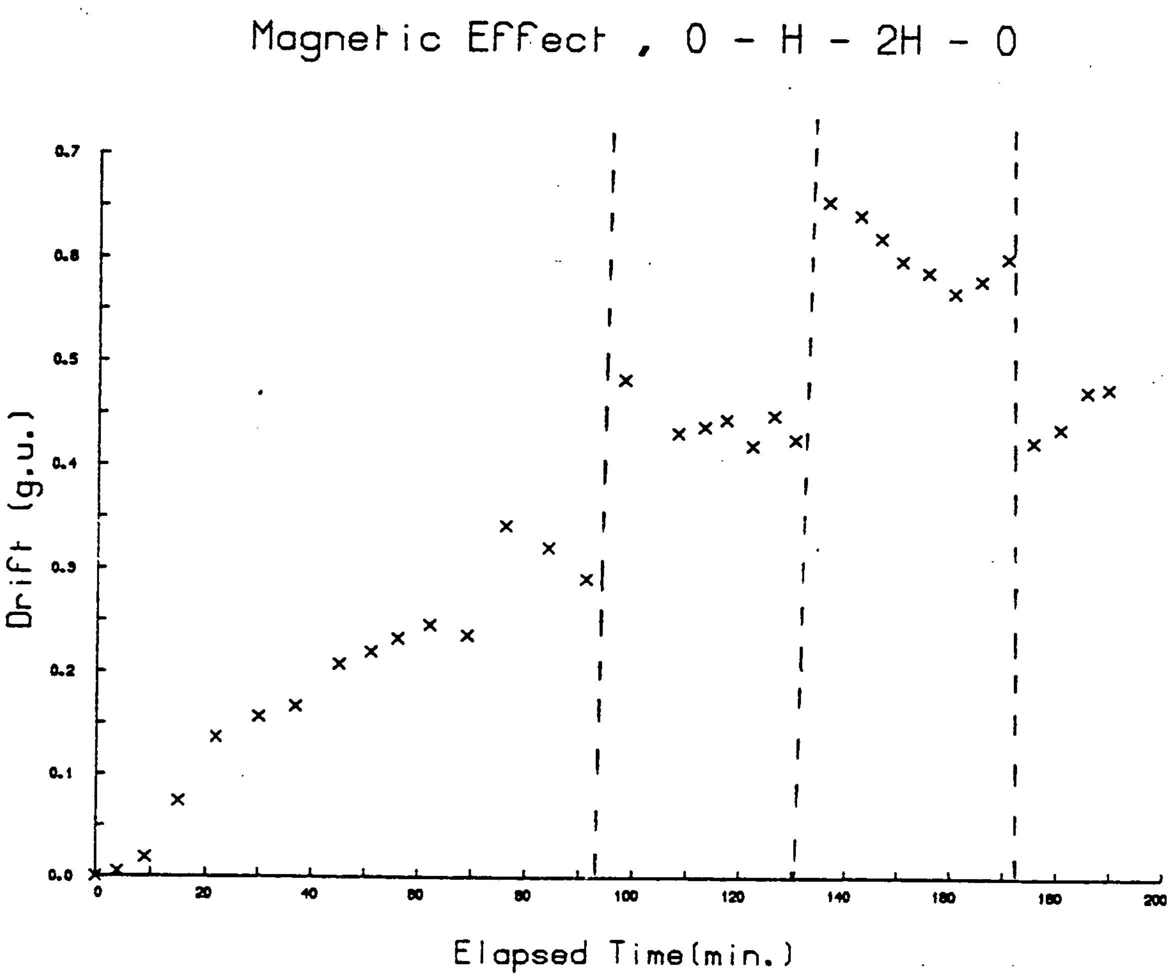



Figure 3.12(b)  MAGB Observations

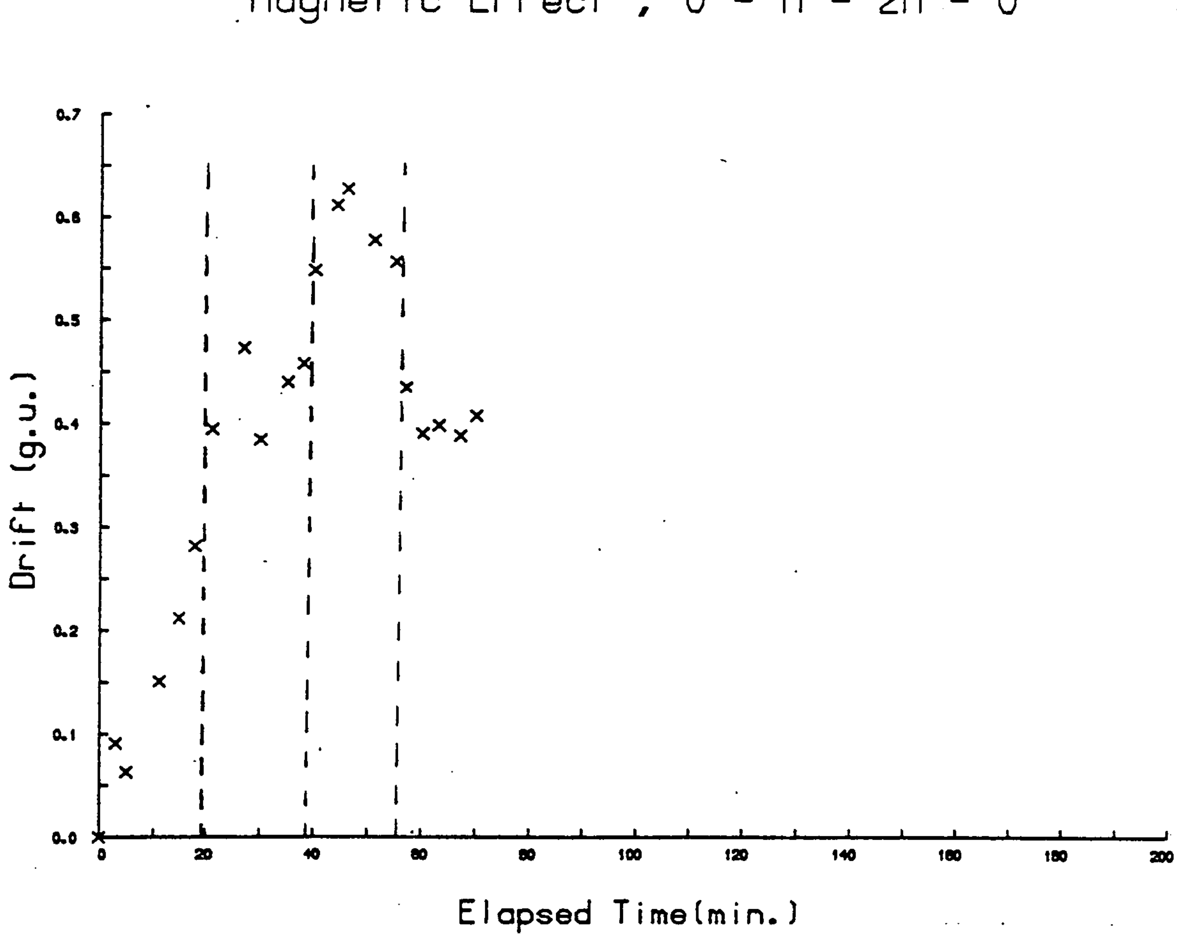



Figure 3.12(c) MAGD Observations

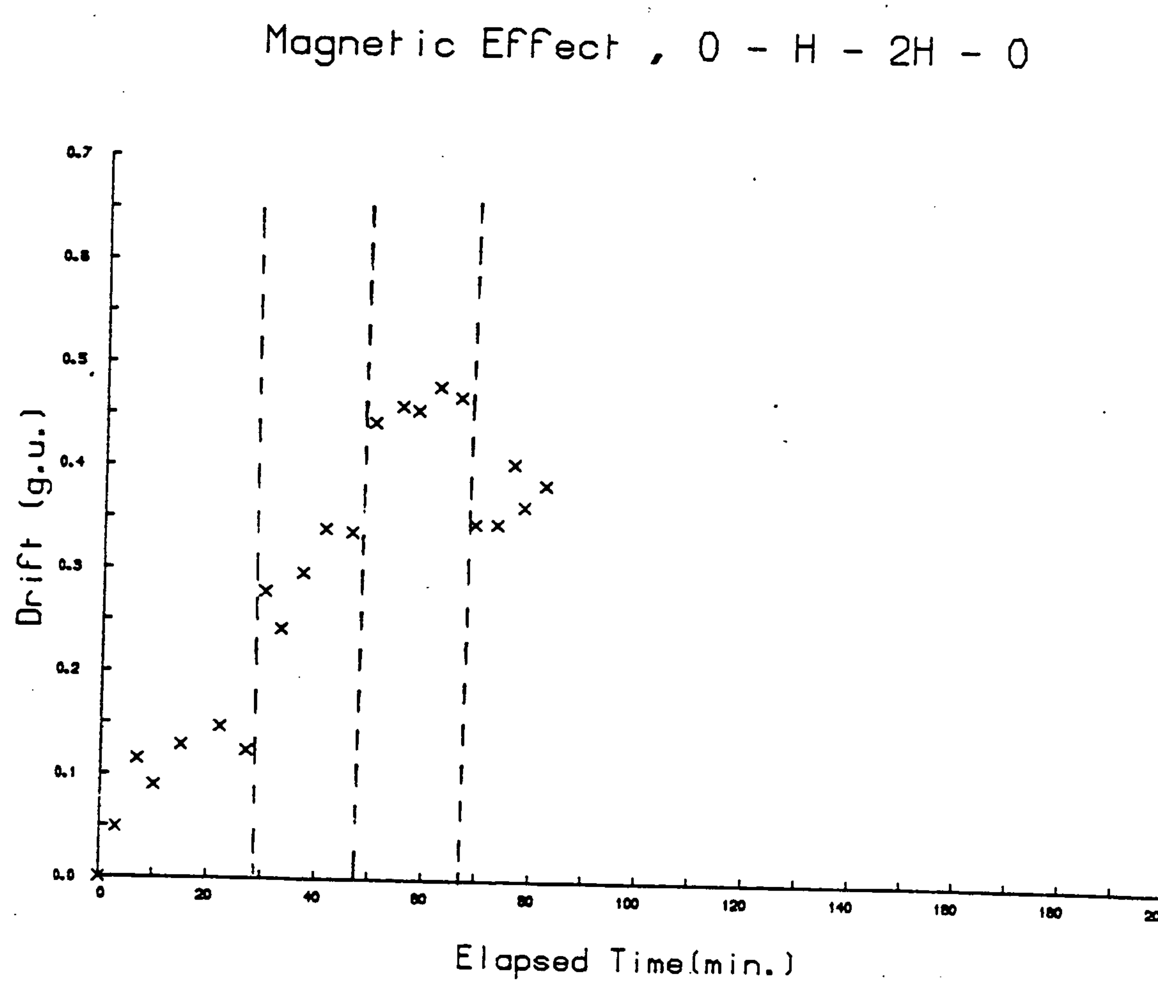



Figure 3.12(d) MAGE Observations .

direction and the observed dial turns for G-275. These data were analysed using a least squares cubic spline computer program (discussed in detail in the Chapter Five) to analytically determine the effect of the applied field transitions. The results of this analysis are presented in Table 3.4. The effect is consistent but does exhibit a large scatter. The final transition (2H-O) causes a negative gravity change which does not equal the sum of the two positive steps (O-H and H-2H) possible due to magnetic hysteresis. The results of some published studies are tabulated in Table 3.5. These vary widely, for example Kivinemi notes no reading change despite a magnetic field change of five times the earth's field whereas Boedecker obtains a 0.40 g.u. change after the application of a 60μT. horizontal component. The values obtained for G-275 falls in between these extremes.

## 3.4 Conclusions

The effects of several environmental parameters have been studied. Temperature variations seem to have no mechanical effect on G-275. Nevertheless precautions should be taken to maintain a constant external temperature whenever possible. Level stablity in particular is susceptible to direct sunlight (see section 8.3 for fieldwork experience of this phenomenom). The effect of pressure variations on G-275 was not evaluated but the literature

Table 3.4

Observed gravity change (meter G.275) due to magnetic field variation. (Units = g.u.)

| | O → H | H → 2H | 2H → O | Number of Observations | Fit rms |
|---|---|---|---|---|---|
| MAGA 21.02.79 | 0.194 | 0.400 | -0.194 | 34 | 0.01 |
| MAGB 24.02.79 | 0.150 | 0.193 | -0.119 | 34 | 0.02 |
| MAGC 24.01.81 | 0.057 | 0.078 | -0.072 | 35 | 0.03 |
| MAGD 29.01.81 | 0.119 | 0.139 | -0.150 | 21 | 0.03 |
| MAGE 02.02.81 | 0.106 | 0.109 | -0.139 | 22 | 0.02 |
| Average(g.u.) | 0.125 | 0.184 | -0.135 | | |
| Std.Dev(g.u.) | 0.051 | 0.128 | 0.045 | | |

Table 3.5

Gravimetric Effect of Magnetic Field Change

| Author | Number of Meters | Field Change | Observed gravity change (g.u.) |
|---|---|---|---|
| Brein et al., 1977 | | | |
| GL | 2 | 250 μT | zero |
| IFAG | ? | 15 μT | .12 max |
| Boedecker, 1978 | 1 | 60 μT | .40 max |
| Williams, 1983 | 2 | 104 μT | < 0.01 |

GL Geodettinen Laitos, Helsinki (Kiviniemi)

IFAG Institut fur Angewandte Geodasie, Frankfurt am Main (Brein) suggests that these will be negligible. Large instanteous voltage variations, substantially greater than probable under feild conditions, caused no perceptible change of reading. Magnetic feild variations have a demonstrable effect on reading accuracy. Observations should be taken well away from large field gradients such as large buildings, pipelines, pylons etc.. The orientation at sites should be noted and conserved when making repeat readings.

# CHAPTER FOUR

# THE EARTH TIDES

## 4.1 Calculation of the Tidal Potential and Tidal Force

If we wish to observe gravity precisely, it is necessary to accurately correct the effect of the constantly varying tidal forces. All celestial bodies exert a Newtonian attraction upon the Earth but only the Sun and Moon need be considered. The greatest disturbing potential exerted by a planet is that of Venus and is more than four orders of magnitude smaller. These forces typically have a range of 1.5g.u. at mid latitudes with a maximum global span of some 2.5g.u.. Thus the time of each gravity reading is noted (to the nearest minute or better), and a tidal correction calculated by a computer program is applied retrospectively to the scaled dial turns.

The original development of the tide generating potential is due to Darwin (1883) (who chaired an Admiralty Committee on the problem of tidal prediction and studied the problem of tidal friction (Darwin 1879,1880); he proposed the model of the Moon ejected from the Earth. Darwin expressed the tidal potential in terms of a harmonic expansion which utilised 'old' lunar theory and referred parameters to the Earth's equatorial plane rather than the eclpitic. Doodson (1922) used the lunar theory of Brown (1908) introducing argument numbers and extending the expansion.

Several standard texts on tidal theory and analysis exist (Godin, 1972 ; Melchior, 1978) and the subject matter is discussed in most general geophysical textbooks. The analysis here is taken from a number of sources in addition to the above (Heikkinen, 1978 ; Cartwright, 1977 ; Stacey, 1977) and principally Vanicek (1980).

We shall first consider the Earth-Moon system illustrated in figure 4.1 ; the attracting acclerations at P and O are :

$$\alpha_o = G \frac{M_m}{\rho_o^2} \quad , \quad \alpha_P = G \frac{M_m}{\rho_P^2} \qquad \text{E 4.1}$$

G = Gravitational constant ($6.67 \times 10^{-11} kgm^3 s^{-2}$) Mm = Moon mass($7.38 \times 10^{22}$ kg.) The difference in the associated forces exert a tidal deforming stress pattern on the Earth. By application of the sine and cosine rules $\rho_P$ may be expressed as

$$\rho_P = \rho_o \left(1 + \left(r_E/\rho_o\right)^2 - 2\left(r_E/\rho_o\right)\cos Z\right)^{1/2} \qquad \text{E 4.2}$$

It is simpler to use the scalar potential, rather than acceleration, g = grad V.

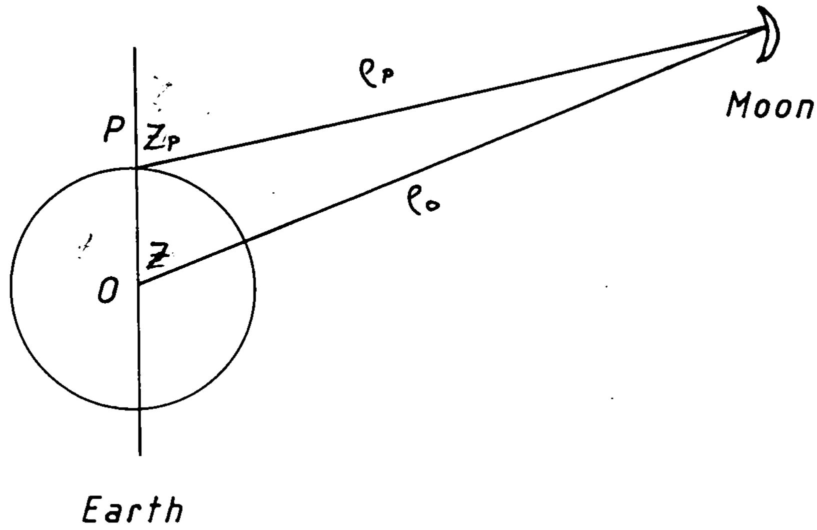



Figure 4.1

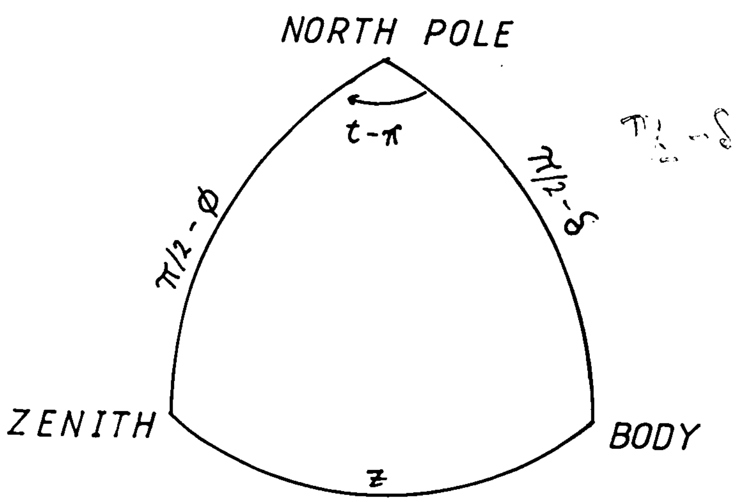



Figure 4.2

So if the tidal potential generated by the Moon at P is denoted $V_m(P)$:

$$V_m(P) = \frac{G M_m}{\rho_p}$$

$$= \frac{G M}{\rho_0} \left(1 + (r_E/\rho_0) + 2(r_E/\rho_0)\cos\phi\right)^{-1/2}$$

E 4.2A

This expression may be expanded using Legendre Polynomials. The tidal potential is given by the removal of the eqivalent point mass (n = 0) and the potential of the constant force field (n = 1). We denote this by $W_n(P)$ for the point P

$$W_n(P) = \frac{G M_m}{\rho_m} \sum_{n=2}^{\infty} (r_E/\rho_0)^n P_n \cos\phi \qquad \text{E 4.3}$$

A similar argument may be applied to any celestial body. In the case of the Moon $r_E/\rho_m = 1.67 \times 10^{-5}$ and in that of the Sun $r_E/\rho_s = 4.33 \times 10^{-5}$ ; so it can be seen that the series converges very rapidly. The first two terms in the Earth-Moon system being over 99 per cent of the total.

$$W_2(P) = \frac{G M}{2\rho_0} \left\{ \frac{r_E^2}{\rho_0} (3\cos^2\phi - 1) \right\} \qquad \text{E 4.4}$$

$$W_3(P) = \frac{G M}{2\rho_0} \left\{ \frac{r_E^2}{\rho_0} (5\cos^3\phi - 3\cos\phi) \right\}$$

E 4.5

The latitude is a locally based co-ordinate and may be referred to geocentric and conventionial asronomical co-ordinates. Consider figure 4.2, from spherical trigonometry.

$$\cos z = \sin\phi \sin\delta + \cos\delta \cos\phi \cos t \qquad \text{E 4.6}$$

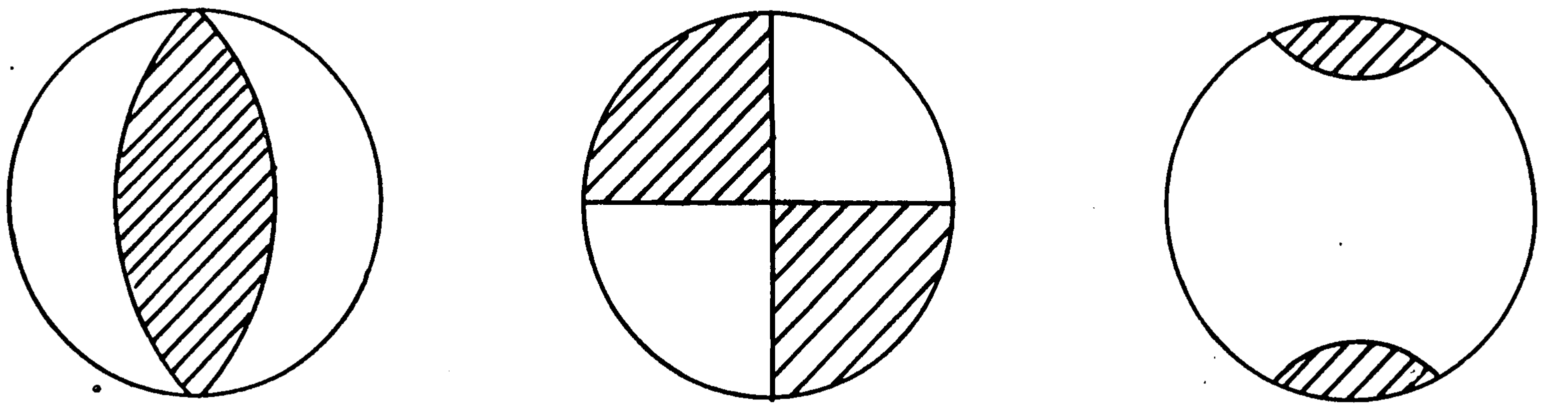
geocentric latitude, $\delta$ = declination, t = hour angle

The expression for W2(P) can then be separated into three distinct terms.

$$W_2(P) = \frac{3}{4} G M_m \frac{r_E^2}{\rho_0^3} \left\{ \begin{array}{ll} \cos^2\phi \cos^2\delta \cos 2t & \text{E 4.7a} \\ + & \\ \sin 2\phi \sin 2\delta \cos t & \text{E 4.7b} \\ + & \\ 3(\sin^2\phi - 1/3)\cdot & \\ (\sin^2\delta - 1/3) & \text{E 4.7c} \end{array} \right.$$

This decomposition into three terms is due to Laplace who demonstrated the spatial dependence of the terms, each representing a type of second order surface as shown in figure 4.3.

The hour angle t of the Moon increases monotonically with time as the Earth rotates, hence the sectorial term is semi diurnal and the tesseral is diurnal. The zonal term causes long term variations in the potential with the squared sine of the declination of the perturbing body, 14 days and 6 months. In practice $\phi, \delta$ and t vary with time



Sectorial  Tesseral  Zonal

Figure 4.3

in a complex manner for both the Moon and the Sun, leading to hundreds of tidal components at discrete frequencies known as multiplets.

Since Darwin's formulation was in terms of the lunar obliquity rather than inclination, his development was quasi -harmonic. The formulation retains constituents which were really slowly variable, (lunar obliquity varies between $18^{\circ} 18^{m}$ and $28^{\circ} 46^{m}$ with a period of 18.6 years). Doodson's formulation utilising Brown's lunar theory derives a series expansion in terms of latitude and longitude. Doodson's purely harmonic expansion contained 386 components whose coefficients are greater than 0.0001 times the greatest. This development was in use for fifty years before being ameliorated by Cartwright and Taylor (1971, ammended Cartwright and Edden, 1973) who slightly altered certain coefficients on the basis of computer spectral analysis of three eighteen year time spans. They also used new astronomical and geodetic constants.

Doodson expressed the potential as an infinite harmonic sum of six independent variables

$$W_T = d_1 \tau + d_2 s + d_3 h + d_4 p + d_5 N' + d_6 p_1$$

Notation as in Doodson where,

$\tau$ = local mean lunar time

$s$ = Moon's mean longitude

$h$ = Sun's mean longitude

$p$ = longitude of the Moon's perigee

$N'$ = -N where N is longitude of the (Moon's ascending) node

$p_1$ = longitude of Sun's perigee

The use of such variables leads to simplified analysis and several elegant points of notation. The 'speeds' of the variables are all positive and hierarchial cassification with regard to $\tau$ , completely separates the constituents without overlapping.

Considering the argument numbers for $W_2$. The argument $d_1$ may be 0, 1 or 2 while $d_2$ to $d_6$ may be positive , negative or zero. The tides are split into different species depending on the value of $d_1$, each consisting of several groups with the same value of $d_2$ .

Doodson suggested a form of notation that is now widely accepted with the exception of Darwin's two character alphanumeric notation for the principal tidal components. For example, consider the following constituent which is a linear function of all six variables.

$$2\tau - 3s + 4h + p - 2N' + 2p_1$$

Doodson suggested the use of a datum of five (since the integer coefficients are seldom greater than 4. So five is added to all the coefficients except that of (which is always positive), obtaining an argument number of 229.637.

Argument No. = 229.637

Constituent = 229

Group = 22

Species = 2

The break down of species into constituents is illustrated in figure 4.4 taken from Doodson (1921).

## 4.2 Earth Deformation

The Earth responds to the tidal potential in a semi elastic manner. The response is complicated by indirect effects generated by the loading of oceanic water bodies. The elastic response of the real Earth was first fully treated by Love (1909) and the elastic effects can be represented by dimensionless constants (known as Love numbers) 'h' and 'k'. 'h' is the ratio of the body tide to the height of the static equilibrium tide and 'k' is defined as the ratio of the additional potential produced by the redistribution of mass to the deforming potential. A third constant, l was later introduced, and is the ratio of horizontal displacement of the crust to that of the equilibrium fluid tide (Shida , 1912).

Consider figure 4.5 which illustrates the deformation of the Earth at a point due to the vertical component of the tidal force. With the application of $F_V$ the equipotential surface passes through C and the Earth's surface uplifts to B. This deformation causes an additional change of the equipotential so that it now passes through D.

The potential difference between the observed W(B) and the rigid Earth potential W(A) is the sum of three terms

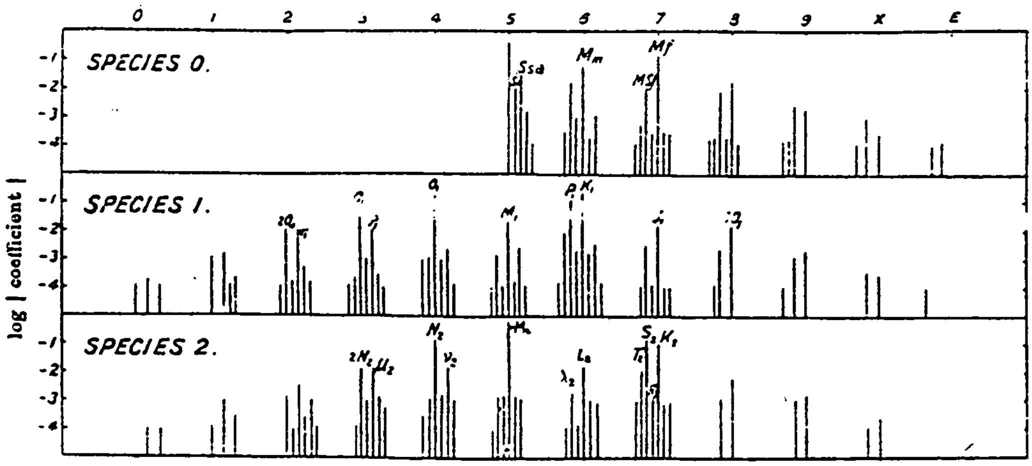



DIAGRAM A: constituents, separable in one year.

The speed scale is indicated by the figures at the top of the diagram; these, with the species-number, give the group-numbers, and the places of the constituents in the diagram can then be readily found. An increment of 1 in the group-number corresponds to an increase in speed of about 13° per mean solar day; the increase in speed for an increase of 1 in the constituent-number is about 1° per mean solar day.

Figure 4.4 Tidal constituents separable ine one year (from Doodson,1921)

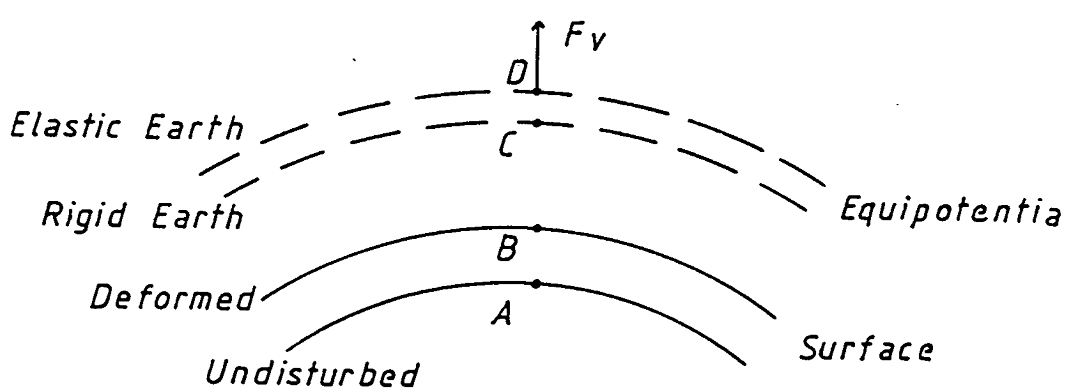



Figure 4.5
(After Vanicek,1973)

(1) The tidal potential $W_2$

(2) $W(u)$ , the loss in potential due to displacement u.

(3) $W(u)_{def.}$, the deformation potential produced by the field change

(1) is given above and the loss of potential $W(u)$ may be simply expressed:

$$W(u) = u \frac{\partial W_A}{\partial \varrho} = -u.g \qquad \text{E 4.9}$$

The theoretical equilibrium height of the oceanic tide will be $W_2/g$. If we assume that distribution of mass is spherically symmetric and that rigidity is constant over the surface we can express the radial displacement u as the product of some function H(r) and the tidal potential:

$$W(u) = H(r).W_2 \qquad \text{E 4.10}$$

$$u = H(r).W_2/g \qquad \text{E 4.11}$$

The deformation potential associated with the displacement of matter may be expressed as the product of the harmonic $W_2$ and some function of r, e.g. $K(r).W_2$. If we write, h = H(A), and k = K(A) , the observed potential is given by;

$$W(B) = W(A) + W_2 + k.W_2 - h.W_2 \qquad 4.12$$

The oceanic tides are diminished by the body tides by the factor

$$1 + k - h : 1$$

For a hypothetical rigid Earth both k and h would be equal to zero, and for a fluid Earth in tidal equilibrium h equals unity and k is a function of the density profile; if this were uniform k = 1.5 for the actual inferred profile k = 0.937. The elastic response of the real Earth is frequency dependent, the higher the frequency the greater the rigidity ,and generally quoted values in the literature refer to M2 and r equal to $r_E$. By differentiating expession (4.12) and substituting (e.g. Vanicek, 1980) it can be shown:

$$g + dg = g - ( 1 - 3/2k + h)\ \delta W_2/\delta r \qquad \text{E 4.13}$$

Theoretical values for h and k can be obtained from hypothetical Earth models, the first of which was postulated by Kelvin in 1876. He demonstrated that a homogenous incompressable Earth requires a mean rigidity greater than that of steel (Lambeck, 1980). Kelvin's Earth is far removed from the real Earth but his treatment was the basis of subsequent more complex models as seismology provided further information (eg. Poincare, 1911). The first successful attempt to solve the problem for a complex heterogeneous Earth was published in 1950 (Takeuchi, 1950). Takeuchi rewrote the Love-Herglotz equations (Melchior,1978 p91) as a function of r/a before num erical integration. The advent of modern computers has greatly facilated the numerical calculations and the information about the elastic structure of the Earth has improved with the inclusion of free oscillations Table (4.1) illustrates the values of h,l, and k obtained from Farrell (1972) ( other similar work includes Takeuchi, Saito and Kobayashi (1962), Longman(1963), Pekeris and Accad (1972)) and figure 4.6

*Theoretical Love numbers of degree n computed by Farrell (1972) for three different Earth models: Gutenberg–Bullen (G–B) Earth model (first line for each n), an Earth model with a typical oceanic upper-mantle structure (second line for each n), and an Earth model with a typical shield upper mantle (third line for each n)*

| | $n$ | $h_n$ | $l_n$ | $k_n$ |
|---|---|---|---|---|
| G–B Earth model | 2 | 0.6114 | 0.0832 | 0.3040 |
| Oceanic mantle | | 0.6149 | 0.0840 | 0.3055 |
| Shield mantle | | 0.6169 | 0.0842 | 0.3062 |
| | 3 | 0.2891 | 0.0145 | 0.0942 |
| | | 0.2913 | 0.0145 | 0.0943 |
| | | 0.2923 | 0.0147 | 0.0946 |
| | 4 | 0.1749 | 0.0103 | 0.0429 |
| | | 0.1761 | 0.0103 | 0.0424 |
| | | 0.1771 | 0.0104 | 0.0427 |

Table 4.1 Love numbers calculated by Farrell(1972) (reproduced from Lambeck, 1980).

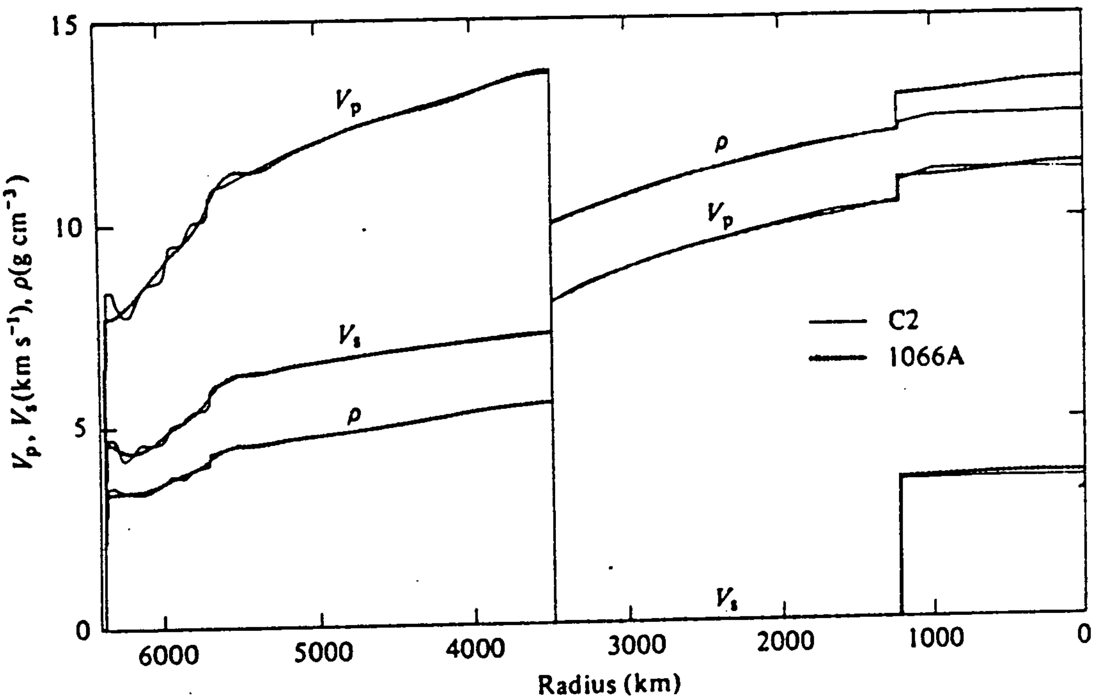



Figure 4.6 Models C2 from Anderson & Hart (1976) and 1066A from Gilbert & Dziewonski (1975) of the Earth's radial seismic velocity and density structure. (from Lambeck, 1980).

illustrates two recent Earth models. The Farrell values of the low degree Love numbers do not appear to be sensitive to mantle structure and yield a gravimetric factor of

$$1 + h - 3/2k = 1.158 \qquad (n=2)$$

This is the generally accepted value for the diurnal and semi-diurnal components.

## 4.3 Ocean Loading

In the preceeding discussion we have not yet considered the effect of the oceans which cover nearly three quarters of the Earth's surface. The oceans are not in equilibrium with the tidal potential and because of their irregular nature perturb the Earth tides in a complex fashion. The ocean tide loading signal consists of three components.

(a) The change in vertical displacement of the surface due to the yielding of the crust

(b) The redistribution of crustal mass

(c) The direct Newtonian attraction of the water body.

Ocean loading can cause a ten per cent difference between the theoretical and observed tide and as such should be carefully evaluated to make correct tidal reductions to observations.

Little is known about the tidal parameters in the deep sea though measurements in coastal areas are commonplace.

These measurements may be used to constrain worldwide numerical models to solve Laplace's tidal equations using finite difference schemes (Hendershott, 1972 (M2); Bogdanov and Magarik ,1967,1969(M2,S2,K1,O1); Pekeris and Accad, (1970) (M2)). The most recent model study of Schwederski (1980) includes dissipative effects . The marine tide is then convolved with the Green's function of an appropriate radially stratified Earth model (such as the Gutenberg-Bullen model, determined seismically) to obtain the gravity signal (Farrell,1973). The ocean loading effect may be determined directly from the analysis of highly accurate continuously recording gravity meters (Earth tide meters ) for periods of at least sixty days at a particular location. The results from these meters (again generally manufactured by the La Coste and Romberg company), are split into tidal components and the theoretical body tide subtracted.

## 4.4 Tidal Predictions using Computer Programs

Several computer programs to predict the vertical component of the tidal acceleration were compiled on the Edinburgh mainframe. Three programs were considered sufficently accurate (better than $10^{-3}$g.u.) to reduce high precision gravity observations.

(1) CART : A program based on the harmonic expansion of Cartwright-Tayler-Edden (see section 4.2) This program was

written at Edinburgh by Dr. R. Hipkin and the author. It is a subroutine in the program PBAS listed in Appendix(4 ).

(2) BZS : A program based on Broucke Zurn and Schlicter (1972, kindly provided by the Earth Tides section, Institute of Oceanographic Sciences, Bidston. (A listing is not appended, but copies of the program may be requested directly from that source).

(3) HEIK : This is an exact copy of the program listed in Heikanen(1978)

The programs BZS and HEIK are generically similar but very different in programming style. They involve the use of a closed expression of the form

$$g_r = Kp^2[(\xi^{-3/2}-1)\cos z - \xi^{-3/2}]$$

where K is a constant, p is the horizontal parallex of the moon, z is the zenith angle of the moon and $\xi$ related to the latitude of the observing station. BZS is essentially an amelioration of Longman (1959) using an improved lunar ephemeris (Eckert, Jones and Clerk, 1954). The vertical solar earth tide is in fact calculated identically to Longman. HEIK also uses the formulae of Eckert Jones and Clerk but the ephemeris of the 1972 Nautical Almanac. The solar formulae is is based directly on Newcomb(1895). Heikanen corrects for the effect of polar motion, (the pole, or point where the axis of rotation passes through the Earth's surface, is in motion relative to the earth itself).

The program CART is however uses a totally different method and is based on a time harmonic expansion of the tidal potential. The analysis is taken directly from Cartwright and Tayler (1971) (see section 4.2), incorporating 504 harmonic components; (all those greater than an arbitary level of 4.5 x $10^{-5}$ times the greatest coefficient). Such a harmonic development has the advantage that the amplitude and phase of each component can be varied to the value of the real earth. All three programs incorporate recent astronomical constants (I.A.U., 1964).

The program BZS was received on card format, together with a sample computation of one month's hourly predictions for the location of Bidston. The program was successfully mounted but gave very slightly different values for the test site. The difference was small with a standard deviation of 1.2 x $10^{-4}$ g.u. on 720 sample points. The listing was carefully checked but no transcription error was detected. The program was compiled and executed on two remote computers because of the possiblity of machine error, but identical results were obtained. (The Edinburgh machine is an ICL2972, the other two machines were an IBM365 at Newcastle and a CDC7600 at Manchester.)

The program HEIK was keyed on to the mainframe computer and after many transcription corrections ran successfully. The program agreed exactly with the five published test values , stated to $10^{-4}$ g.u.. In addition to these values the program author Dr Heikanen kindly supplied a sample of 72 hourly values at the location of one of the Finnish secular variation sites (Vaasa, see figure 2.2). Agreement was again complete. The program BZS was executed with the same coordinates and differed with a standard deviation of 3 x $10^{-4}$ g.u.. The program CART was already mounted on the Edinburgh mainframe computer. It produced standard deviations of 6.2 x $10^{-4}$ g.u. and 7.4 x $10^{-4}$ g.u. respectively, when compared with the BZS values at Bidston and Vaasa.

All the programs agree within the required standard of accuracy ($10^{-3}$ g.u.) for tidal corrections to precise gravity observations but there are other factors. If we consider central processing unit time on the Edinburgh computer (an ICL 2972) there is a considerable difference in time between the programs. BZS takes an average of one hundredth of a second to perform each calculation whereas CART takes an average of two hundredths of a second for an identical location. The program HEIK requires an astonishing 8.3 seconds making it unsuitable for many analyses (e.g. almost two hours processor time for one month of hourly values). Although BZS is the fastest program the routine CART was used in data reduction because of the facility to alter amplitude and phase of tidal component groups.

# CHAPTER FIVE

# SPLINE FITTING AND DATA ADJUSTMENT

## 5.1 Introduction

Piecewise polynomials are ideally suited to the fitting of geophysical data which are often irregular but repeatable in nature (eg. waveform matching in seismology and palaeomagnetism). Cubic spline functions are most commonly used to approximate continuous functions of one variable because they present computational advantages. These are cubic polynomials joined such that the second derivative is continuous. Furthermore the definition of splines in terms of polynomials has the statistically important consequence that a spline function, when fitted to data by least squares conserves the first two moments of the data (Wold, 1974).

Figure 5.1 illustrates a cubic spline curve and its four composite cubic polynomials. Let us define a cubic polynomial f(t) ; the condition that f''(t) and f'(t) are continuous at the joining points (called knots or nodes) gives rise to equations that have to be satisfied. With refence to figure 5.2, within any nodal interval $t_n < t < t_{n+1}$ the function f(t) is represented by:

$$f(t) = f_n(t) = a_n + b_n(t-t_n) + c_n(t-t_n)^2 + d_n(t-t_n)^3 \quad (5.1)$$

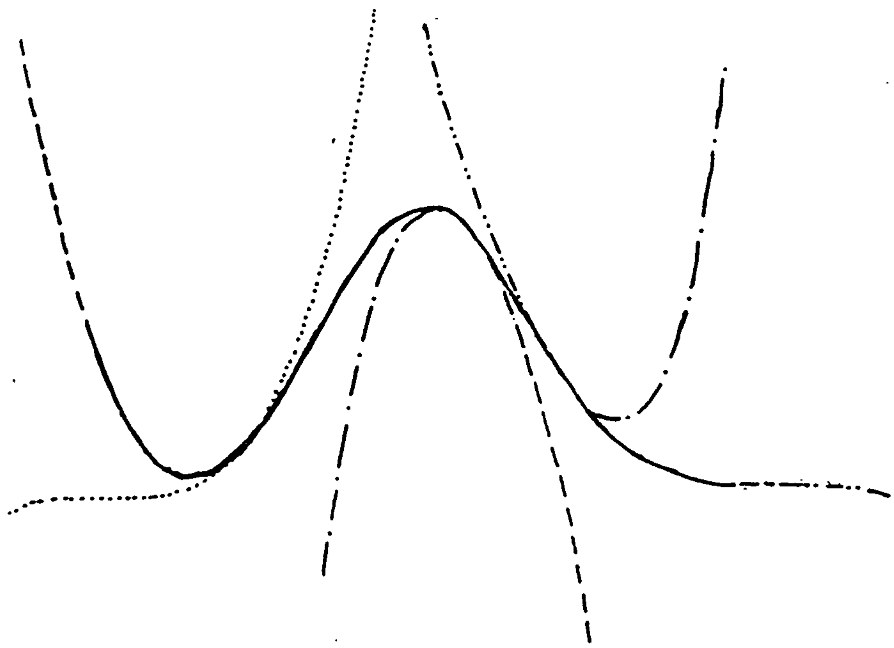


Figure 5.1 Cubic spline curve illustrating the component third degree curves.

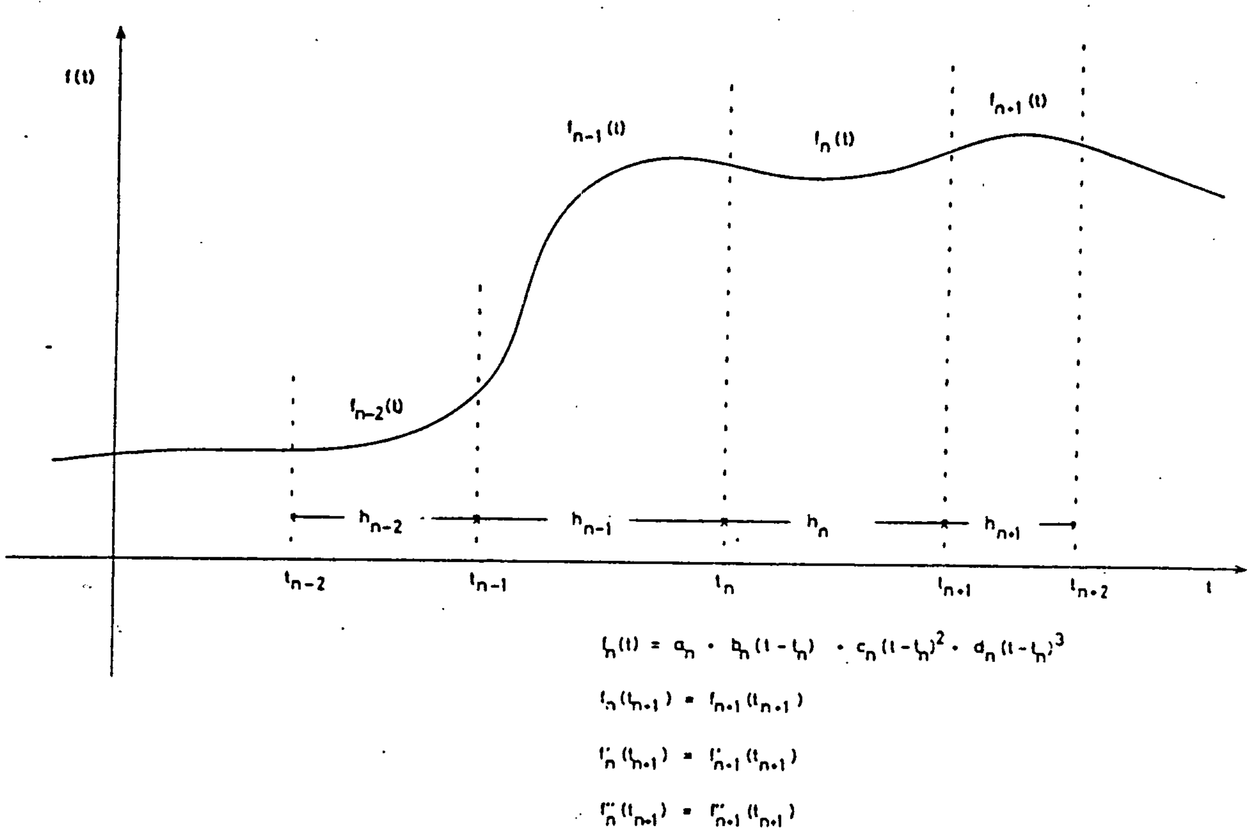



Figure 5.2 Arbitary spline function f(t) with nodal positions $t_{n-2}$, $t_{n-1}$, etc. indicated.

with continuity conditions

$$f_n(t_{n+1}) = f_{n+1}(t_{n+1}) \qquad (5.2)$$

$$f'_n(t_{n+1}) = f'_{n+1}(t_{n+1}) \qquad (5.3)$$

$$f''_n(t_{n+1}) = f''_{n+1}(t_{n+1}) \qquad (5.4)$$

These continuity conditions impose recurrence relations of the form.

$$\begin{aligned} a_n = a_1 &+ b_1 \left\{ (t_n - t_1)|_{n \geq 2} \right\} + c_1 \left\{ \frac{2h_1}{3} \Big|_{n \geq 2} + h_1 (t_n - t_n)|_{n \geq 3} \right\} \\ &+ c_n \left\{ \frac{h_{n-1}^2}{3} \Big|_{n \geq 2} \right\} + c_{n-1} \left\{ \tfrac{1}{3} (2h_{n-1} + h_{n-2}) . (h_{n-1} + h_{n-2})|_{n \geq 3} \right. \\ &+ \sum_{r=2}^{n-2} c_r \left\{ \tfrac{1}{3} (h_r + h_{r-1}) \left[ (2h_{n-1} + h_{n-2} + 3(t_n - t_{r+1}) \right] \Big|_{n \geq 4} \right\} \end{aligned} \qquad (5.5)$$

$$\begin{aligned} b_n = b_1 &+ c_1 \left\{ h_1 |_{n \geq 2} \right\} + c_n \left\{ h_{n-1} |_{n \geq 2} \right\} \\ &+ \sum_{r=2}^{n-1} c_r \left\{ (h_r + h_{r-1}) |_{n \geq 3} \right\} \end{aligned} \qquad (5.6)$$

$$d_n = c_{n+1} - c_n / 3h_n \qquad (5.7)$$

where $h_n = t_{n+1} - t_n$

Thus if there are N nodal intervals there are N+3 degrees of freedom with independent parameters.

$$a_1, b_1, c_1 \ldots\ldots c_{N+1}$$

The number of degrees of freedom may be reduced to N+1 (the number of knots) by the application of boundary conditions (De Boor, 1978, p54)> One option is to fix the second derivative of the end points to zero.

$$f''(t_1) = f''(t_{N+1}) = 0 \Rightarrow c_{N+1} = c_1 = 0 \qquad (5.8)$$

Such an end condition produces a so called natural spline (by analogy with flexed wires whose end points are fixed).

In practise it was found that such a constraint did not greatly alter a least squares spline solution when applied to gravimetric data. The expressions given here are derived from first principles and computational advantages to be obtained by a scaled divided difference known as Basis spline or B-spline, were thought unnecessary.

## 5.2 Drift adjustment with the spline fitting program NSPL

Because of the complex and highly individual nature of any particular gravity meter's drift, cubic spline functions are well suited to the problem. ('Spline functions are the most successful approximating functions for practical applications so far discovered ', Rice, 1963, p123). The observation equation has the form

$$g(t) = G(m) + f(t) + e \qquad (5.9)$$

where G(m) is the gravity value at site m, f(t) is the meter drift to be represented by a cubic spline function and the residual squared, $e^2$ is to be minimised. With reference to the previous section the number of degrees of freedom for an unconstrained least mean squares cubic spline fit to the data is N + M + 3 (M is the number of sites) with free parameters

$$a_1, b_1, c_1 \ldots\ldots c_N, c_{N+1}, G_1, G_2 \ldots\ldots G_M \quad e$$

A computer program, NSPL, was written by Dr R. Hipkin and the author to evaluate these coefficients using the expressions (5.5), (5.6) and (5.7), and this is listed in Appendix (1).The program retains many different options because of the different possible measuring sequences. A flow diagram of the program is presented in figure 5.3.

There are seven control parameters which are itemised below

(1) The number of observations, J

(2) The number of different gravity sites, M

(3) The number of nodal intervals, N.

(4) A parameter controlling the least squares adjustment altered according to the observation sequence known as PARTS

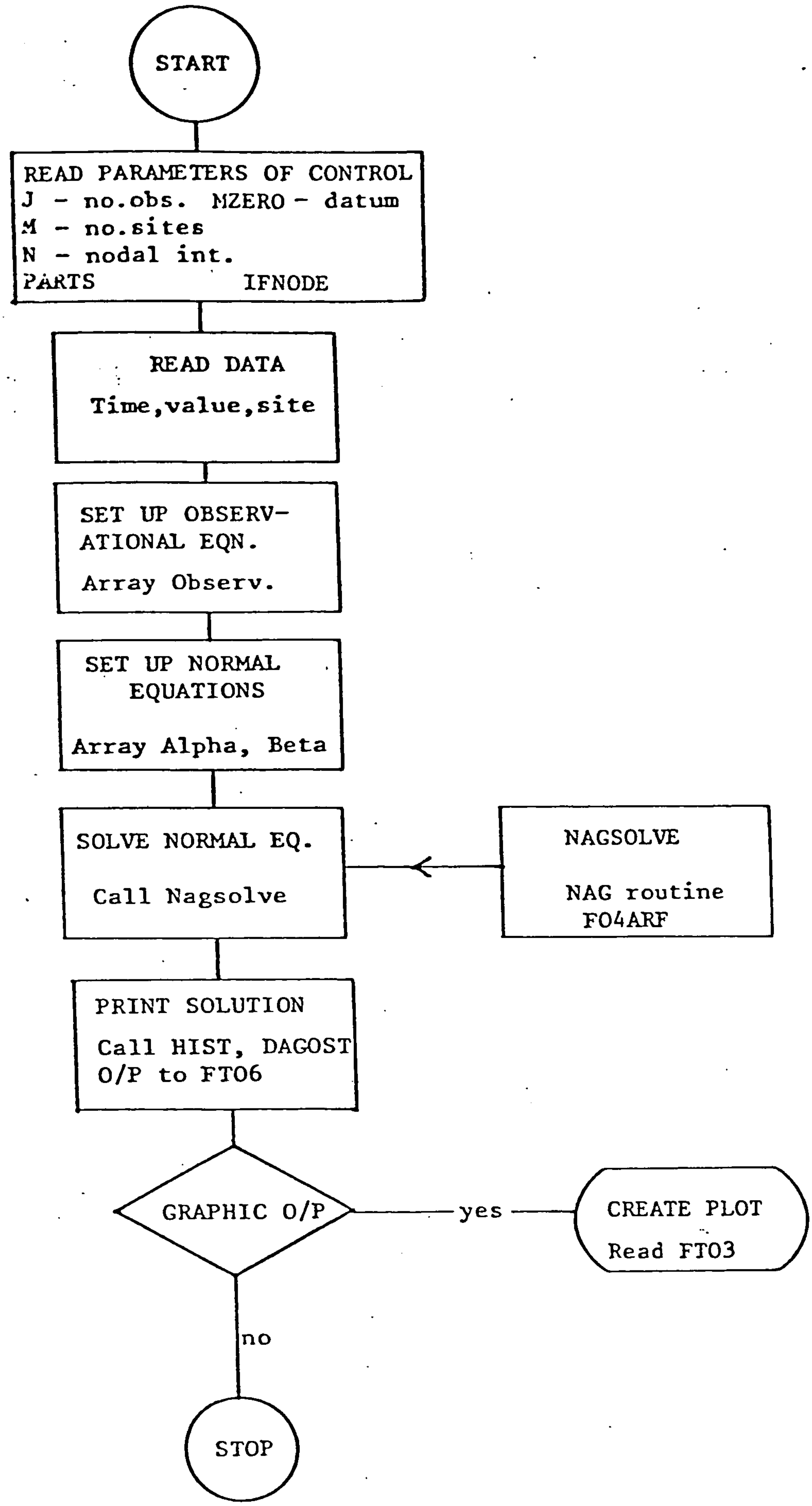
(5) Identification of the datum site, MZERO

(6) Control of nodal spacing, IFNODE

(7) Control of output mode, PDRIFT

The number and location of the nodes can be varied by explicit inclusion in the data set or the program may be divided into a specific fixed or increasing number of equi-spaced nodes. The parameter PARTS exists to ameliorate the adjustment of differently observed data sequences as discussed in section and has three distinct cases; PARTS = 1, PARTS <-1, PARTS >1 .

Figure 5.3 Schematic flow diagram of program NSPL



(a) PARTS = 1

This is applicable to single station continuous observation sequences such as a laboratory drift curve, when the observations are represented simply by the equation 5.9.

(b) PARTS < -1

This provision is intended to evaluate a datum shift between several independent observation sequences while calculating a single continuous spline function. In this case the data sets are joined 'head to tail' with a specified time gap between each section. This occurs when, for example, a measurement sequence is repeated at the same sites on separate occasions, the fixed gravity values constraining the adjustment. The magnitude of the time gap in relation to the nodal positions is crucial in such an application since the nodal density should be sufficiently great to accommodate gradient changes between the independent sequences.

(c) PARTS > 1

In this case it is assumed that the independent observation sequences follow the same observational routine and a common drift curve is fitted so that the initial times of the superimposed data sections are coincident. It is essential that a single observational practise is maintained and with these arguments of symmetry the drift function should be related to elapsed time only. The program calculates the appropriate least squares datum shift for each section or 'PART'.

This form of parameterisation allows the user a large degree of flexiblity to select the adjustment best suited to a particular data collection pattern. The program NSPL wasused extensively during the processing of data collected by the author. The number of unknowns is equal to

$$M + N + PARTS + 1$$

thus a typical observation sequence of twenty readings four times (PARTS = 4, M = 1) is well constrained since the total number of observations is eighty ( $J = 4 \times 20$ ).

The facility to increase the number of nodes should be used with care since imprudent selection of N can lead to overfitting. Overfitting occurs when the spline function oscillates about the general trend in an attempt to minimise the error contribution of minor reading fluctuations. The solutions obtained on well constrained data sets differ only minimally as the number of nodes are initially increased. The solutions are very similar to those obtained with low order polynomials. Solutions with a single nodal interval were generally applied rather than more complex adjustments which would not be intercomparable at differing orders.

## 5.3 Adjustment of some collected data

A laboratory test was undertaken to examine the effect of transportation. This is presented in this section as an illustration of the variation of NSPL parameters and also to introduce the 'equilibrium' method of observation.

The Edinburgh instrument's characteristic drift curve attains a maximum after which the drift slope is approximately level and the meter appears to be in equilibrium with the disturbing force. Therefore it may be more accurate to use this value or the entire drift curve rather than the convential single initial value. The meter is observed at a site for between eighty and one hundred minutes (a minimum of twenty readings), and then transported to the next site. A single link is insufficiently strong so a triple link (A-B-A-B) is completed. Such a sequence occupies a complete working day.

Four single solutions for a study in which the meter was stationary between reading sequences are shown in figure 5.4. The effect of altering the number of nodes is shown in figures 5.5 and 5.6. The latter demonstrates the problem of overfitting (to a point where the r.m.s. error is zero). A single least squares solution may be fitted to the four curves, automatically adjusting the datum level of the independent data sequences (PARTS = 4, M = 1), as shown in figure 5.7. This diagram is similar in form to the composite drift curves obtained in Chapter Eight from field data collected in Scotland (see figures 8.5,8.6,8.7).

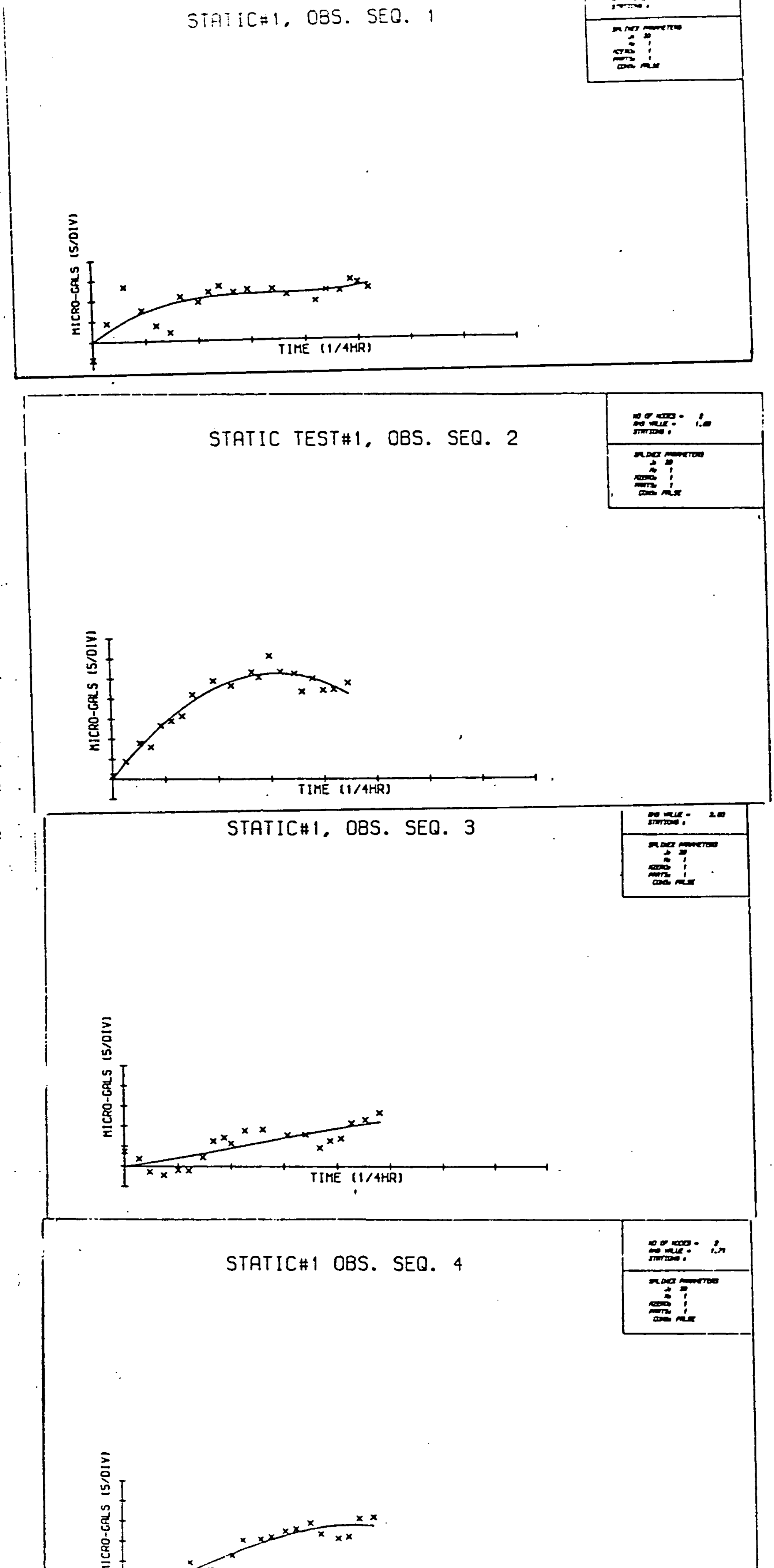



Fig.5.4
Four seperate reading sequence taken at the same site on the same day

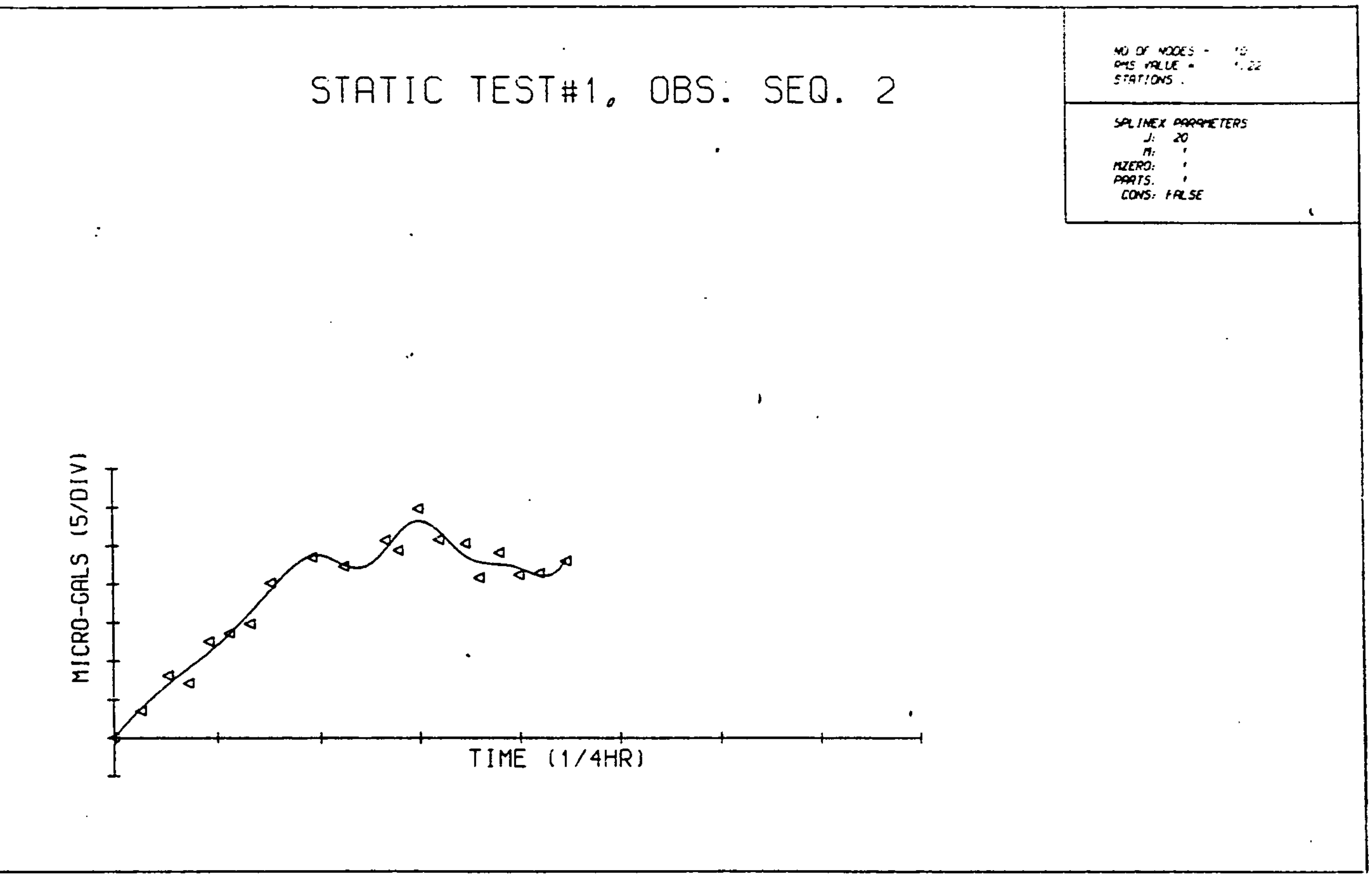



Figure 5.5 10 nodes

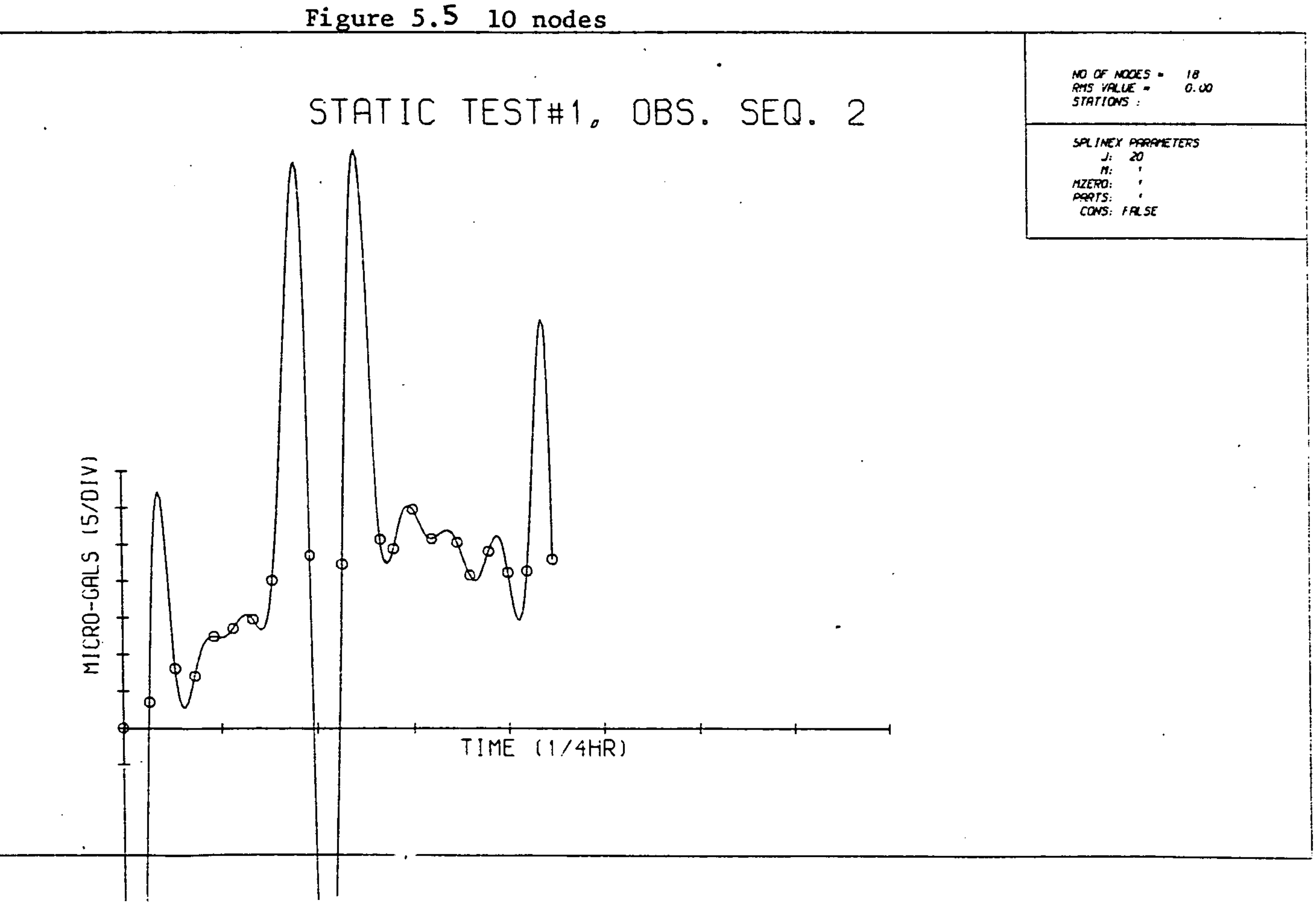



Figure 5.6 18 nodes

Table 5.1

Static / Transported Meter Test

| | Observed gravity 'difference' at the same site (g.u.) | r.m.s. value (g.u.) |
|---|---|---|
| Static 1 | -0.050 | 0.033 |
| Static 2 | +0.045 | 0.040 |
| Transport 1 | +0.093 | 0.045 |

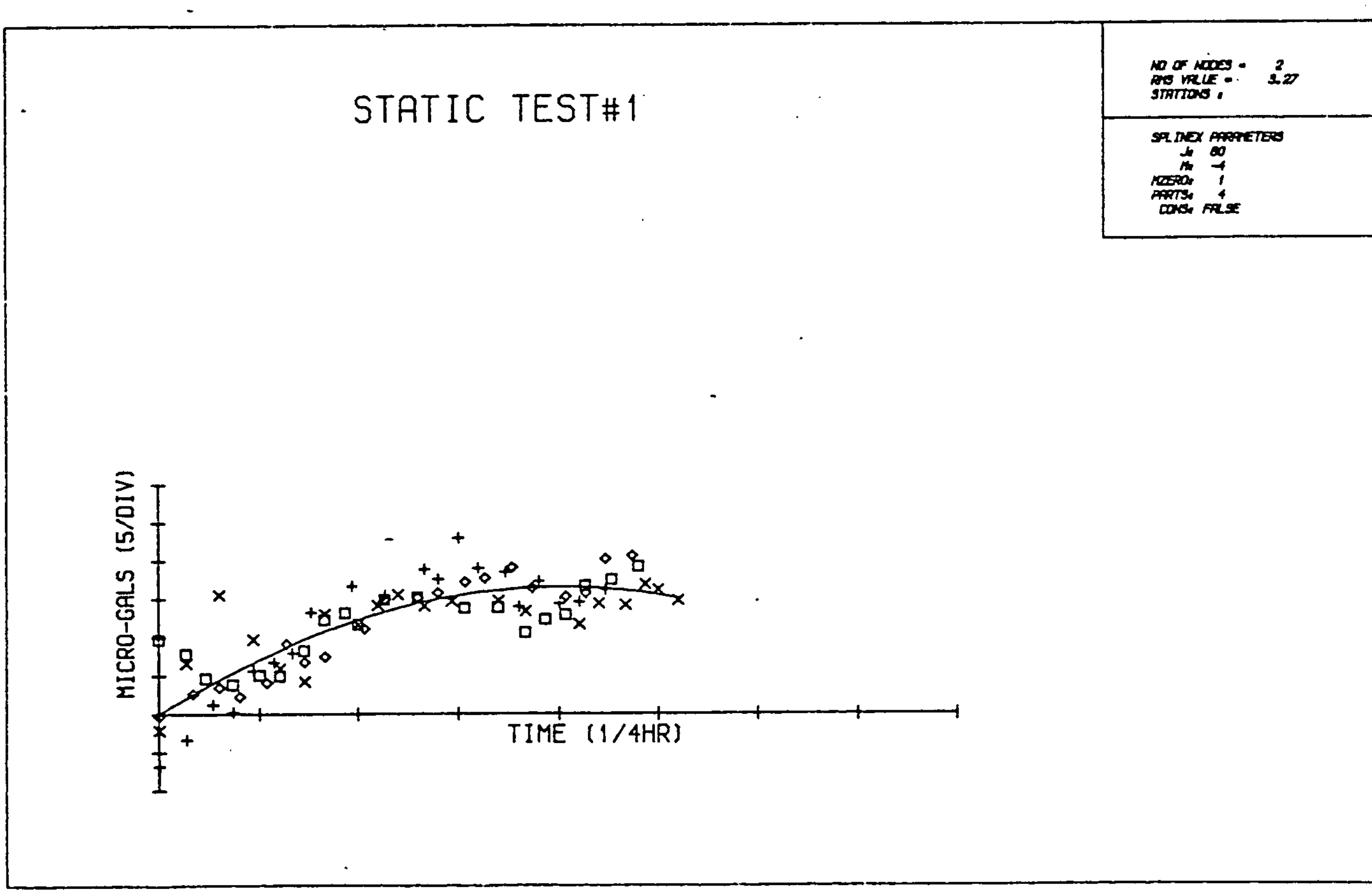



Figure 5.7 'Superposition' of data sets, PARTS = 4

Alternatively the reading sequences may be adjoined (PARTS = -4) rather than superimposed. Figure 5.8 displays the eleven node solution for the same data set as above whereas figure 5.9 demonstrates a better behaved field solution. (Field data sets often have a more pronounced maxima).

The output of adjustments with |PARTS| > 1, yields independent parameter pairs (datum and time) for each reading sequence. These form the input for a simple least squares weighted linear fit (using the program WFIT listed in Appendix (2)) to obtain the final solution. The results obtained using WFIT on the laboratory test data are given in Table 5.1 The two static test, during which the instrument remained undisturbed between reading sequences indicate gravity 'changes' which are just greater than the root mean square error bounds. These figures are tolerably zero but the observed gravity 'change' at the same site when the meter was transported between reading sequences is non zero. The transportation method was identical to that followed during field observations in Scotland (Section 8.3). The gravity meter, bolted to the secondary plate, was suspended from a rigid frame in the center of a vehicle, using elasticated cords. Thick sponge was placed beneath the baseplate to provide damping. These results are an estimate of the intrinsic accuracy of the instrument and the effect of road vibration (Hamilton

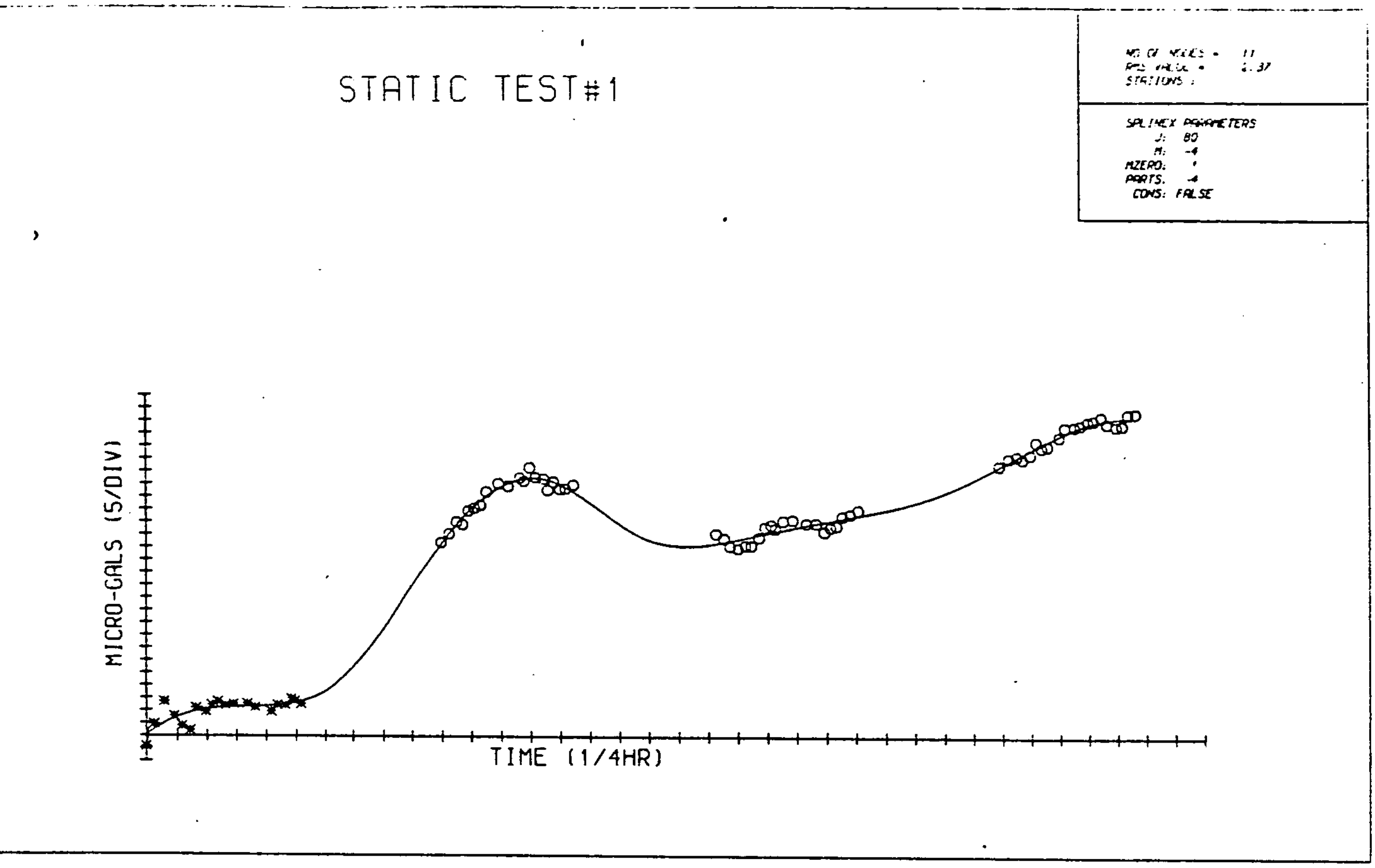



Figure 5.8 Eleven node solution for test data set.

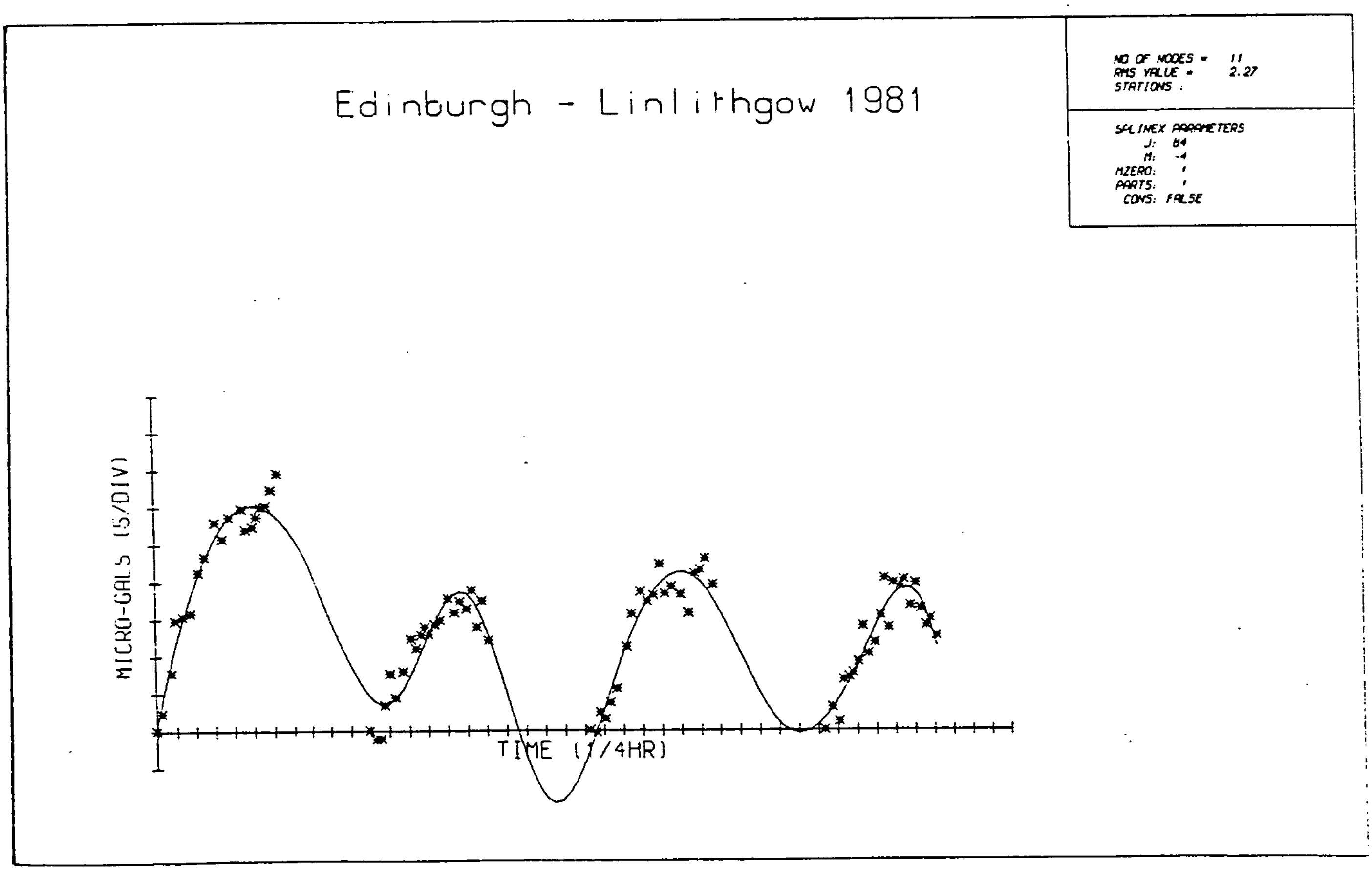



Figure 5.9 Eleven node solution for feild example

and Brule, 1963 find a resonance frequency at 49Hz for gravimeters). In fact field experience shows that instrument precision can occasionally vary quite widely without obvious reason.

## Multilinear

In addition to the spline based solution, data were adjusted using a network adjustment program MULTILINEAR (a modified version of Lagios and Hipkin, 1980). This program performs a least squares adjustment to all the data and also incorporates an independent first order fit to each observation sequence. This program was used in the adjustment of data collected in Greece (Chapter Nine) which was not observed using the equilibrium technique.

A schematic diagram of the overall data reduction procedure is given in figure 5.10. The raw data is first corrected for earth tides (using the program PBAS discussed in Chapter Four) to obtain data sets of time and relative gravity reading. These are now input to either the network program (MULTILINEAR) or spline adjustment (NSPL). The output from an independent PARTS solution is input to WFIT for a simple least squares weighted fit. The input/output channels of these programs are interconnected and graphical output may be obtained by responding to a query during an interactive terminal session.

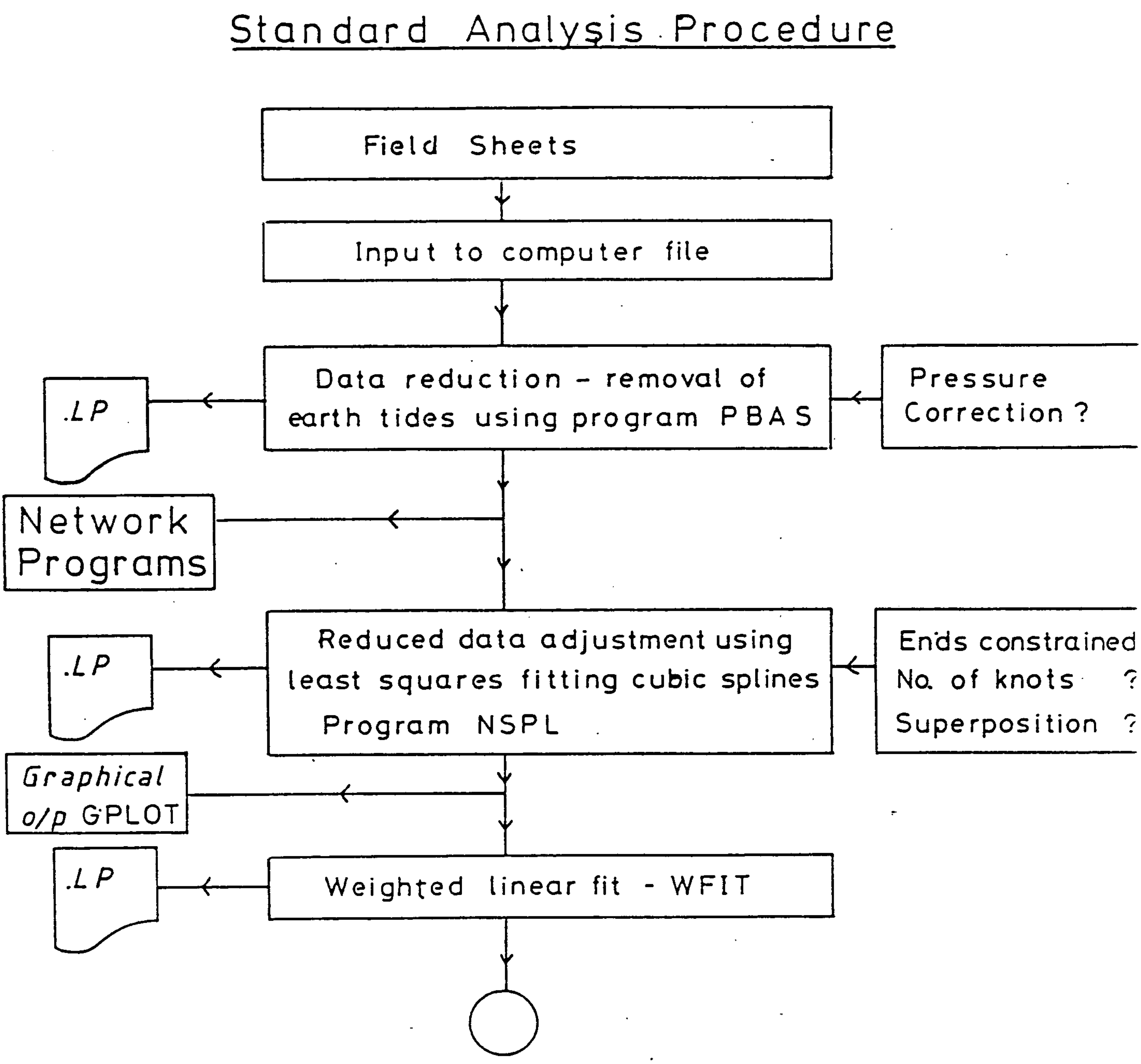



Figure 5.10 Schematic flow diagram of general data reduction procedure.

# CHAPTER 6

# INSTRUMENT CALIBRATION

## 6.1 Introduction

The complex internal mechanism of La Coste and Romberg spring gravimeters has been discussed in section 3.1. Gravity differences are determined by differencing the noted spindle revolutions at sites, then multiplying by the calibration factor . The calibration function is continuous over the range of spindle revolutions but the manufacturer supplies a piecewise linear approximation in the form of a single factor for every hundred revolutions of the spindle. The calibration table for G-275 is reproduced in table 6.1, and shown graphically in figure 6.1. The calibration factor is given to one part in $10^5$ whereas the 'factor interval' is rounded to 0.01mgal. Thus gravity differences between sites with gravity values lying in different table intervals will be in error if this is not considered.

Calibration in the factory is acheived by adding a small calibrating mass to the gravity meter beam to simulate gravity diffences with a twenty milligal interval, known as the Cloudcroft Junior method (Lambert, 1981). Coarse adjustment is acheived by a threaded mass added along the axis of the beam (figure 6.2). This method is only possible if one has the necessary ancillary equipment and a detailed

| COUNTER READING* | VALUE IN MILLIGAL | FACTOR FOR INTERVAL | COUNTER READING* | VALUE IN MILLIGAL | FACTOR FOR INTERVAL |
|---|---|---|---|---|---|
| 000 | 000.00 | 1.05115 | | | |
| 100 | 105.12 | 1.05108 | 3600 | 3786.12 | 1.05337 |
| 200 | 210.22 | 1.05104 | 3700 | 3891.46 | 1.05347 |
| 300 | 315.33 | 1.05100 | 3800 | 3996.81 | 1.05356 |
| 400 | 420.43 | 1.05095 | 3900 | 4102.16 | 1.05365 |
| 500 | 525.52 | 1.05093 | 4000 | 4207.53 | 1.05376 |
| 600 | 630.62 | 1.05090 | 4100 | 4312.90 | 1.05380 |
| 700 | 735.71 | 1.05090 | 4200 | 4418.28 | 1.05385 |
| 800 | 840.80 | 1.05090 | 4300 | 4523.67 | 1.05392 |
| 900 | 945.89 | 1.05090 | 4400 | 4629.06 | 1.05399 |
| 1000 | 1050.98 | 1.05094 | 4500 | 4734.46 | 1.05405 |
| 1100 | 1156.07 | 1.05097 | 4600 | 4839.86 | 1.05411 |
| 1200 | 1261.17 | 1.05103 | 4700 | 4945.27 | 1.05415 |
| 1300 | 1366.27 | 1.05107 | 4800 | 5050.69 | 1.05417 |
| 1400 | 1471.38 | 1.05115 | 4900 | 5156.11 | 1.05416 |
| 1500 | 1576.49 | 1.05124 | 5000 | 5261.52 | 1.05415 |
| 1600 | 1681.62 | 1.05133 | 5100 | 5366.94 | 1.05412 |
| 1700 | 1786.75 | 1.05140 | 5200 | 5472.35 | 1.05407 |
| 1800 | 1891.89 | 1.05150 | 5300 | 5577.76 | 1.05402 |
| 1900 | 1997.04 | 1.05160 | 5400 | 5683.16 | 1.05395 |
| 2000 | 2102.20 | 1.05170 | 5500 | 5788.55 | 1.05388 |
| 2100 | 2207.37 | 1.05180 | 5600 | 5893.94 | 1.05380 |
| 2200 | 2312.55 | 1.05187 | 5700 | 5999.32 | 1.05372 |
| 2300 | 2417.74 | 1.05198 | 5800 | 6104.69 | 1.05364 |
| 2400 | 2522.93 | 1.05207 | 5900 | 6210.06 | 1.05355 |
| 2500 | 2628.14 | 1.05216 | 6000 | 6315.41 | 1.05344 |
| 2600 | 2733.36 | 1.05226 | 6100 | 6420.76 | 1.05330 |
| 2700 | 2838.58 | 1.05237 | 6200 | 6526.09 | 1.05315 |
| 2800 | 2943.82 | 1.05248 | 6300 | 6631.40 | 1.05297 |
| 2900 | 3049.07 | 1.05260 | 6400 | 6736.70 | 1.05275 |
| 3000 | 3154.33 | 1.05270 | 6500 | 6841.97 | 1.05253 |
| 3100 | 3259.60 | 1.05283 | 6600 | 6947.23 | 1.05227 |
| 3200 | 3364.88 | 1.05295 | 6700 | 7052.45 | 1.05200 |
| 3300 | 3470.18 | 1.05305 | 6800 | 7157.65 | 1.05163 |
| 3400 | 3575.48 | 1.05316 | 6900 | 7262.82 | 1.05115 |
| 3500 | 3680.80 | 1.05326 | 7000 | 7367.93 | |

* Note: Right hand wheel on counter indicates approximately 0.1 milligals.

10-14-71
AWS

Table 6.1 Manufacturer's Calibration Table (G-275).

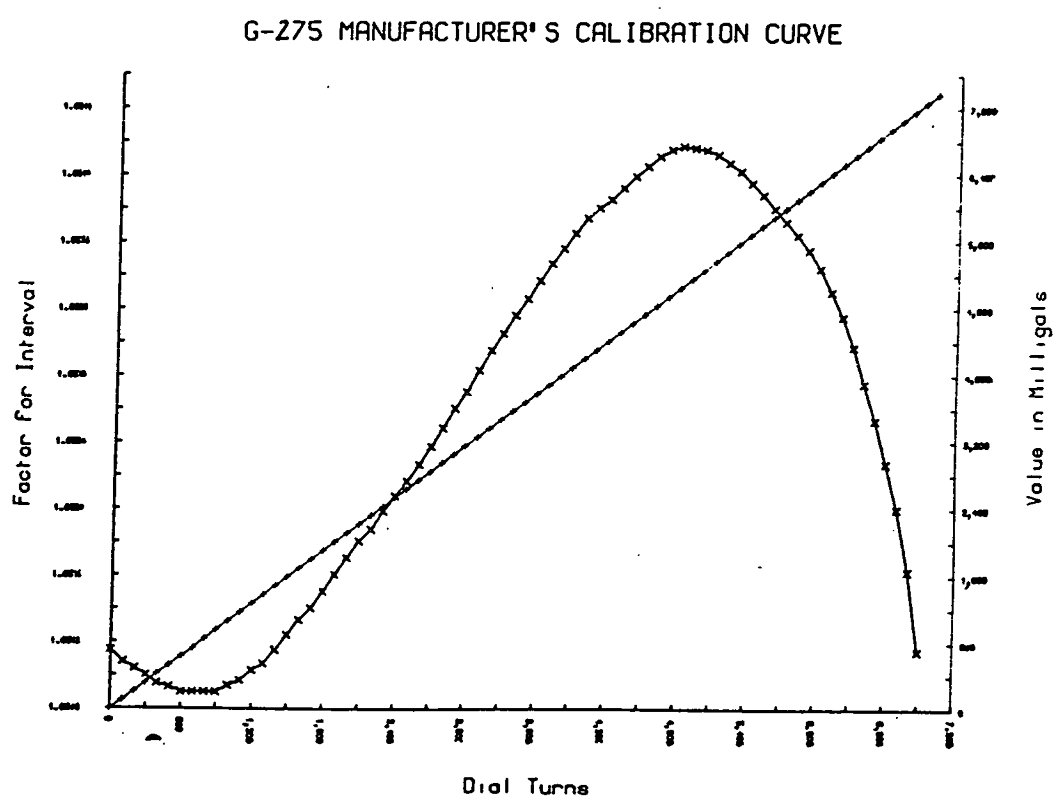



Figure 6.1 Graphical representation of the manufacturer's calibration table.

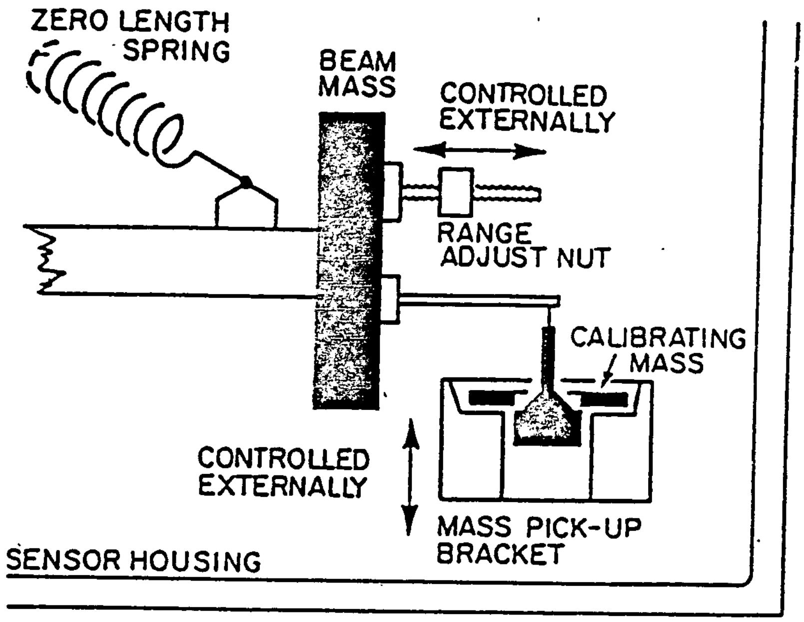



Figure 6.2 The Cloudcroft Junior method

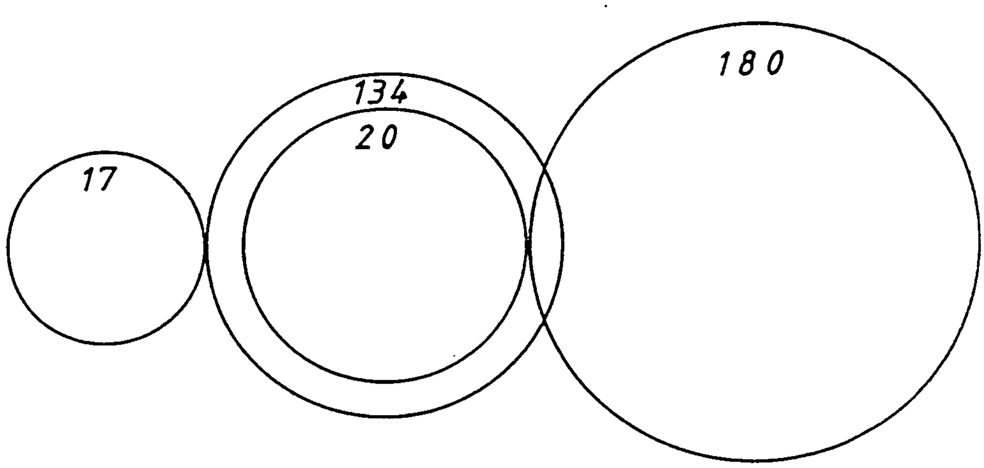



Figure 6.3 *Schematic representation of model 'G' gearbox*

knowledge of the internal mechanism. The normal procedure to calibrate an instrument is to observe on a well determined gravity difference which has been measured by a large number of instruments.

## 6.2 Periodic errors

Every revolution of the dial on the top plate of the gravity meter is translated into a minute movement of the measuring beam by means of reduction gears and lever arms. A schematic representation of the gear box is shown in figure 6.3. The final drive acts on a spindle ( pitch 184 t.p.i.) which moves the first arm of a lever system with a reduction ratio of 77.8:1. Imperfections in the machining of the component gears may generate cyclic errors with the following periods.

1206.0, 603.0, 70.94, 35.47, 7.88, 3.94, 1.00 counter units

In addition to periodic errors, irregularities in the manufacture of the spindle may generate large local errors.

Becker (1981) reports tests on one model G (G-258) on a vertical calibration line previously observed six times with D-38. Becker obtains an amplitude of 0.027g.u. for the one dial turn period. Kanngieser and Torge (1981) have conducted extensive tests on six model G and two model D meters on special calibration lines with gravity ranges of

2, 20, 200, 2,000, 20,000, g.u.. They obtain the following average values for the respective periodicities .

| Amp. (g.u.) | Period (Dial Turns) |
|---|---|
| 0.04 | 1 |
| 0.01 | 3.94 |
| 0.05 | 7.89 |
| 0.05 | 35.45 |

## Part (1) Calibration by measurement of a 'known' gravity difference

### 6.3 U.K. Calibration Lines

The United Kingdom does not possess such a range of well determined gravity differences, the best possible being the two Short National Calibration Lines established by the Institute of Geological Sciences (Masson-Smith et al,1974). These two lines are situated in north central England. The first extends from North Rode village (elev. 145.7m.) to the Cat and Fiddle inn (514.7m.), the second line links Hatton Heath (21.7m.) and Prees (85.9m.). The precision of transfer from the first to the second calibration line was degraded by the use of pressure sensitive gravity meters. After a period of time it became obvious there was a systemmatic difference between measurements before and after 1964 and the calibration line values were revised in 1971 after extensive remeasurement. When the United Kingdom was included in the International Gravity Standardisation Net (Morelli et al, 1971) the values were again revised to:

| | Gravity Diff.(g.u.) | Std. Error (g.u.) |
|---|---|---|
| NR-CF | 604.53 | 0.08 |
| HH-P | 556.51 | 0.09 |

Since that date the Institute of Geological Sciences has noted ' inexplicable differences of the order of one part in one thousand' between the two lines (Masson-Smith personal communication, 1983). This fact seems to have recently emerged after analysis of the results by I.G.S. when establishing the New Long Calibration Line (1983). It is also important to note that measurements prior to 1971 were made largely with Worden meters. Until that time I.G.S. did not correct readings for earth tides but simply applied linear interpolation. Furthermore the I.G.S. has never applied pressure corrections to their observations though these will be very small.

In addition to the Short Calibration Lines there exists the New Long Calibration Line of airport stations based upon existing measurments (NGRN73 Airport Net, see figure 6.4), together with two extra stations.
Most stations lie very close to runways making measurement by private aircraft desirable.

## 6.5 University Measurements

The Edinburgh instrument, G-275 has measured on three occasions on the Hatton Heath Prees calibration line and on four occasions on the Cat and Fiddle line. Table 6.2 illustrates the occasions on which the Edinburgh instrument G-275 has measured on the short calibration lines. Also shown are the measurement epochs of several other La Coste and Romberg meters. (Data kindly provided by Dr. P. Maguire, Dr. R. Barker, and Dr. G. Stuart of the universities of Leicester, Birmingham and Leeds respectively). Some stations of the Airport Net were measured with G-275 in conjunction with Fundamental Bench Mark and Pendulum sites as shown in figure 6.5. This line was measured in a single sequence A-B- --- -H-J on two separate days of twelve hours driving.

All these data were processed in an identical fashion, except for two sets of G-275 observations which were measured using the 'equilibrium technique'. The observation procedure was identical for all other data sets. In these the observers 'shuttle' back and forth between the two sites as often as possible in a working day (ie A-B-A...B-A-B).The dial turns were multipled by a constant scale factor derived from the manufacturer's tables. After the removal of the Earth tides (using program PBAS, section 4.4), the reduced observations were input to the spline fitting program NSPL. A simple least squares cubic solution was obtained for each of the 'shuttle data'. The 'equlibrium' data were processed by superimposing data sets in the manner described in section 5.2.

Table 6.2

Measurements on short calibration lines

| Meter | Date | Measurement Technique | Number of Observations | Gravity Difference (g.u.) | rmse | k' (x $10^{-4}$) |
|---|---|---|---|---|---|---|
| Hatton Heath - Prees (I.G.S., 556.51 (std. err. 0.09) g.u.) | | | | | | |
| G275 | 26.05.79 | S | 8 | 555.752 | 0.065 | 13.68 ± 2. |
| | 13.05.81 | S | 12 | 555.766 | 0.100 | 13.38 ± 3. |
| | 12.05.81 | E | 90 | 555.914 | 0.093 | 10.72 ± 3. |
| G16* | 02.05.81 | S | 13 | 555.202 (556.612) | 0.168 | 23.55 ± 4. |
| | 14.06.81 | S | 13 | 554.957 (556.367) | 0.197 | 27.98 ± 5. |
| | 21.07.81 | S | 14 | 555.108 (556.518) | 0.177 | 25.26 ± 4. |
| G545 | 28.05.81 | S | 13 | 555.346 | 0.229 | 20.96 ± 5. |
| | 02.12.81 | S | 13 | 555.109 | 0.172 | 25.24 ± 4. |
| G471 | 14.06.81 | S | 11 | 555.776 | 0.242 | 13.21 ± 5. |
| | 11.10.81 | S | 13 | 556.033 | 0.083 | 8.58 ± 3. |
| | 04.07.82 | S | 13 | 555.832 | 0.097 | 12.20 ± 3. |
| Cat and Fiddle - North Rode (I.G.S., 604.53 (std. err. 0.08) g.u.) | | | | | | |
| G275 | 25.05.79 | S | 6 | 604.242 | 0.079 | 4.77 ± 2. |
| | 09.01.80 | S | 9 | 604.265 | 0.063 | 4.38 ± 2. |
| | 10.05.81 | S | 12 | 604.138 | 0.033 | 6.49 ± 1. |
| | 11.05.81 | E | 99 | 604.111 | 0.088 | 6.95 ± 2. |

S - 'Shuttle', i.e. A-B-A-B......

E - 'Equilibrium', A-B-A-B.

* Gravity difference in brackets refer to value obtained after application of correction factor of 1.00254.

k' is the scale factor correction, (I.G.S. value - Observed/Observed)

Figure 6.4  U. K.  airport net (Masson-Smith et. al.,1974)

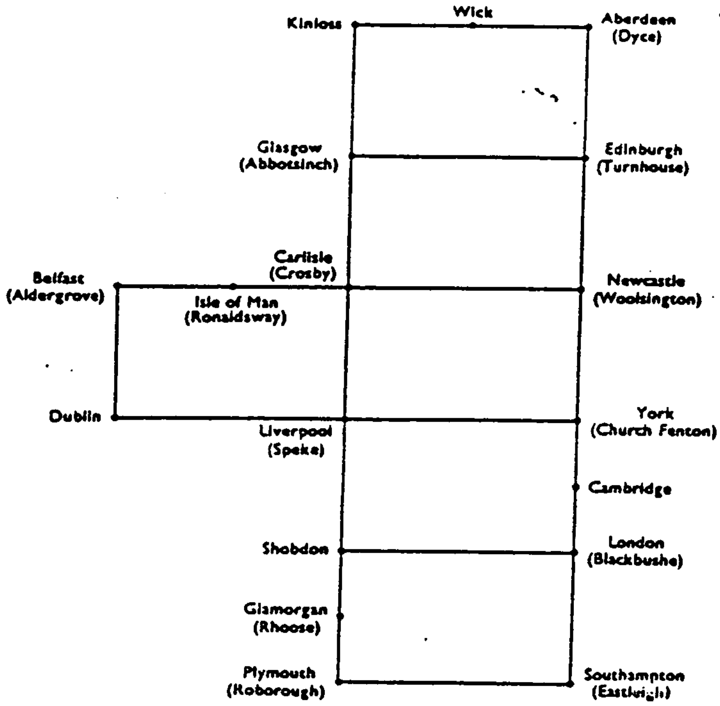
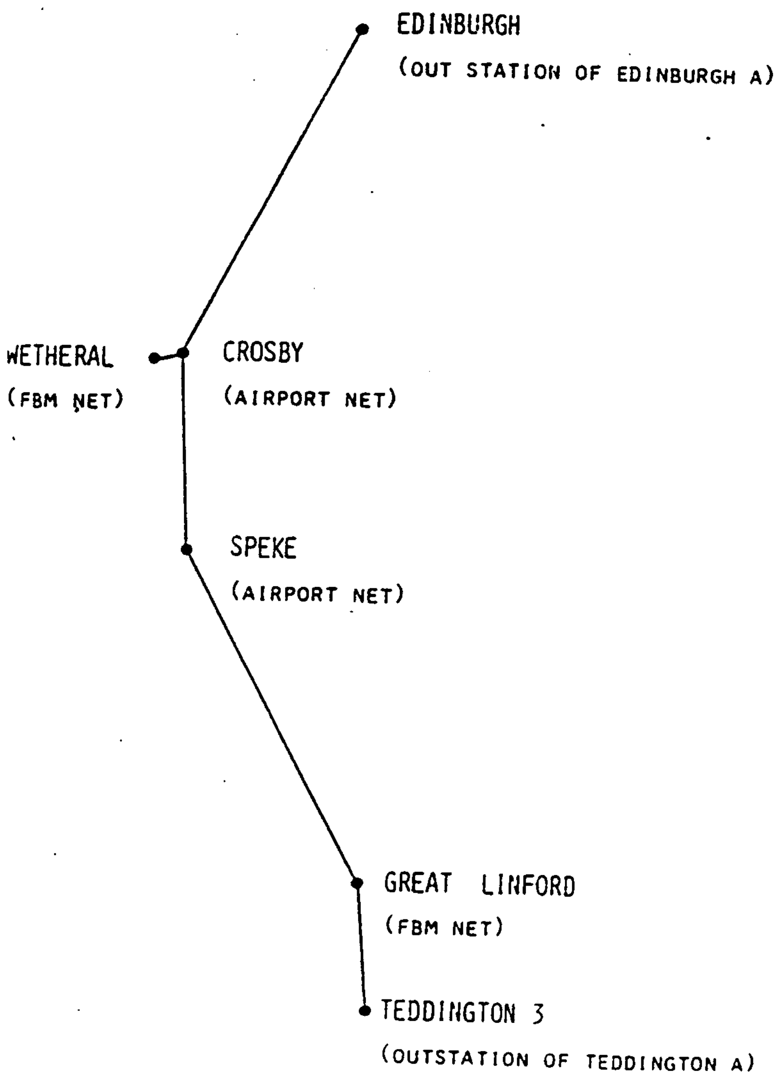



Figure 6.5  Stations measured with G-275 on long calibration run



The results of the solutions are shown in table 6.2 and they are displayed graphically in figure 6.6. It can be seen that nine independent sets of data from four different instruments processed using the manufacturer's scale factor are consistently lower than the stated NGRN73 value. (The Leicester University group mistakenly apply a 'correction' of 1.00254 on the basis of the 21-07-81 readings). The rightmost column of table 6.2 gives the scale factor error assumming the NGRN73 value. These are of the order of one or two parts in a thousand which is almost an order of magnitude greater than typical errors quoted in the literature (eg. Torge, 1971 quotes 0.1 to 6.0 x $10^{-4}$ ; Nakagawa and Satomura, 1978 obtain 2.1,6.6, and 6.4 x $10^{-4}$).

The results obtained from the long calibration run (Table 6.3) exhibit scale factor corrections very similar to the Cat and Fiddle line. (These data were adjusted using MULTILINEAR ). All the combined evidence seems to suggest the quoted value for the Hatton Heath calibration line (the basis for the British gravity unit!) is erroneous. The calibration line is situated on the Chesire plain where extraction and infusion of water to obtain salt is a large scale industrial operation. This may be a possible cause for the discrepancy. The results indicate that G-275 underestimates the gravity difference between sites by four parts in ten thousand. Furthermore, the Edinburgh

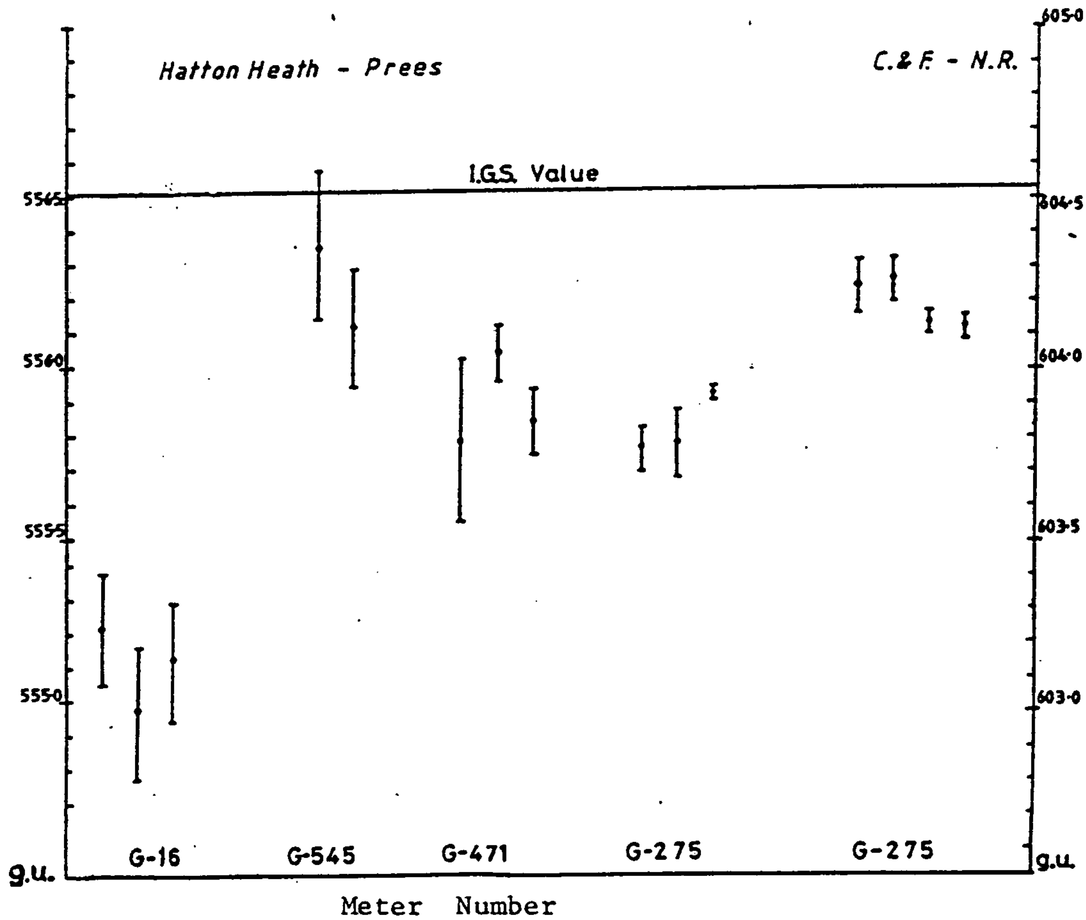



Figure 6.6 Results of university observations on U.K. short calibration lines. Four different meters observing on Hatton-Heath Prees line and one observation on Cat & Fiddle North Rode line.

Table 6.3

Measurements on Long Calibration Line

| Station Name | NGRN73 Value (g.u.) | Quoted Std. Err. (g.u.) | G-275 Value (g.u.) | rmse (multi-linear) (g.u.) | Difference (NGRN-G275) (g.u.) | k' (x 10 |
|---|---|---|---|---|---|---|
| Edinburgh (JCMB) Out station of Edinburgh A° | 3967.06+ | 0.22 | 3965.44 | 0.11 | 1.62 | 4.08 ± 0 |
| Crosby 1* | 3165.06 | 0.20 | 3163.46 | | 1.60 | 5.06 |
| Wetheral FBM | 3117.73 | 0.22 | 3116.58 | 0.20 | 1.15 | 3.69 ± 1. |
| Speke 1* | 1909.01 | 0.17 | 1908.05 | 0.02 | 0.96 | 5.03 ± 1. |
| Gt Linford FBM | 540.29 | 0.31 | 539.38 | 0.11 | 0.91 | 16.87 ± 7. |
| Teddington 3 Out station of Teddington A° | 0.00++ | 0.17 | 0.00 | 0.04 | | |

Values are quoted relative to Teddington 3 (NGRN73 value 981182.038)

° Pendulum Station

* U.K. Airport Net

k' Scale factor correction (NGRN73-G275/G275)

+ Based on Edinburgh A - Edinburgh (JCMB) = -159.48 ± 0.18 g.u. (Lagios and Hipkin, 1981).

++ Based on Teddington A - Teddington 3 = -2.41 ± c0.13 g.u. (Turnbull, personal communication) meter has previously been shown to be in good agreement with other NGRN stations (Lagios and Hipkin, 1981).

## Section (2) - Calibration by Tilting

### 6.6 The Method

It is possible to simulate a variation in gravity by simply tilting the gravity meter. If the beam is assumed to be supported by a perfect pivot, and thus constrained to have one degree of freedom, the force experienced by the mass is simply $g_o \cos\theta$ as shown in figure 6.7. The vector $g_o$ is the accleration due to gravity in the direction of the local vertical. When $\theta$ equals zero (ie the meter is levelled) the force experienced by the mass relative to the instrument case is a maximum. When the meter is tilted through small positive and negative angles ($d\theta$) the acceleration change (dg) may be expressed as.

$$dg = g_o \cos (d\theta)$$
$$dg = g_o (\theta/2)^2$$

This is the equation of a parabola, symmetric about the maximum value. This property is commonly used to level the glass vials by checking that the cross hair

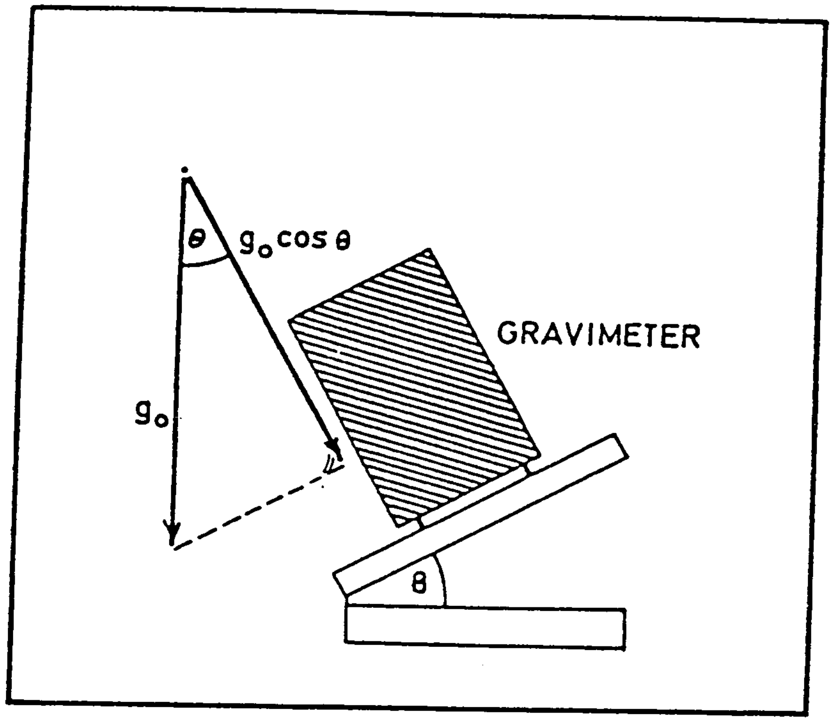



Figure 6.7  Simplified diagram of gravimeter tilting.

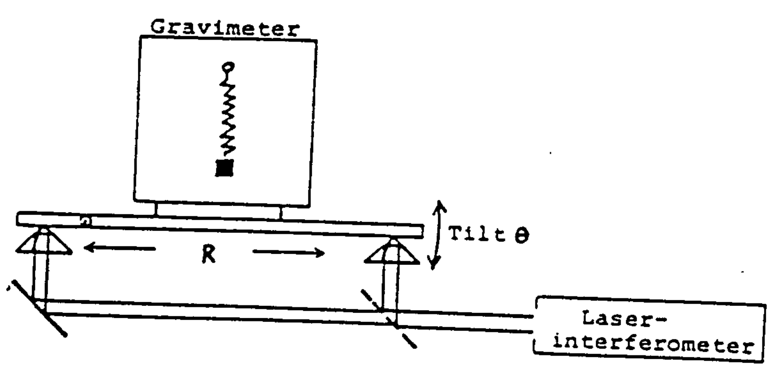
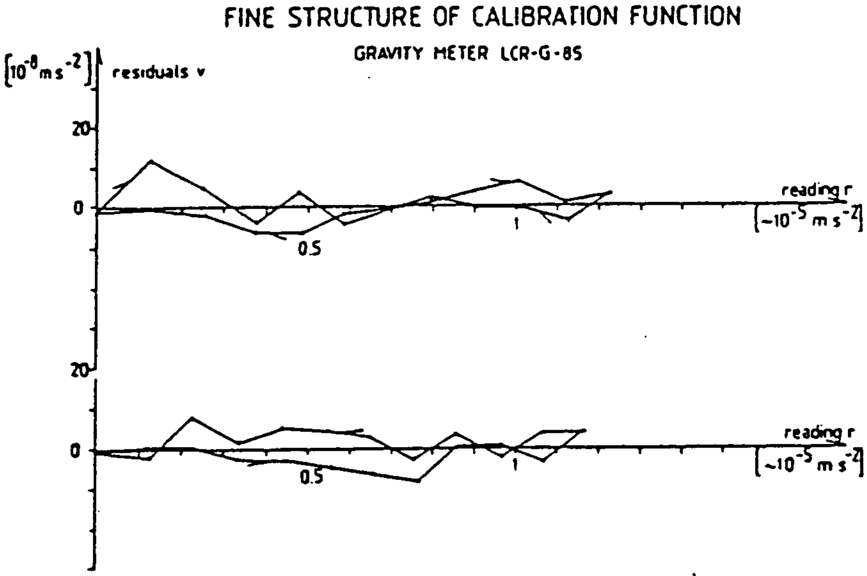



Figure 6.8  Boedecker's experimental arrangement.

displacement is equivalent when the meter is tilted one bubble division in either direction parallel to the vial. The procedure is not commonly used to determine the absolute calibration factor for model G meters but is frequently used with earth tide meters, (e.g Wenzel, 1976 describes the calibration of an Askania tide meter at Hannover, and list several references to similar work at Brussels). The tilt calibration of a fed back La Coste and Romberg observatory gravimeter is described in Moore and Farrell (1970). The instrument is tilted by a motor driven micrometer screw coupled to a metal film potentiometer to measure the number of rotations of the screw. Boedecker(1981) measured the tilt of a platform interferometerically using two corner cube reflectors (figure 6.8) to measure the vertical displacement of one reflector to the second fixed on the pivoting axis. Boedecker wished to calibrate model G meters in this way but reports 'doubtfull results'. However he used the adjustments residuals to determine periodic components as shown in figure 6.9. Despite Boedecker's reported difficulties it seemed to the author that laser interferometry is the optimum method to measure the tilting angle . Such a method is independent of a micrometre thread which may generate periodic errors and uses a well determined physical constant, the wavelength of the laser beam to determine the displacement.



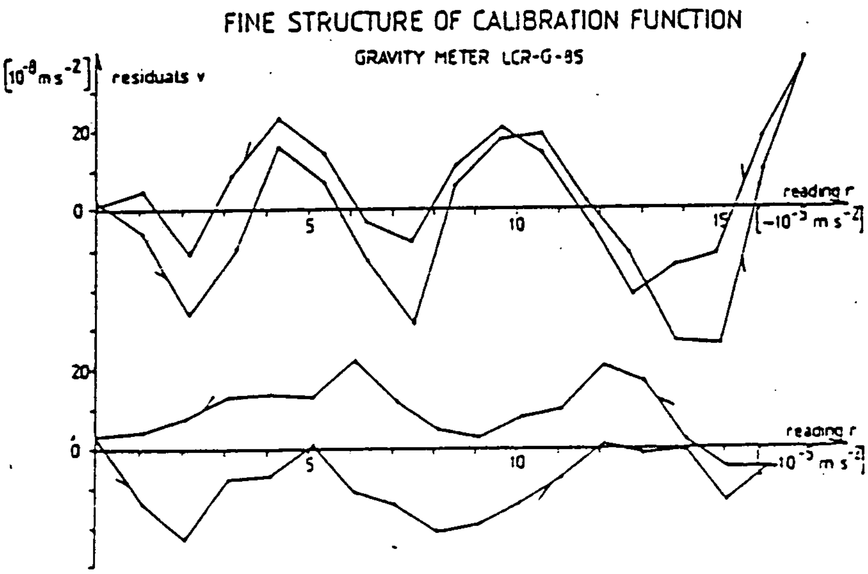




Figure 6.9 Fine structure of calibration constant, as observed by Boedecker.

## 6.7 Experimental Procedure

In a preliminary set of experiments the meter was mounted on the secondary platform (section 3.2) and the tilt angle adjusted and measured by means of the new screw feet. The serrated edge of the adjustable foot served as an index to count the number of rotations of the screw. A brass pointer was mounted on the barrel of the foot and every tenth count was annotated. One revolution of the screw (one fortieth of an inch) corresponds to 123 serrations. Hence one serration along the long axis approximates to 2.43 seconds of arc for small angles. Three preliminary experiments were undertaken using the foot screw to derive tilt angles. The meter was alternately tilted equal angles (ie serration counts) in opposite directions and observed. Additionally every third reading was taken in the levelled horizontal position to control drift. The drift curves (after tidal reduction) so obtained are shown in figure 6.10. After the instrumental drift is removed it is possible to plot observed gravity against the angular displacement of the platform (figure 6.11).

## 6.8 Interferometeric Measurement of the Tilting Angle

Boedecker's experiment required the use of two corner cube reflectors which were both unattainable and expensive to purchase. After consulation with Mr. R. Silitto, of the Physics Department, Edinburgh University a simpler arrangement observing Newton's Rings was set up (figure

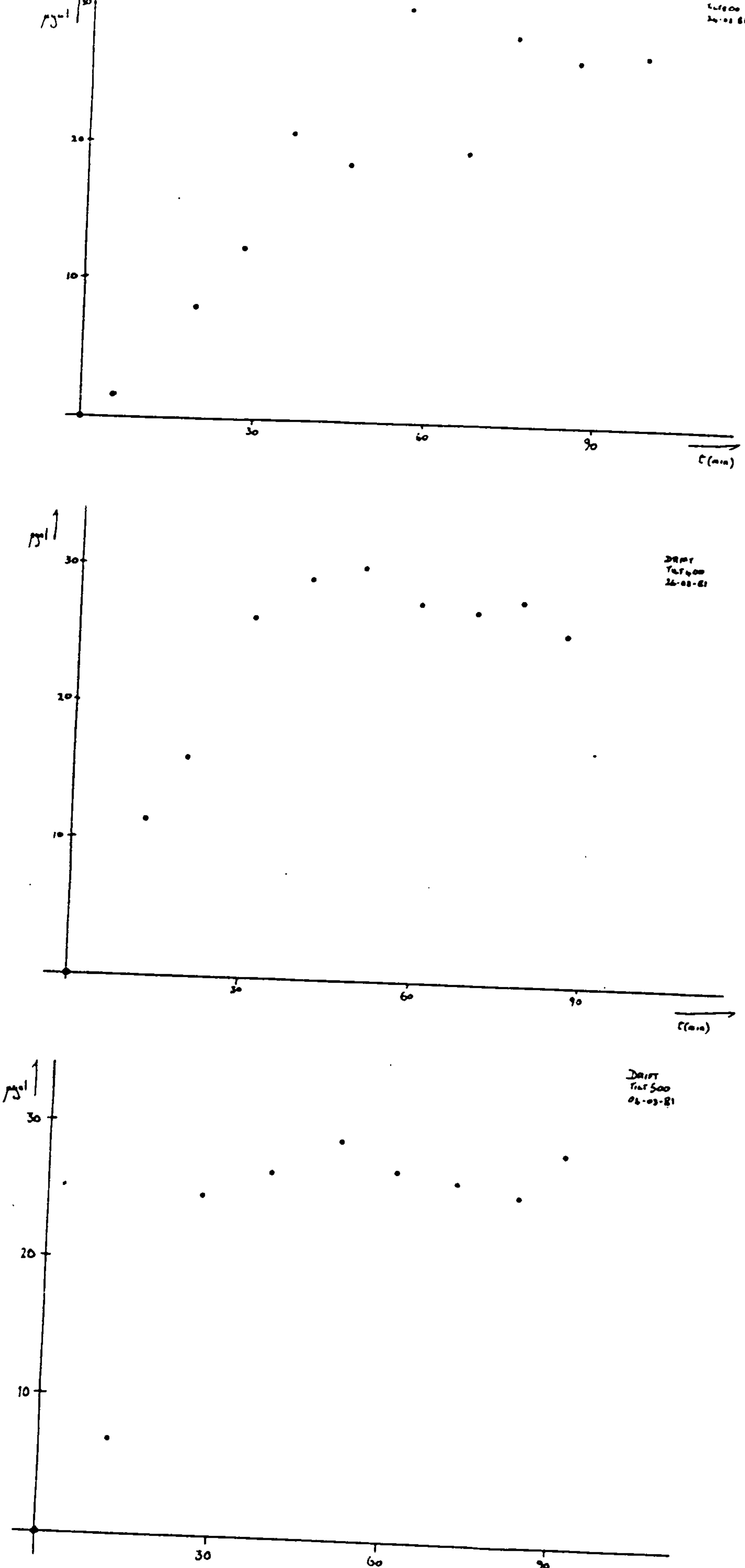
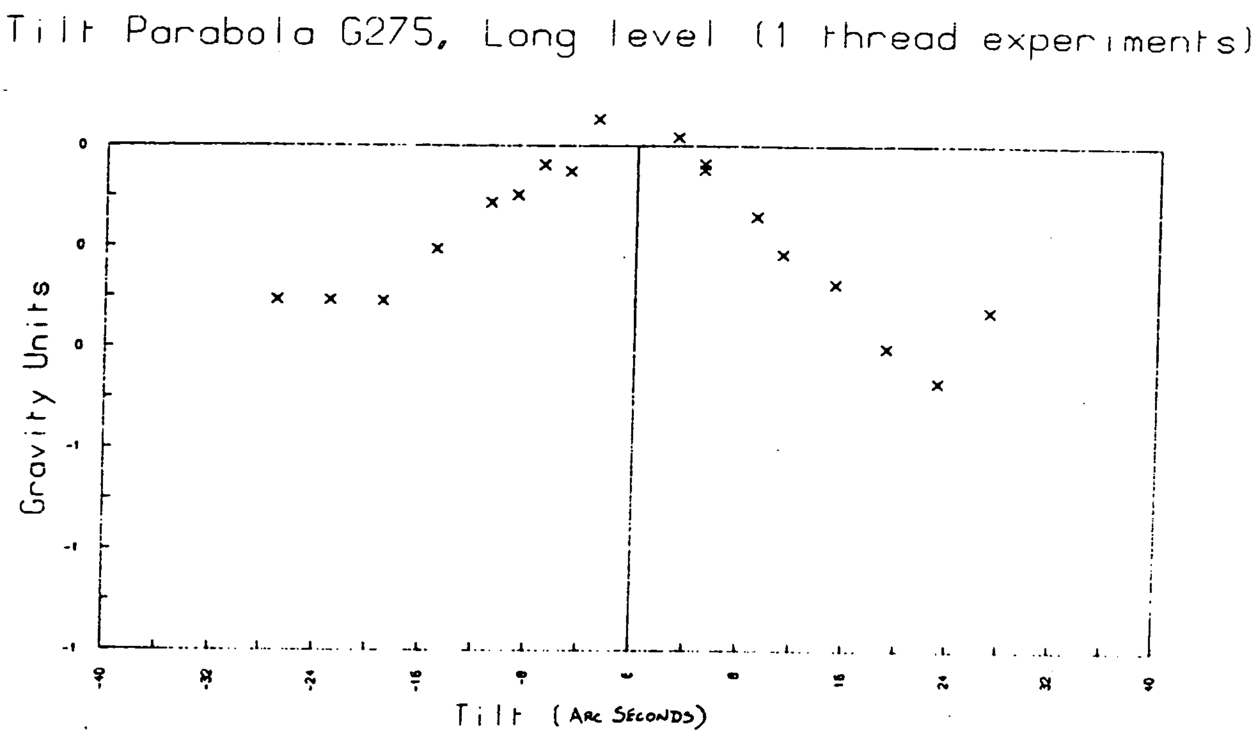



Figure 6.10 Examples of observed drift (preliminary experiments, angle estimated from screw thread).



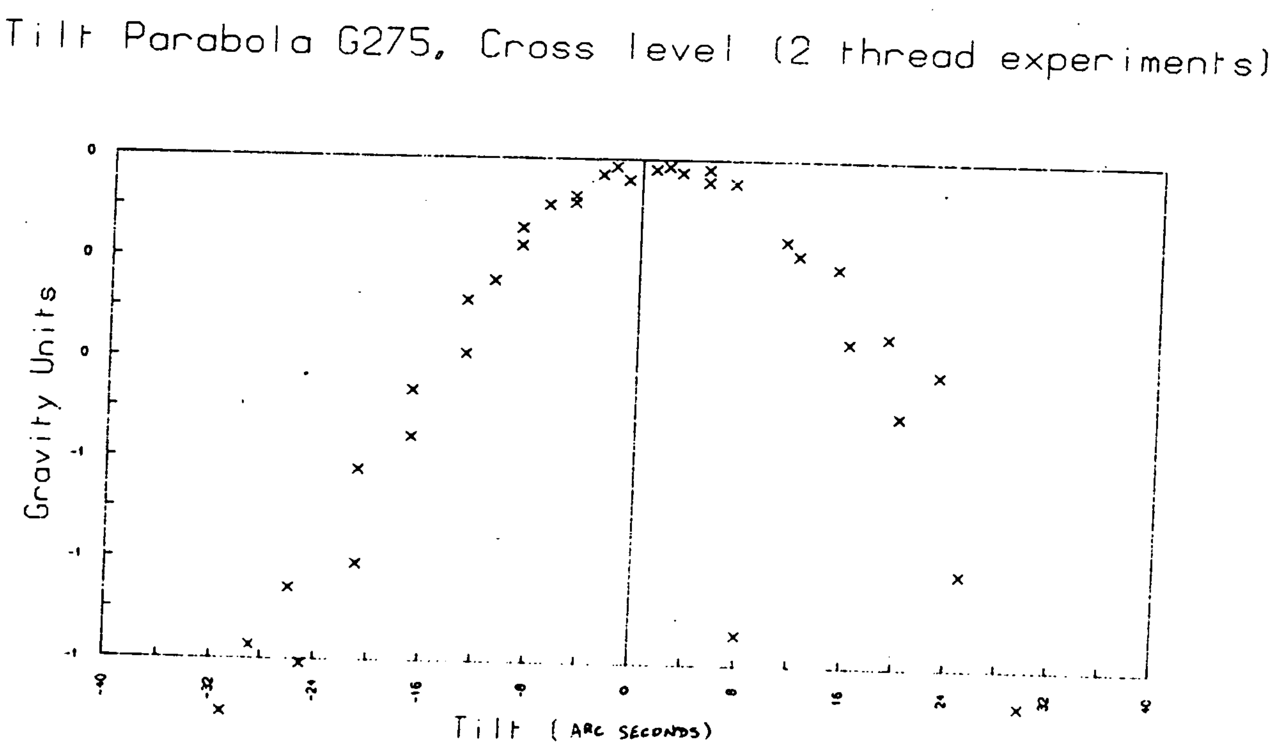




Figure 6.11 Observed tilt parabolas (preliminary experiments).

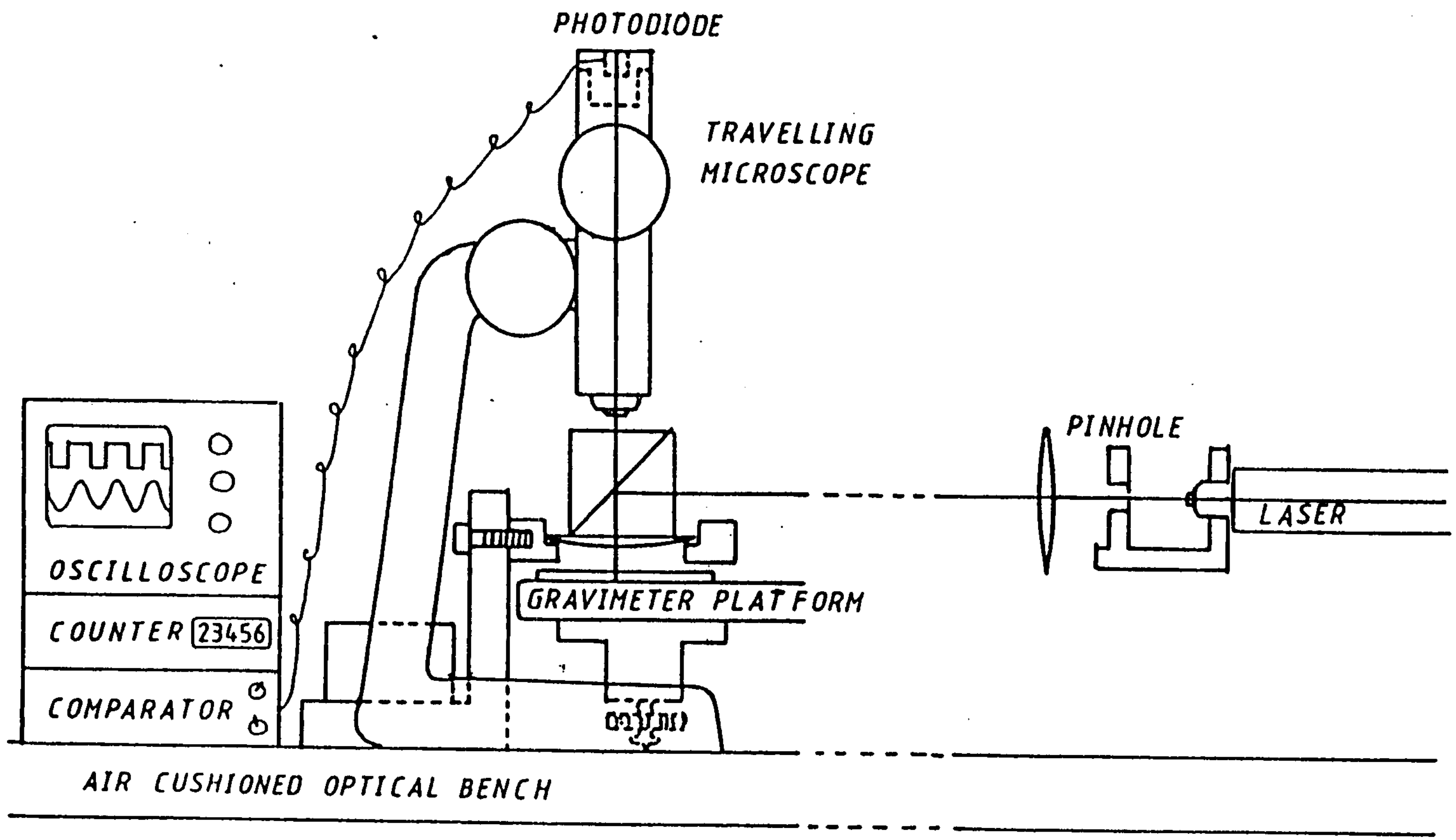
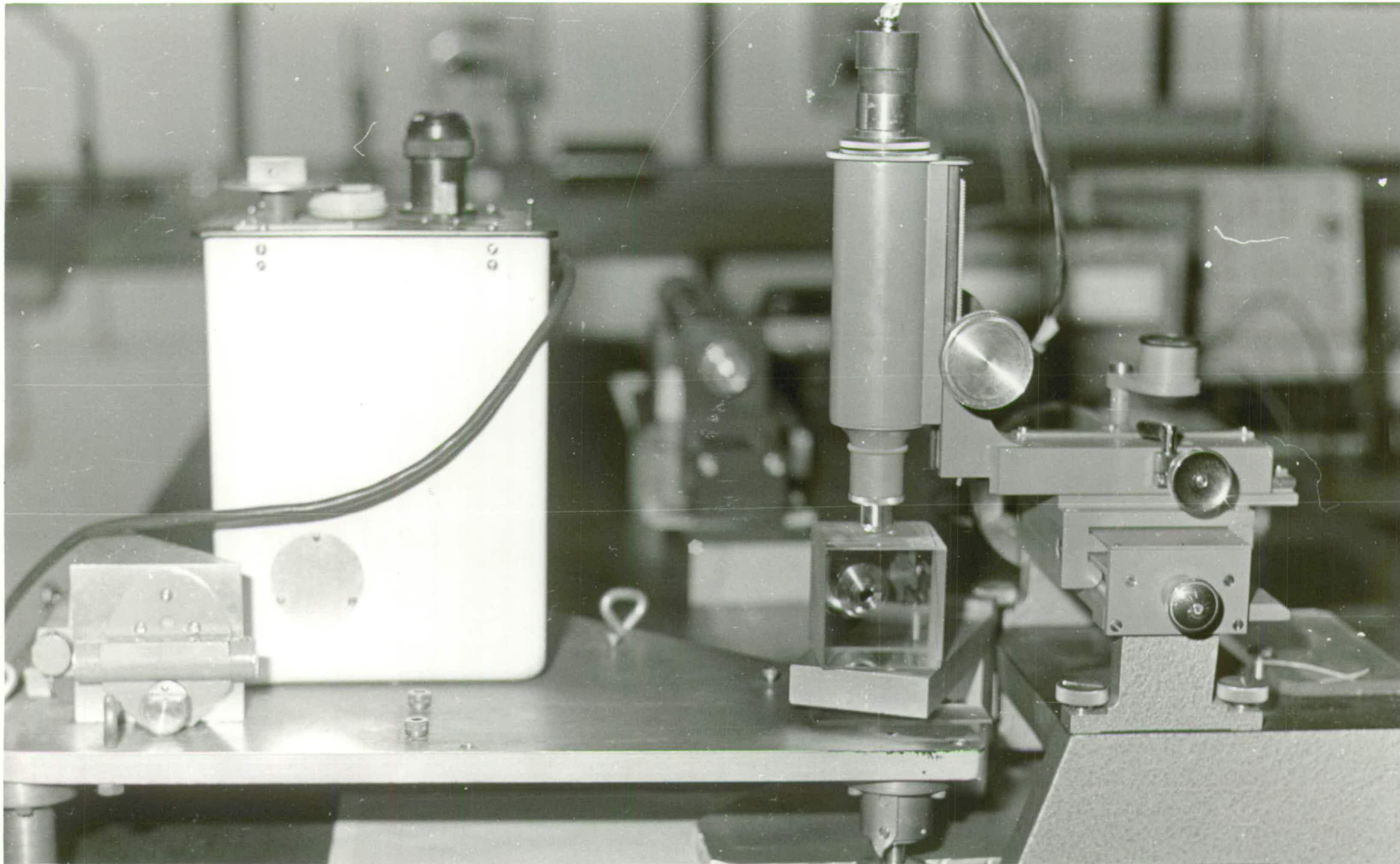



Figure 6.12 Experimental arrangement for the interferometric determination of tilting angle.

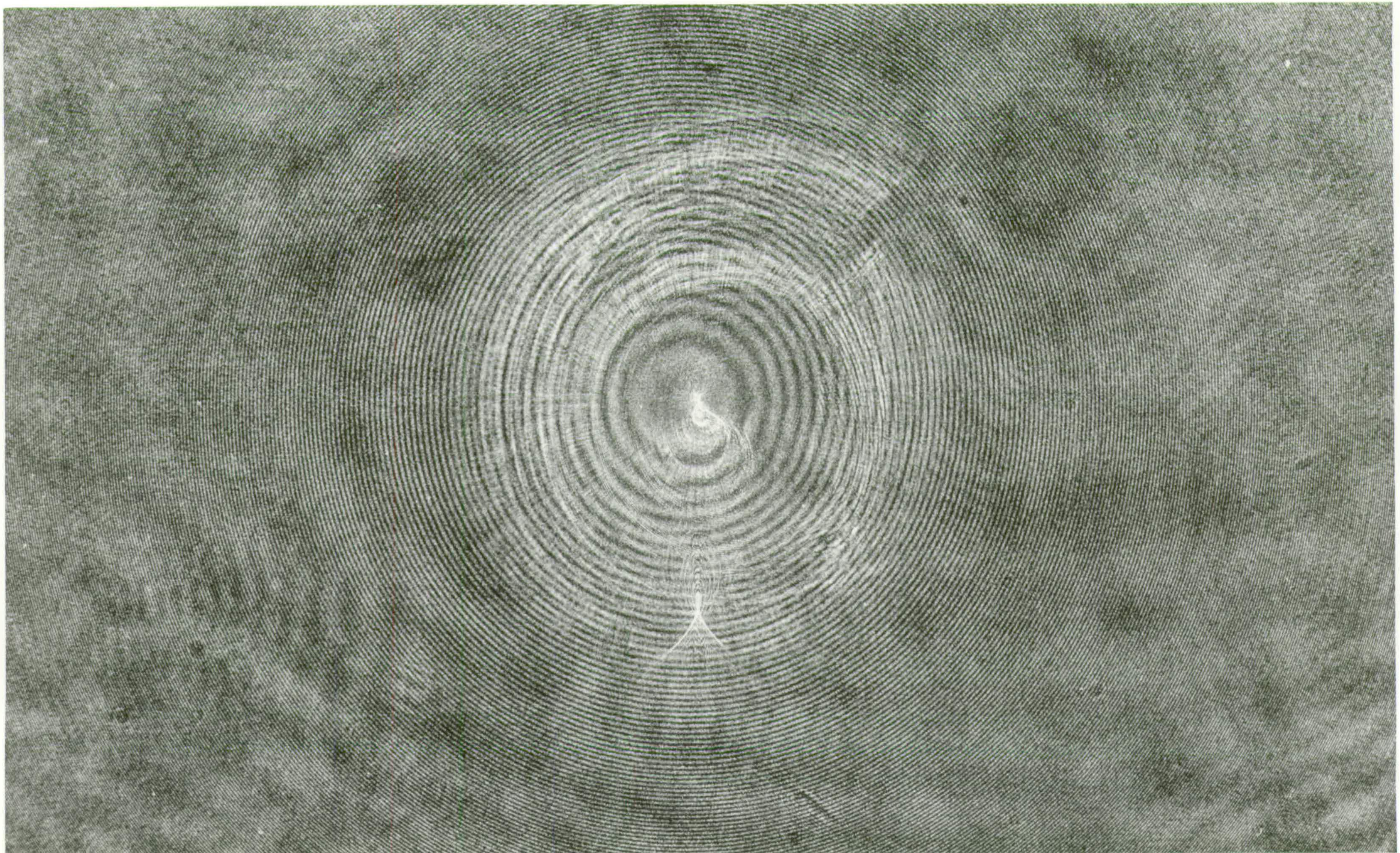


6.12 and plate 6.1). Mr Sillitto provided the necessary optical equipment and importantly the use of a stable optical bench.

Coherent light (in this case , a two milliwatt He-Ne laser) is directed on to a double prism. One ray of the split beam passes through through a planoconvex lens of long focal length and reflected perpendicularly off an optical flat resting on the surface of the platform. This is similar to the arrangement for the classic Newton's Rings experiment, the theory of which is described in any standard Physics or Optics textbook (e.g.Born and Emil, 1980). Light reflected from the top of the optical flat and the concave surface of the lens interfer to form concentric circles of maxima and minima with a large amplitude central pattern (amplitude varies radially as a sinc function). Movement of the platform alters the air gap between the lens and the optical flat changing the optical path length and the rings appear to grow outwardly from the centre or collapse in from the perimeter (depending on the direction of movement). A photgraph was taken by substituting a 35mm. camera with adaptor for the microscope eyepiece (plate 6.2). This photograph was taken at an early stage of the experiment (when an inclined optical flat was used in place of a double prism) and the ring quality was rather poor.

An initial attempt to count the collapsing maxima mentally was found to be totally impractical. Apart from

Plate 6.2: An example of the eyepiece image.



numerical errors the time involved precluded repeated observation of the gravity meter. The fringes were counted electronically using a simple electronic comparator and photodiode together with a standard electronic counter. Several cicrcuits were designed and constructed before a satifactory arrangement was found. A diagram of the final circuit is shown in figure 6.13. This consists of two inexpensize op-amps (type 741) in a two stage amplifier, the second of which is driven to saturation , giving a square wave output. Potentiometers VR1 and VR2 determine the theshold voltage at which saturation occurs. Specific comparator integrated circuits (e.g. type 693) did not operate as well as this arrangement. Circuit performance was checked using a digital oscilloscope and a tracing from a polaroid photograph of a typical input and out trace is shown in figure 6.14. The lower trace illustrates the input signal from the photodiode (amplitude 6mv) and the upper the amplifier output (20V). The trace illustrates the screw foot being wound down to a static position; as the screw rotation rate decreases the waveform narrows. Vibrational noise was found to be a large problem but this was almost completely eliminated by supporting the optical bench on planks resting on inflated car tyres. This proved remarkably effective and most of the noise visible on figure 6.14 is electronic. The square wave pulses were counted using a Hewlett Packard model 5300B/53088A measuring system. The fringe counter is most likely to generate errors when tilting commences or

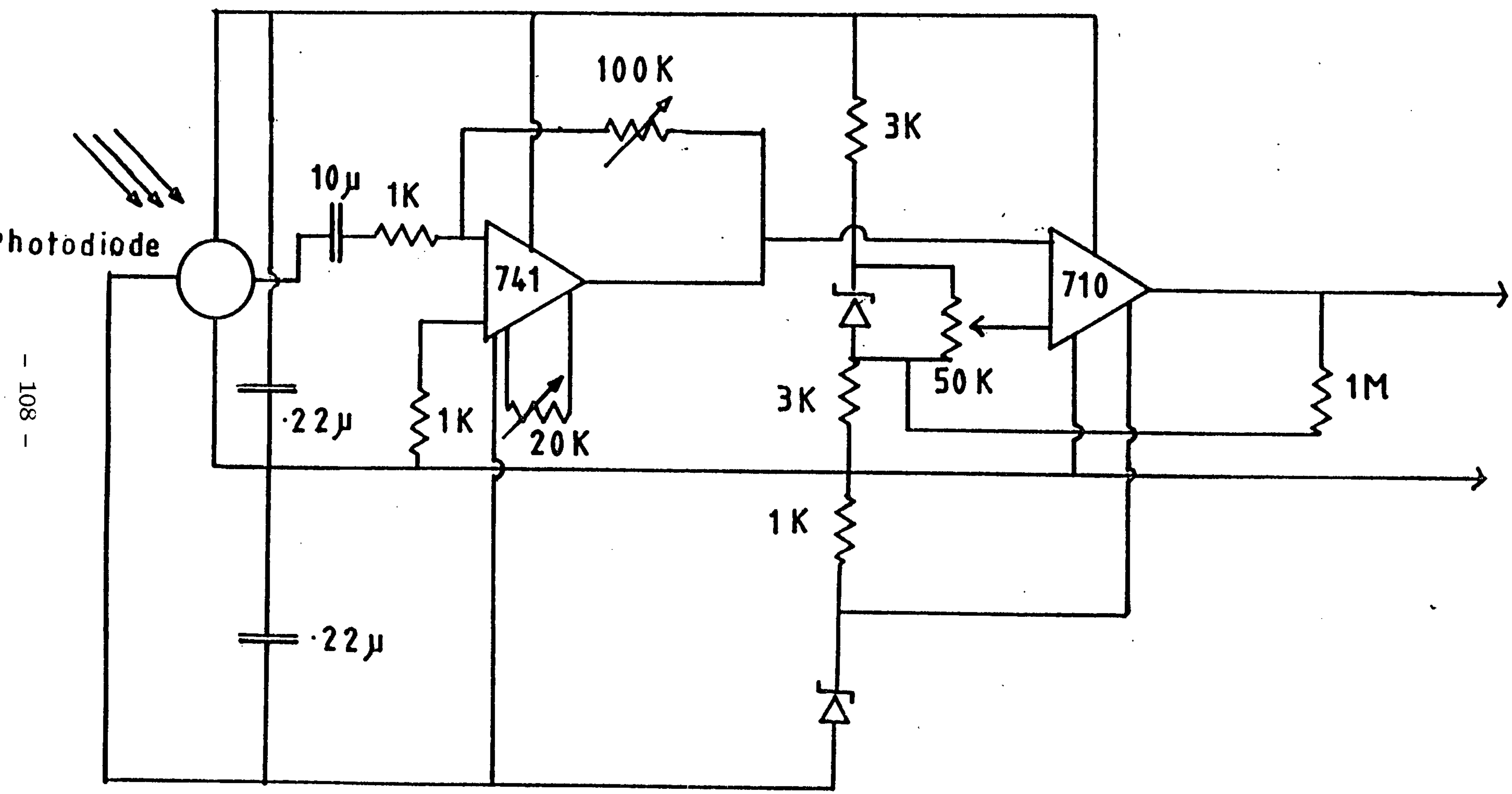



Figure 6.13 Electronic circuit diagram of comparator.

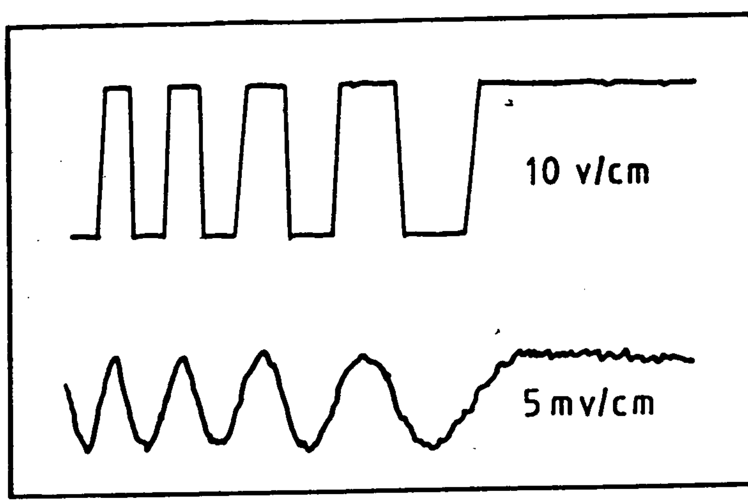



Figure (6.14)

Dual 741 driven to power rails

Oscillocope trace (taken from Polaroid photograph) of comparator input and output.

finishes as shown in figure 6.14. but repeated tests gave very satisfactory registration. The cushioning of the optical bench reduced vibration to such a small level that it was barely perceptible through the microscope eyepiece and it was possible to register zero counts when the apparatus was left unattended for several hours outside normal working hours. This was not the case during week days so all experimentation was carried out at night or weekends.

The reading procedure was similar to that outlined above, the first and every third reading was taken with the meter levelled to control instrument drift. Ten experiments were carried out, six tilting parallel to the cross axis and four parallel to the long axis, before it was necessary to vacate the optical laboratory. The position of the central interference pattern was scribed on the top surface of the secondary plate whilst sighting down the microscope. The distance to the from this point to the pivoting axis was determined on a cast iron flat bed using a vernier height guage.

## 6.9 Data Reduction and Results

The central maxima oscillates in intensity from dark to dark again as the platform is displaced one half of a wavelength. Thus for small angles

$$\theta \doteqdot h/R = n\lambda/2R \qquad \text{E 6.2}$$

where h = air gap thickness

R = pivot radius

n = the fringe count

$\lambda$ = the wavelength of the source

The relative uncertainity in the measured angle is largely dependent on the uncertainity in fringe counting and the estimation of R since the error associated with the wavelength is negligble. The fringe count error will always be positive and a pessimistic estimate of this error would be one part in five hundred. The distance R is about 0.35m. and the error in measuring between the scribed lines using machine shop guages is better than $10^{-4}$m..

If the meter is not horizontal when levelled using the vials but at a small angle $\theta_o$, then at some angle $g_1$

$$\tilde{g} = g_o \cos\theta_o - g_o \cos\theta_1$$
$$= g_o \{(1-\cos\theta_1) - (1-\cos\theta_o)\}$$
$$= g_o \{\sin\theta_1^2/2 - \sin\theta_o^2/2\}$$
$$\simeq g_o \{\theta_1^2/2 - \theta_o^2/2\}$$

$$\tilde{g} = \theta_o \partial\theta\, g_o - \partial\theta^2/2 \qquad \text{E 6.3}$$

$$\partial\theta = \theta_1 - \theta_o$$

Thus the observed gravity is described by a second degree polynomial whose second coefficient relates dial turns to gravity and the first degree coefficient is related to the levelling error. The data were reduced using existing programs (PBAS) which converts the dial turns to gravity units using the manufacturer's scale factor and relates obsereved gravity to the first reading. In addition to a first and second degree coefficient the is a constant term, being any error associated with the first reading Subsistuting equation 6.2 into equation 6.3 and adding a constant term, $\alpha$ gives

$$\tilde{g} = \alpha + \frac{n\lambda}{2R} \theta_0 g_0 - \left(\frac{n\lambda}{2R}\right)^2 g_0 \qquad \text{E 6.4}$$

The constant and first degree coefficients differ for each observation sequence but the second degree coefficient is common to those sequences tilting along the same axis.

A least squares adjustment program, LSQTILT (see appendix 5 ) was written to fit a common second degree coefficient to a tilting data suite. For N observation sequences there are 2N+1 unknowns, N constant coefficients, N first degree coefficients plus the common second degree coefficient. The least squares solutions for the long level data suites is hown in figures 6.15.

The cross level data suite is evidently of lower quality than that of the long level. This is also apparent on examination of tables 6.4 and 6.5, the output from the program LSQTILT. The standard deviation for the cross level set is greater than one gravity unit and the regression parameter R (Draper and Smith, 1966) is unsatisfactorily low. Tilting the meter parallel to the cross level

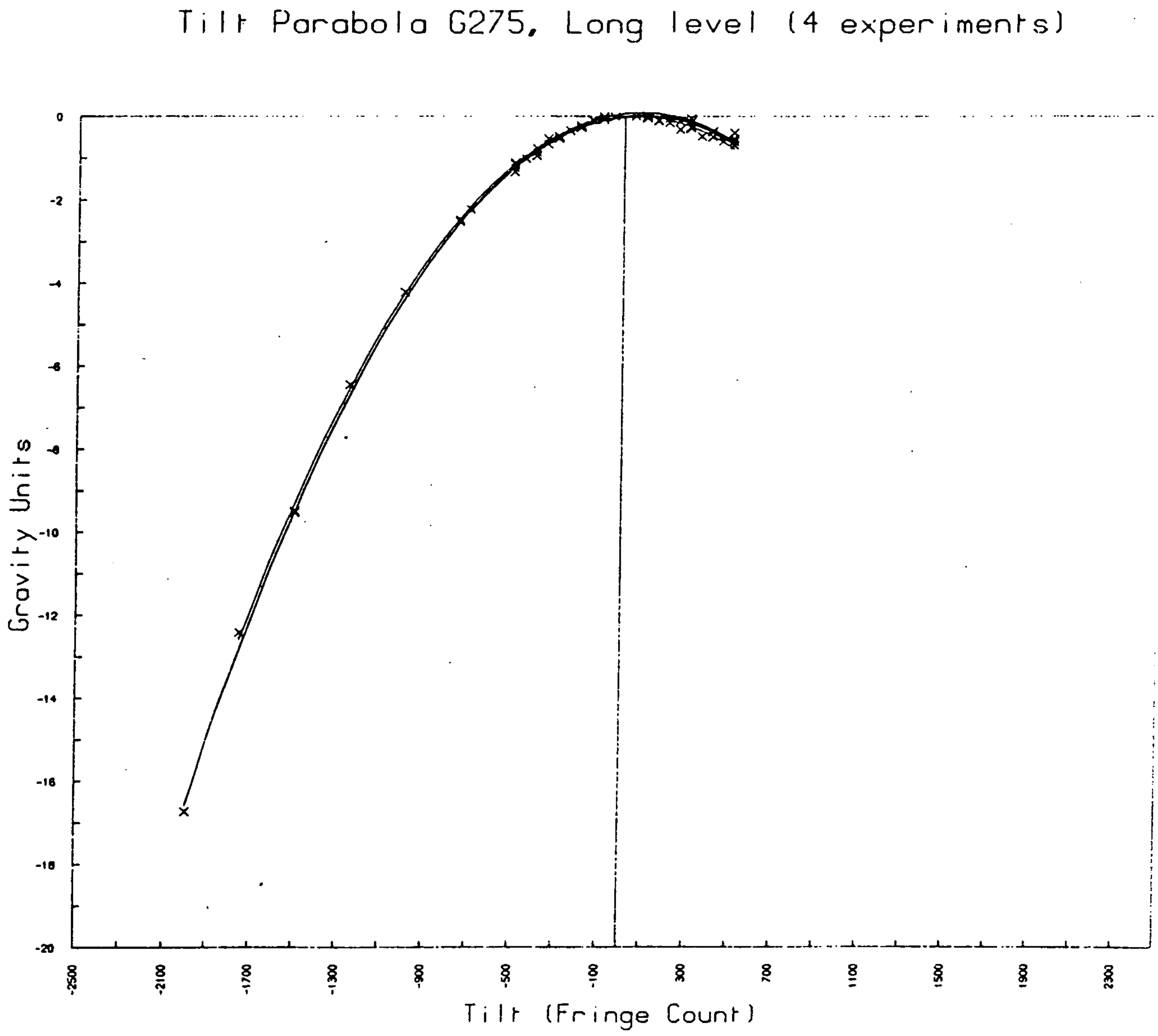



Figure 6.15 Least squares fit to long level tilt observations.

Table 6.4

Results of analysis of tilting experiment

LONG AXIS

The number of observations is 59 with 9 constraints

The estimated standard deviation of the fit is 0.0951

R squared for fit: 0.99922

The Regression Coefficients with their variances (st. err. squared) are

| | | |
|---|---|---|
| 1 | -0.30340E-01 | 0.46532E-03 |
| 2 | 0.70109E-01 | 0.87535E-03 |
| 3 | 0.81648E-03 | 0.63155E-03 |
| 4 | 0.67385E-01 | 0.13580E-02 |
| 5 | 0.42231E-03 | 0.46955E-08 |
| 6 | 0.47546E-03 | 0.34683E-08 |
| 7 | 0.55704E-03 | 0.52658E-08 |
| 8 | 0.60765E-03 | 0.45869E-08 |
| 9 | -0.38598E-05 | 0.14437E-14 |

CCORRN is: 0.996139704

Table 6.5

Results of analysis of tilting experiment

CROSS AXIS

The number of observations is 92 with 13 constraints

The estimated standard deviation of the fit is 1.1313

R squared for fit: 0.96122

The Regression Coefficients with their variances (std. err. squared) are

| | | |
|---|---|---|
| 1 | -0.54962E-01 | 0.80249E-01 |
| 2 | -0.12757E+00 | 0.71584E-01 |
| 3 | -0.33386E+00 | 0.19456E-00 |
| 4 | -0.15989E+01 | 0.13700E-00 |
| 5 | -0.79983E-02 | 0.80515E-01 |
| 6 | 0.10930E+01 | 0.11675E+00 |
| 7 | -0.31512E-03 | 0.60088E-06 |
| 8 | 0.12748E-02 | 0.39080E-06 |
| 9 | 0.21348E-02 | 0.34244E-07 |
| 10 | -0.10506E-02 | 0.73662E-07 |
| 11 | 0.40928E-03 | 0.45346E-06 |
| 12 | 0.42466E-03 | 0.50191E-07 |
| 13 | -0.36177E-05 | 0.14472E-13 |

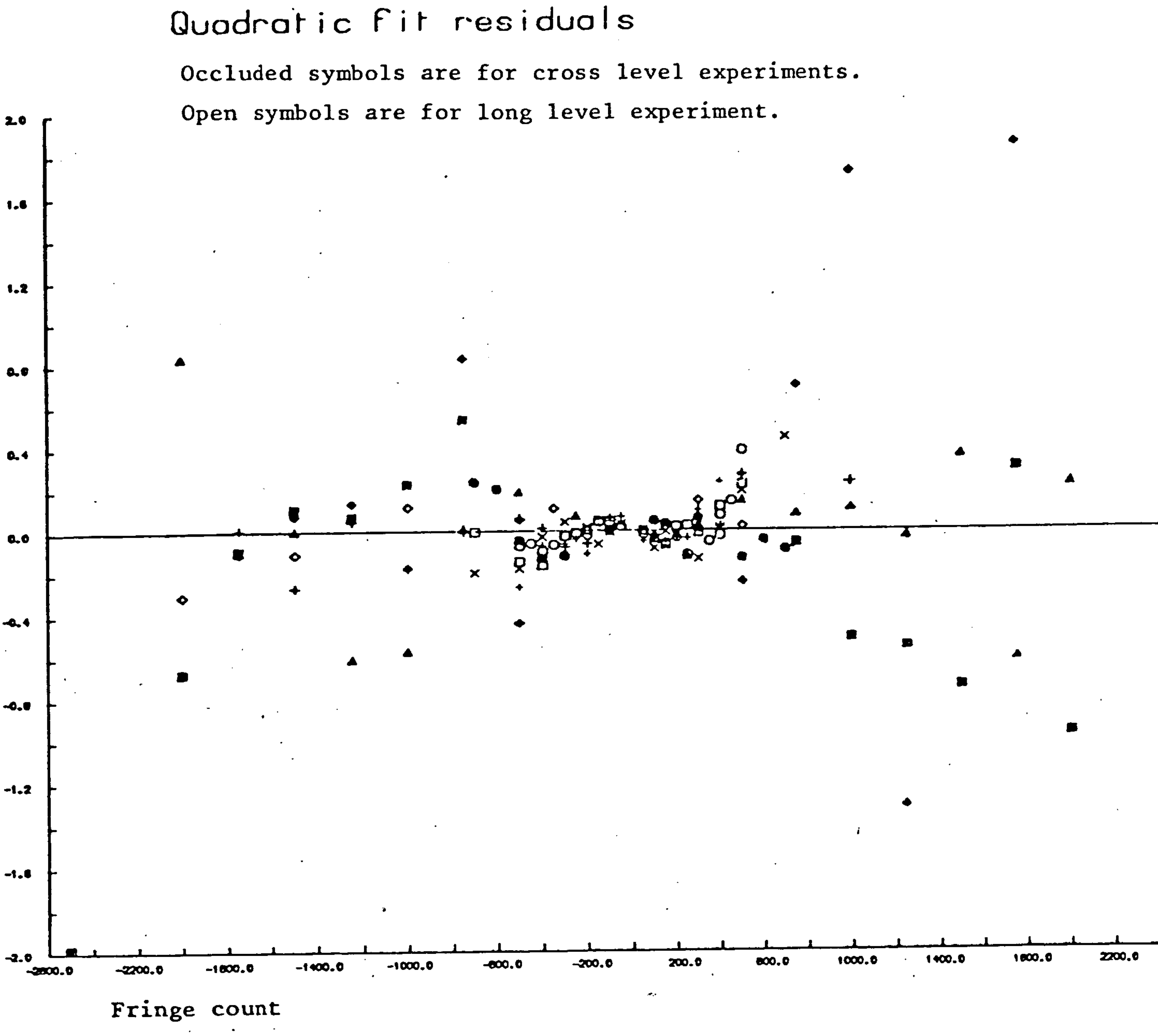
CCORRN is: 1.152106255

generates greater errors because of the irregular torques placed on the pivots and leaf springs of the mechanism. Only the results from tilting parallel to the long level will be considered.

The long level observations have been successful (R equals 0.9992, a standard error of 0.09g.u.) but the standard error on the second degree coefficient is almost one percent. The variable CCORN (program line 113,119) is the ratio of the theoretical second degree coefficient to the observed value. This implies a correction factor of 1.0039 $\pm$ 0.0099 , encompassing both the Hatton Heath and Cat and Fiddle correction factors. It would be necessary to increase the number of observation sequences by at least ten fold to obtain a reasonable standard error on the second degree coefficient.

Figure 6.16 shows the quadratic fit residuals for both the cross and the long level tilting. These demontrate the increase in error as the tilting angle is increased. Figure 6.17 is a plot of the least square solution residual against the noted gravimeter spindle position for the long level only. It is not possible to note any periodicity at the one dial turn interval because of the lack of data.

Figure 6.16


Quadratic fit residuals
Occluded symbols are for cross level experiments.
Open symbols are for long level experiment.
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
-2.0
-2600.0
-2200.0
-1800.0
-1400.0
-1000.0
-600.0
-200.0
200.0
600.0
1000.0
1400.0
1800.0
2200.0
Fringe count

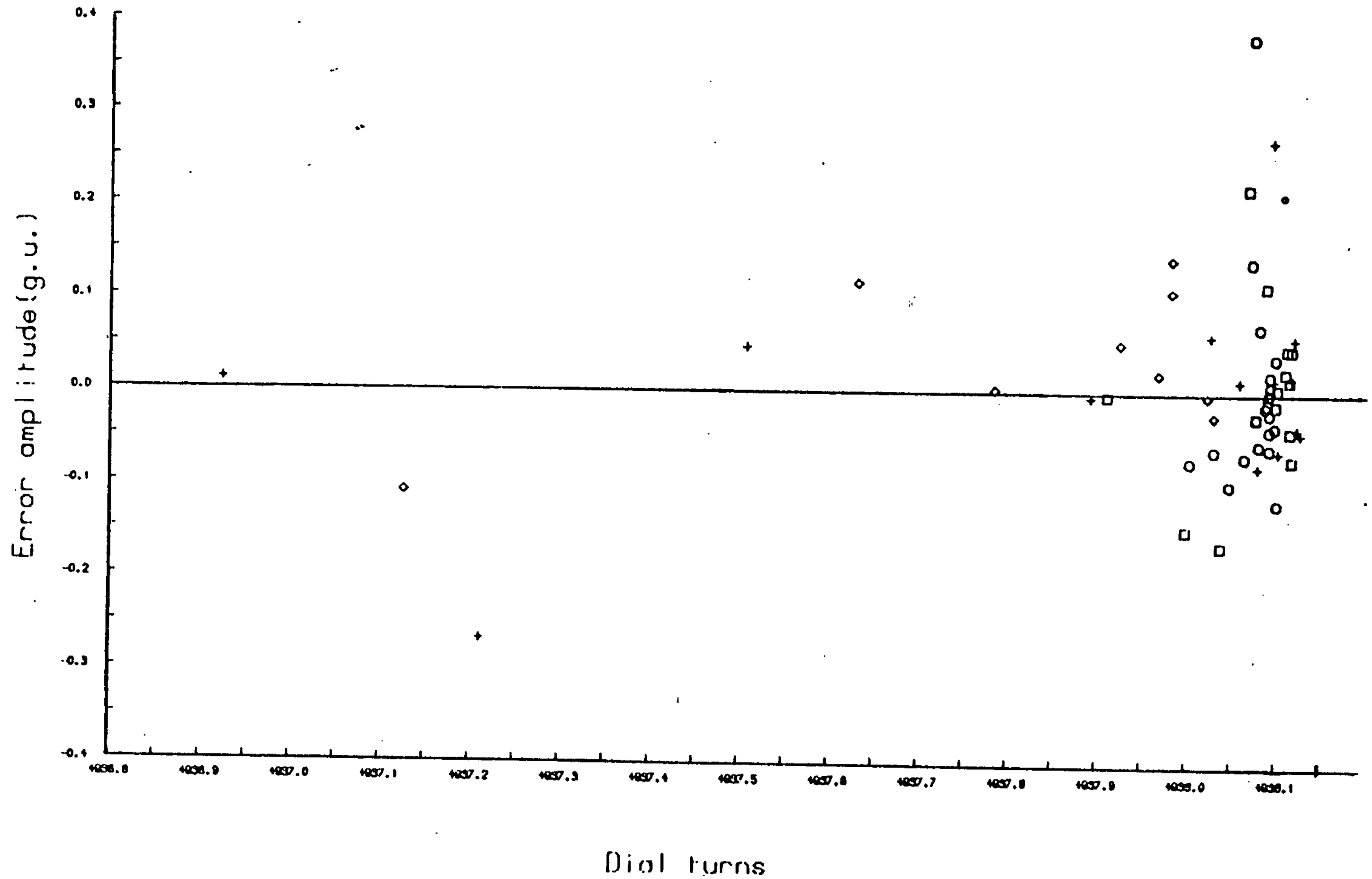



Figure 6.17

Misfit amplitude as a function of observed dial turns

## 6.10 Conclusions

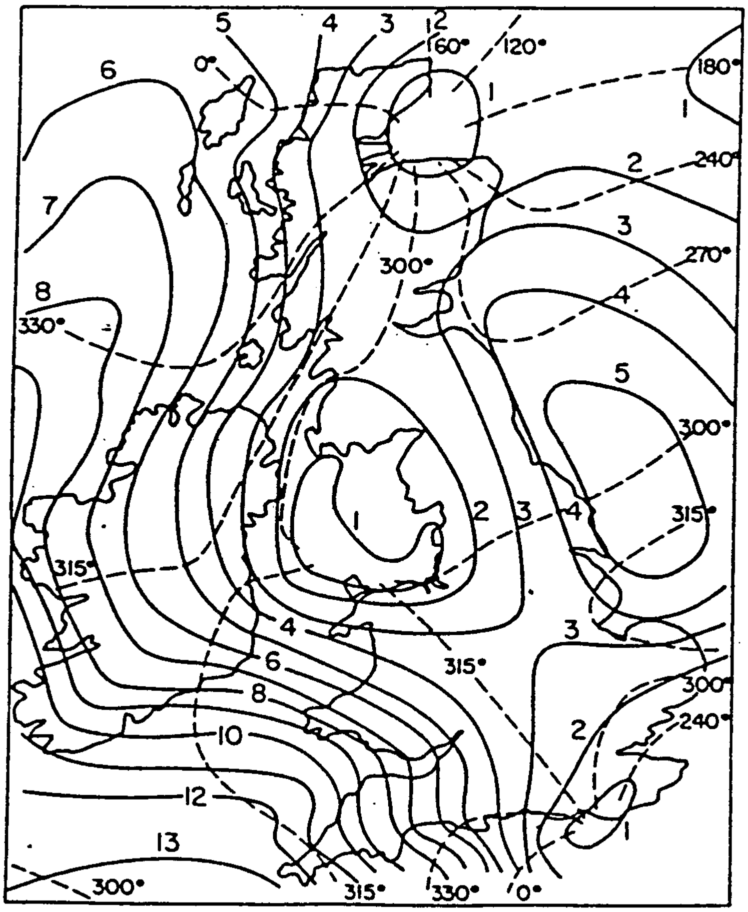
Field calibration tests with G-275 and three other gravimeters indicate that the accepted figure for the gravity difference between Hatton Heath and Press is incorrect. The scale correction factor obtained for G-275 ($4.0 \times 10^{-4}$) on two independent field tests, a long calibration run and the Cat and Fiddle line are in good agreement. Laboratory test were undertaken to verify this and the field values fall within the error limits of the laboratory determined scale factor. The feasiblity of a Newton's rings interferometeric technique has been demonstrated but a large number of observations are required. This method has the advantage of being independent of other meter readings and network adjustments.

# CHAPTER SEVEN

# DETERMINATION OF OCEAN LOADING AT ESKDALEMUIR

## 7.1 Introduction

As discussed in section (4.3), the accurate determination of the Earth Tide is complicated by the ocean loading effect. Baker (1980) presents the most recent and accurate ocean load effect model for the British Isles. Figure 7.1 illustrates the theoretical $M_2$ gravity loading obtained by Baker using the method of Farrell (1972,1973). Baker uses the $M_2$ ocean tide model of Hendershott and Munk (1970) for more distant water bodies together with a detailed model of the local shelf seas (Flather, 1976, numerical model B, plus sub gridding near coastal sites). Locally determined Earth models from seismic refraction surveys were used wherever possible (Blundell and Parks, 1969; Holder and Bott, 1971) but it was found that there is negligible difference between the Green's function of differing Earth models beyond seven kilometres from the load point. Baker discusses in detail the agreement of this model with the results of eight Earth tide stations, established by himself and others at locations in England and Wales. The model agreement with the observations is good (maximum residual 0.6 microgals) but the most northerly station is located at Bidston (latitude 53.3 N) which is rather unsatisfactory for the purpose of a microgravimetric investigation in central




The $M_2$ tidal gravity loading in Britain. The full lines are the contours of the calculated loading amplitude in μgals and the dashed lines are contours of the phase lag of the loading with respect to the tidal potential in the Greenwich meridian.

Figure 7.1 $M_2$ tidal gravity loading in Britain (from Baker 1980)

Scotland. The only reference for Scottish studies in the literature is to an unreliable registration carried out by Tomachek, reading a Frost gravimeter hourly (Tomachek, 1958).

It was found that workers from the University of California had installed a modified La Coste and Romberg meter permanently at Eskdalemuir in Southern Scotland (latitude 55.3 N). A tidal analysis of these data was carried out to ascertain the validity of Baker's model studies at more northerly latitudes. The gravimetric factors so obtained were to be used in the tidal reduction program PBAS (section 4.4) for the reduction of gravity observations in Scotland. .

## 7.2 The I.D.A. Instrument

The gravimeter located at Eskdalemuir is part of a worldwide network of eighteen such instruments known as the International Deployment of Acclerometers (I.D.A.) (Agnew et al., 1976). The primary purpose of the I.D.A. meters is to monitor free oscillations of the Earth which have periods of one hour or less but a second channel suitable for tidal analysis is also recorded. Figure 7.2 is a block diagram of the instrument, which is essentially a modified G-meter with a three plate capacitive position sensor as described in Block and Moore (1966). Position detection is performed within a narrow band; a five kilohertz signal being applied to the outer plates and the

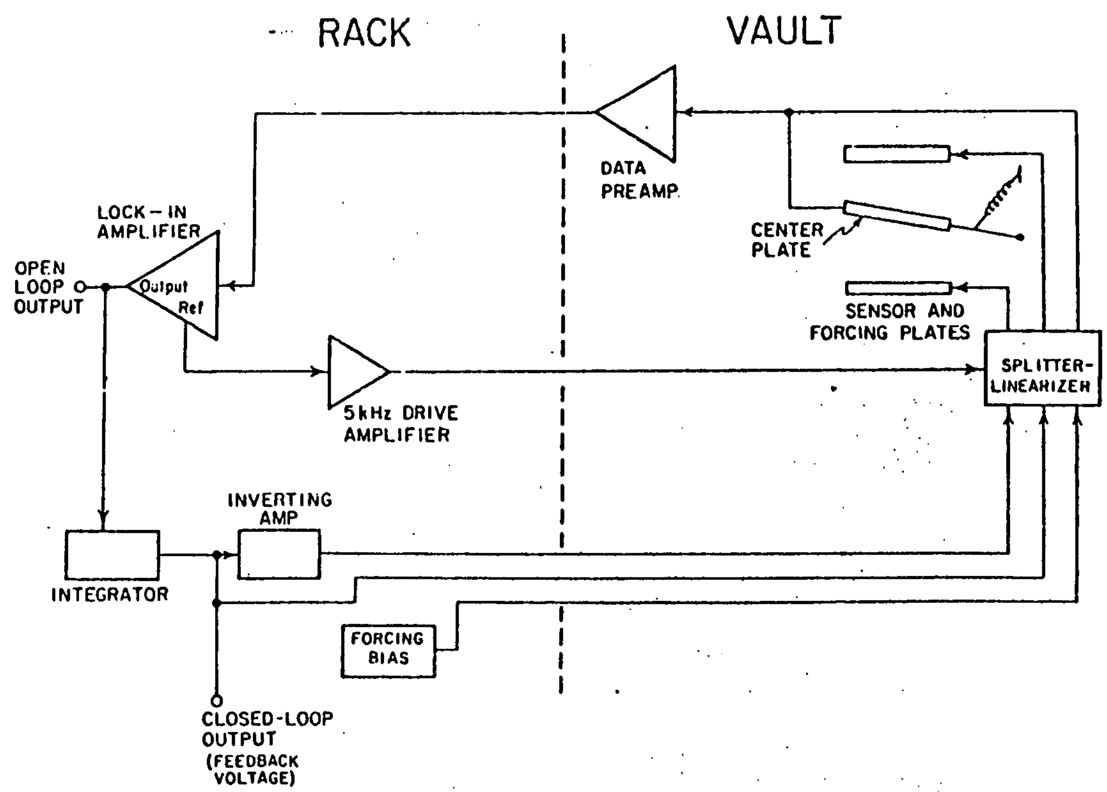



Figure 7.2 Block diagram of I.D.A. meter system

amplified votage induced in the centre plate is input to a lock in amplifier. The lock in amplifier operates with a very narrow band width centred at five kilohertz to minimise the problems of electronic noise and outputs an equivalent bandwidth at d.c.. Negative feedback is used to centre the mass and linearise the output. Since the spring is kept at a constant extension the calibration will be stable. The instrument is hermetically sealed in a thermostatically controlled cannister which sits in a larger vessel ( 0.6 metres high, 0.46 metres diameter) filled with polystyrene beads. In this way the mechanism and preamplifiers are isolated from thermal shocks and the inner chamber is maintained at a fixed temperature $\pm 5.10^{-4}$ C , close to the inversion point of the spring. In the case of Eskdalemuir the meter sits on an isolated concrete pier inside an earth covered bunker. The site, which includes an WWSN station is remote from all sources of manmade and coastal noise.

### 7.3 I.D.A. Instrument Response

Before digitising, the output signal undergoes analogue pre-filtering and is then written to cassette tape. The absolute gain of the instrument is measured by tilting the meter on a triangular plate having a motor driven micrometer screw at one corner. A metal film potentiometer is geared to the micrometer to guage rotation (Moore and Farrell, 1970) . The frequency response is measured using a cross spectral method inputting a random telegraph signal (Berger et. al.,1979). Furthermore each instrument is also run at Pinon Flat observatory for comparison with the superconducting gravimeter (see section 2.2) . The calibration funtion is given as a rational function C(f) with real coefficents, but is a complex valued funtion of frequency.

$$C(f) = A \left\{ \frac{p_0 + p_1 (i\nu) + p_2 (i\nu)^2 + \dots p_n (i\nu)^n}{q_0 + q_1 (i\nu) + q_2 (i\nu)^2 + \dots q_m (i\nu)^m} \right\}$$

The coefficients of C(f) are given in Table 7.1 and the amplitude and phase response are shown in Figure 7.3.

The response at tidal frequencies ($M_2$ = 28.98°/hr) is flat and can be described by two constants. The last column of the tabulated response ordinates (Table 7.2) is the group delay (i.e. the derivative of phase with respect to frequency). It is nearly constant at tidal frequencies and the phase shift can be accurately given as;

$$( -360 * 44.95 )/ T \quad \text{degrees} \qquad T = \text{Period(sec.)}$$

The amplitude response may be stated as 0.5688 ugal per least count (1/1.7571 * 0.9995, the gain of the TIDE filter ).

The error amplitudes are obtained by examining the misfits between the smooth function C(f) and the cross spectral estimates. The response function is not

Eskdalemuir 1

STATION: ESK

CHANNEL: Tide

APPLICABLE 258 / 1978 TO ____ / ____

Time (and place) of calibrations:

ABSOLUTE: 255/1978 (ESK)

INSTRUMENT: 257/1978 (ESK)

FILTER: 117/1978 (LJC)

A= 1.758 ± .009 ($10^8$ counts per $m/s^2$) ($g = 9.81\, m/s^2$)

$f_0$= .01 Hz

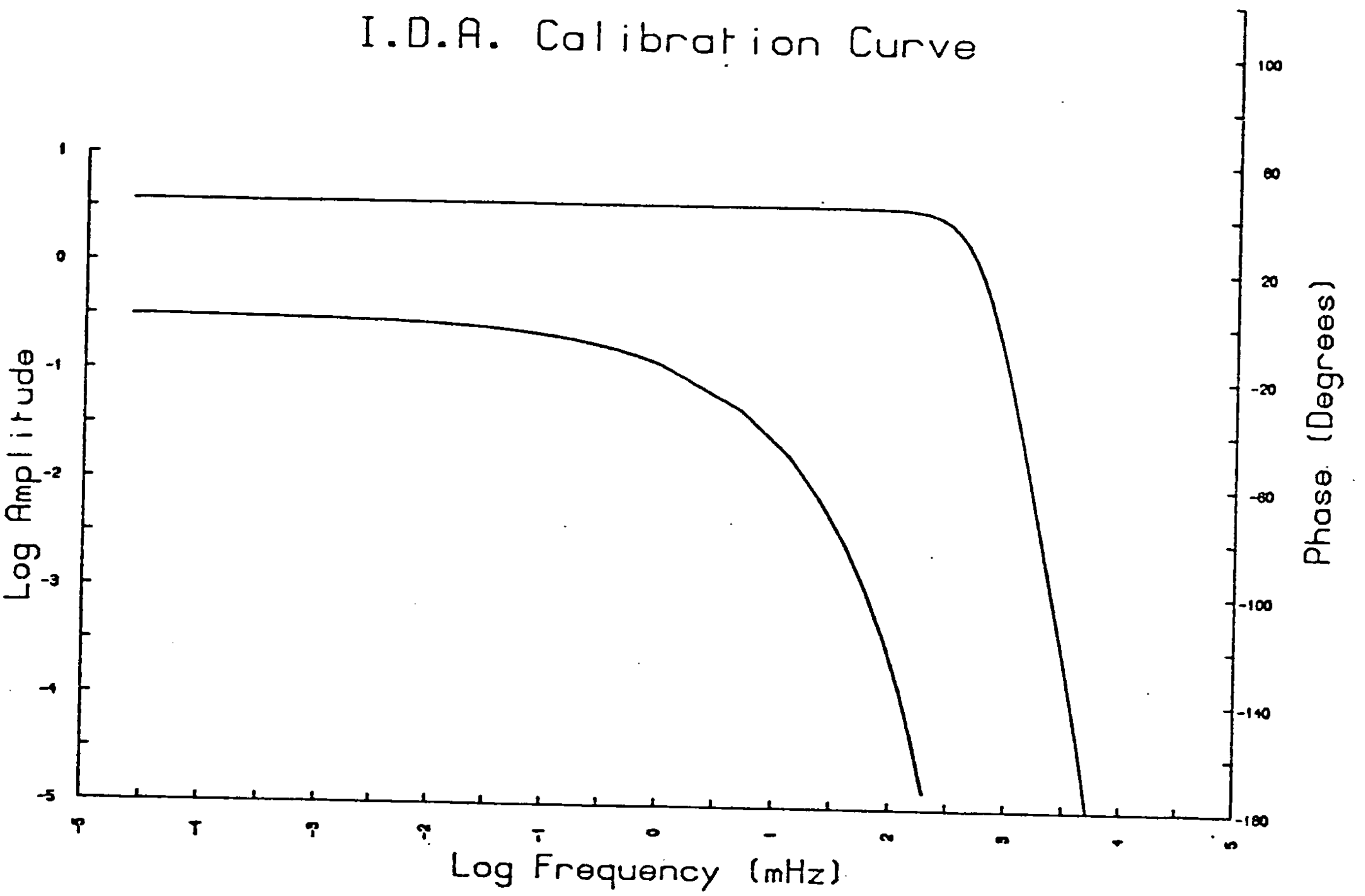
(10[9] counts per g - approx)
(1 count per μgal approx.)

| | | | |
|---|---|---|---|
| n= | 1 | m= | 11 |
| $p_0$ | 1. | $q_0$ | 1.000490 |
| $p_1$ | .2315552 | $q_1$ | 3.05763 |
| $p_2$ | | $q_2$ | 4.649246 |
| $p_3$ | | $q_3$ | 4.536808 |
| $p_4$ | | $q_4$ | 3.062363 |
| $p_5$ | | $q_5$ | 1.472665 |
| $p_6$ | | $q_6$ | .5018679 |
| $p_7$ | | $q_7$ | .117243 |
| | | $q_8$ | .01806866 |
| | | $q_9$ | $1.717076 \cdot 10^{-3}$ |
| | | $q_{10}$ | $8.160125 \cdot 10^{-5}$ |
| | | $q_{11}$ | $1.788909 \cdot 10^{-6}$ |
| | | $q_{12}$ | |
| | | $q_{13}$ | |
| | | $q_{14}$ | |
| | | $q_{15}$ | |

ERROR: 2 % ( ____ % in tidal band)

REMARKS:

Table 7.1 Polynomial coefficients of the calibration factor for Eskdalemuir instrument (from manual).



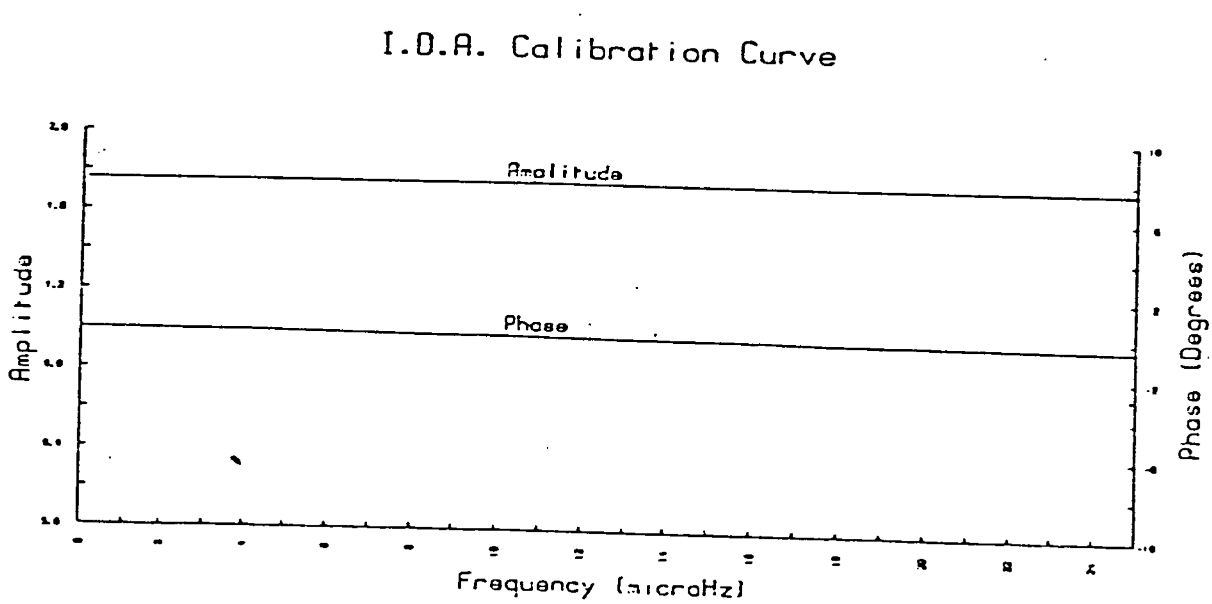




Figure 7.3 Eskdalemuir response curves

determined at tidal frequencies but is obtained by extrapolation. The tilting procedure to obtain the absolute gain is effectively carried out at d.c. and it can be seen from Table 7.2 that the response function is almost completely constant with the d.c. value at tidal frequencies. Although the response function is determined at higher frequencies the manufacturers are confident about the extrapolation to d.c. levels because of the instrument design. Being a feed back instrument the beam does not move at long periods and the rheology of the spring is not a problem. The absolute gain is determined by fitting a tilt parabola to the output voltage and in the case of this instrument the standard error was 0.5 per cent (Duncan Carr Agnew, personal communication). The overall timing error is estimated to be good to 1.2 seconds (c. $0.01^{\circ}$ at $M_2$ frequencies ).

## 7.4 Data Analysis

The data were supplied on 2,400 feet, 800 bytes per inch computer tapes whose files exactly coincide with the on-site cassette tapes. Since the primary function of I.D.A. stations is to examine free oscillations of the Earth with periods typically in the range one to ten millihertz, the digitising interval is twenty seconds (this has since been amended on the tidal mode to 640 seconds). All the unpacking, binary conversion and reformatting was completed in an interactive one-stage process by the

| Frequency(mHz) | Gain(dB) | Amp.(least cnt./(m/s$^2$)) | Phase (deg,-ve for lag) | Delay (sec.) |
|---|---|---|---|---|
| 0.0 | 164.90 | 0.17571E+09 | -0.0000 | -44.955 |
| 0.1 | 164.90 | 0.17571E+09 | -1.6184 | -44.955 |
| 0.2 | 164.90 | 0.17571E+09 | -3.2368 | -44.957 |
| 0.3 | 164.90 | 0.17571E+09 | -4.8553 | -44.961 |
| 0.4 | 164.90 | 0.17571E+09 | -6.4740 | -44.966 |
| 0.5 | 164.90 | 0.17571E+09 | -8.0929 | -44.973 |
| 0.6 | 164.90 | 0.17571E+09 | -9.7121 | -44.981 |
| 0.7 | 164.90 | 0.17571E+09 | -11.332 | -44.991 |
| 0.8 | 164.90 | 0.17571E+09 | -12.952 | -45.003 |
| 0.9 | 164.90 | 0.17572E+09 | -14.572 | -45.015 |
| 1.0 | 164.90 | 0.17572E+09 | -16.193 | -45.030 |
| 2.0 | 164.90 | 0.17574E+09 | -32.440 | -45.262 |
| 3.0 | 164.90 | 0.17577E+09 | -48.803 | -45.671 |
| 4.0 | 164.90 | 0.17578E+09 | -65.348 | -46.283 |
| 5.0 | 164.90 | 0.17573E+09 | -82.155 | -47.134 |
| 6.0 | 164.89 | 0.17552E+09 | -99.316 | -48.253 |
| 7.0 | 164.86 | 0.17494E+09 | -116.93 | -49.661 |
| 8.0 | 164.80 | 0.17372E+09 | -135.11 | -51.348 |
| 9.0 | 164.68 | 0.17142E+09 | -153.93 | -53.262 |
| 10.0 | 164.48 | 0.16752E+09 | -173.47 | -55.283 |

Table 7.2 Frequency response of Eskdalemuir calibration polynomial.

computer program NEWSM9 (listed in Appendix 6). This program is designed to run interactively on the 'Edinburgh Multi Access System ' (EMAS) , but could be very easily adapted to any facility supporting FORTRAN77. A fast machine is preferable to support the interactive procedures which have the advantage that that the user can easily vary parameters to accommodate individual data adjustments. The output file of this program consists of hourly tidal amplitude estimates which were then input to a tidal analysis program, HYCON (Schuller, 1977) . This program was implimented with assistance from Dr. R. Edge of the Earth Tides Branch, Institute of Oceanographic Sciences, Bidston.

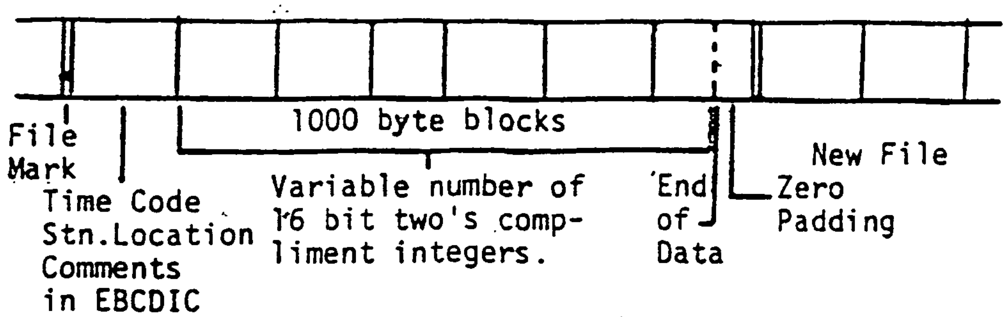
An outline flow diagram of the program NEWSM9 is shown in figure 7.4. The data were generally smooth but a number of sample points contained random spikes, earthquake noise, binary drop outs or saturation and small offsets not uncommon with even the highest quality analogue-to-digital conversion. Those adjacent points with differences greater than twenty five uncalibrated units were examined manually and the necessary remedial action taken. This consisted of:

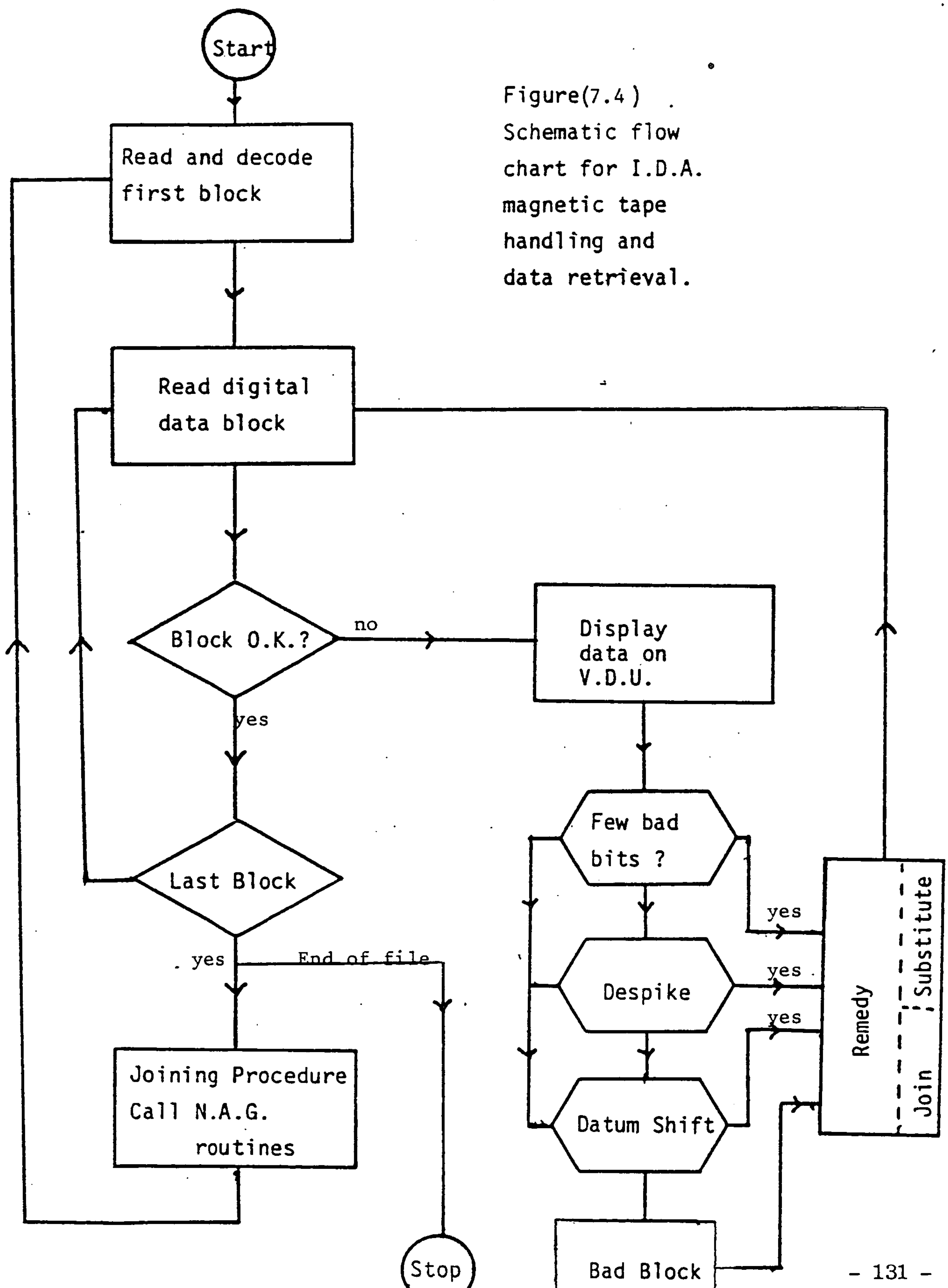
(a) Substitution of a few data, interpolation judged by operator

(b) Quadratic interpolation

(c) Application of a datum shift . An attempt

Magnetic Tape Structure




Figure(7.4)
Schematic flow chart for I.D.A. magnetic tape handling and data retrieval.

to perform this automatically was found to be unsatisfactory and again human judgement was found to give the smoothest curve.

In addition to these error conditions it was necessary to concatenate files with a time gap between them. The data gap, being the time to change a cassette, was typically fifteen minutes (45 samples), and quadratic interpolation using N.A.G. routines E02ADF and E02AEF was used. The first 1000 bytes of each file contains timing information and additional comments as shown on figure 7.5. This enables the user to check the sample cursor position after each concatenation. In this manner a complete 20 second data ensemble was formed from which it was necessary to obtain hourly values suitable for Standard Earth Tide analysis procedures. This was acomplished by outputting the central value of a quadratic fit. An example of the I.D.A. instrument output together with the theoretical Earth tide (determined using the method of Broucke, Zurn and Slichter) is shown in figure 7.6.

## 7.5 Tidal Analysis

After examination of a total of two years data, a continuous section (25-09-78 --> 12-05-79) consisting of a total of 5448 hourly observations was chosen. This particular section was totally free of prolonged data gaps which generally have an unpredictable effect on tidal data.

```
ESK   TIDE      1978 268   8  52    0  1978 278   13   43   40 44076.  ESK 02
 20.   0.0   0.0   1 0 15   1286.00  16 -1293.00
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| -2 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | 0 | -1 | -2 | -1 | -1 | -1 | -1 |
| -1 | -1 | -1 | 4 | 9 | 9 | 10 | 10 | 13 | 15 |
| 7 | 20 | 23 | 22 | 20 | 17 | 19 | 22 | 23 | 22 |
| 4 | 33 | 34 | 34 | 31 | 31 | 34 | 35 | 35 | 32 |
| 7 | 30 | 35 | 34 | 32 | 28 | 27 | 33 | 31 | 32 |
| 4 | 31 | 27 | 26 | 28 | 27 | 25 | 24 | 24 | 24 |
| 5 | 24 | 22 | 23 | 24 | 23 | 22 | 21 | 22 | 22 |
| 0 | 19 | 19 | 18 | 19 | 18 | 16 | 16 | 17 | 15 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| -7 | -8 | -8 | -8 | -7 | -6 | -7 | -8 | -6 | -6 |
| -6 | -6 | -6 | -7 | -6 | -5 | -5 | -7 | -7 | -7 |
| -6 | -6 | -6 | -6 | -5 | -6 | -12 | -10 | -6 | -7 |
| -7 | -8 | -7 | -7 | -7 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 7.5 Decoded I.D.A. magnetic tape. Header (one block of 1000 bytes) followed by data blocks (two's compliment integers), final block padded out with zeroes.

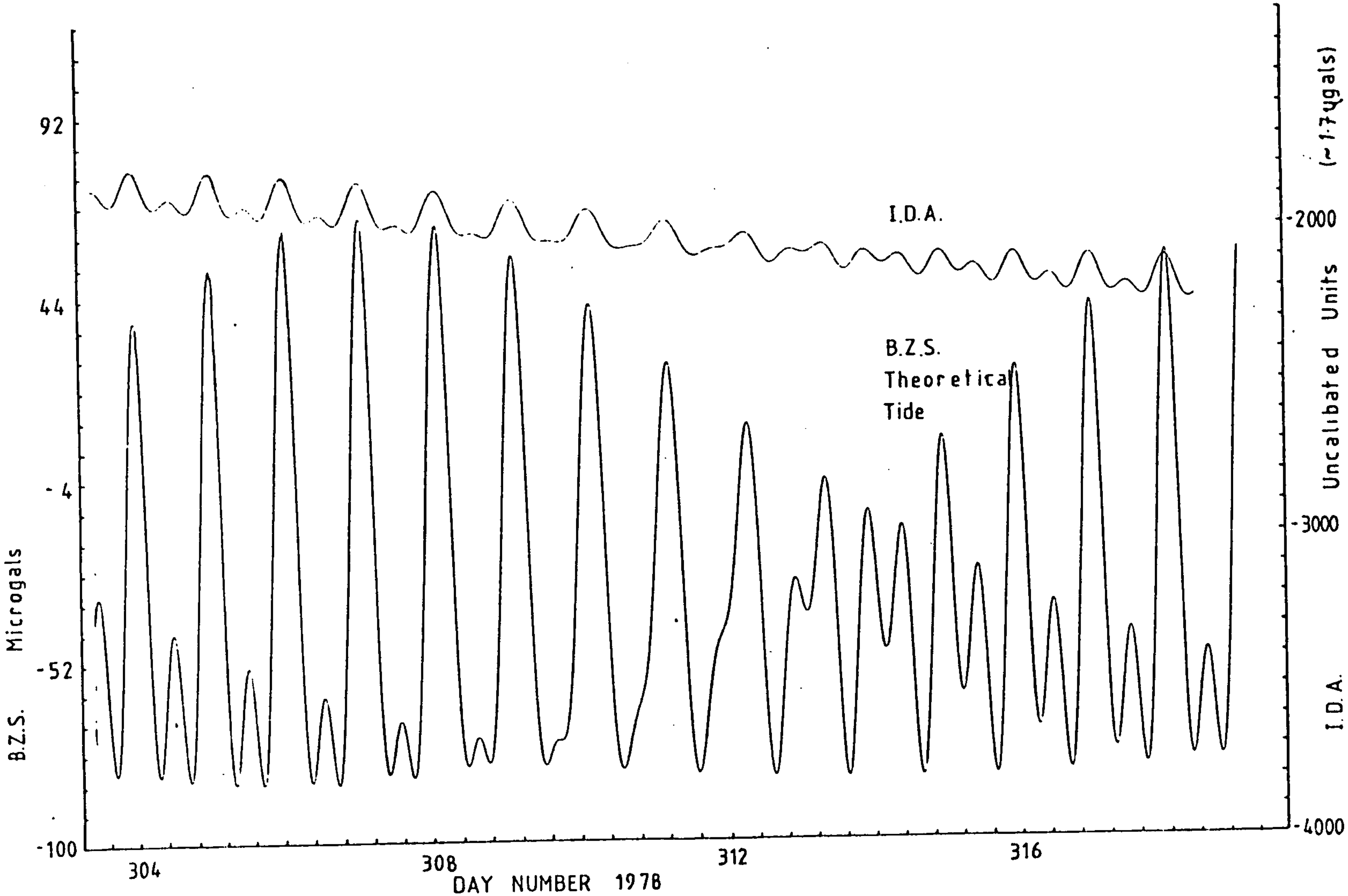



Figure 7.6 IDA data compared with theoretical tide for Eskdalemuir

These data were then taken to I.O.S. Bidston for processing using the S.E.R.C. computing facilities at Daresbury.

The data were first filtered using a Doodson- Lennon Xo tidal filter which is a simple linear combination {10100101102011021120 ....}. This filter removes long period drift, and other transient signals, (eg. exponential trends) which would otherwise produce noise at all frequencies. The Xo filter is symmetric , producing no phase shift and the Fourier amplitude spectrum is reproduced in Figure 7.7 .

The program HYCON was used to perform a standard analysis to calculate the tidal component amplitudes and phases. The analysis is completed for all 505 Cartwright-Talyer-Edden (see section 4.2) constituents in thirteen groups.It is just possible to separate $S_2$ ($30^{o}h^{-1}$) from $K_2$ ($30.082137^{o}h^{-1}$) and [illegible] and $S_1$ ($15.000002^{o}h^{-1}$) from $K_1$ ($15.041069^{o}h^{-1}$), but I have not attempted to do so in my analysis. The results of the analysis for the seperable groups are presented in Table 7.3 together with the results of Baker's stations. A subset of 85 days was randomly selected for fourier analysis and the power density spectrum is displayed in Figure 7.8 The data was first filtered in the time domain using a high pass filter with a 48 hour cut off.

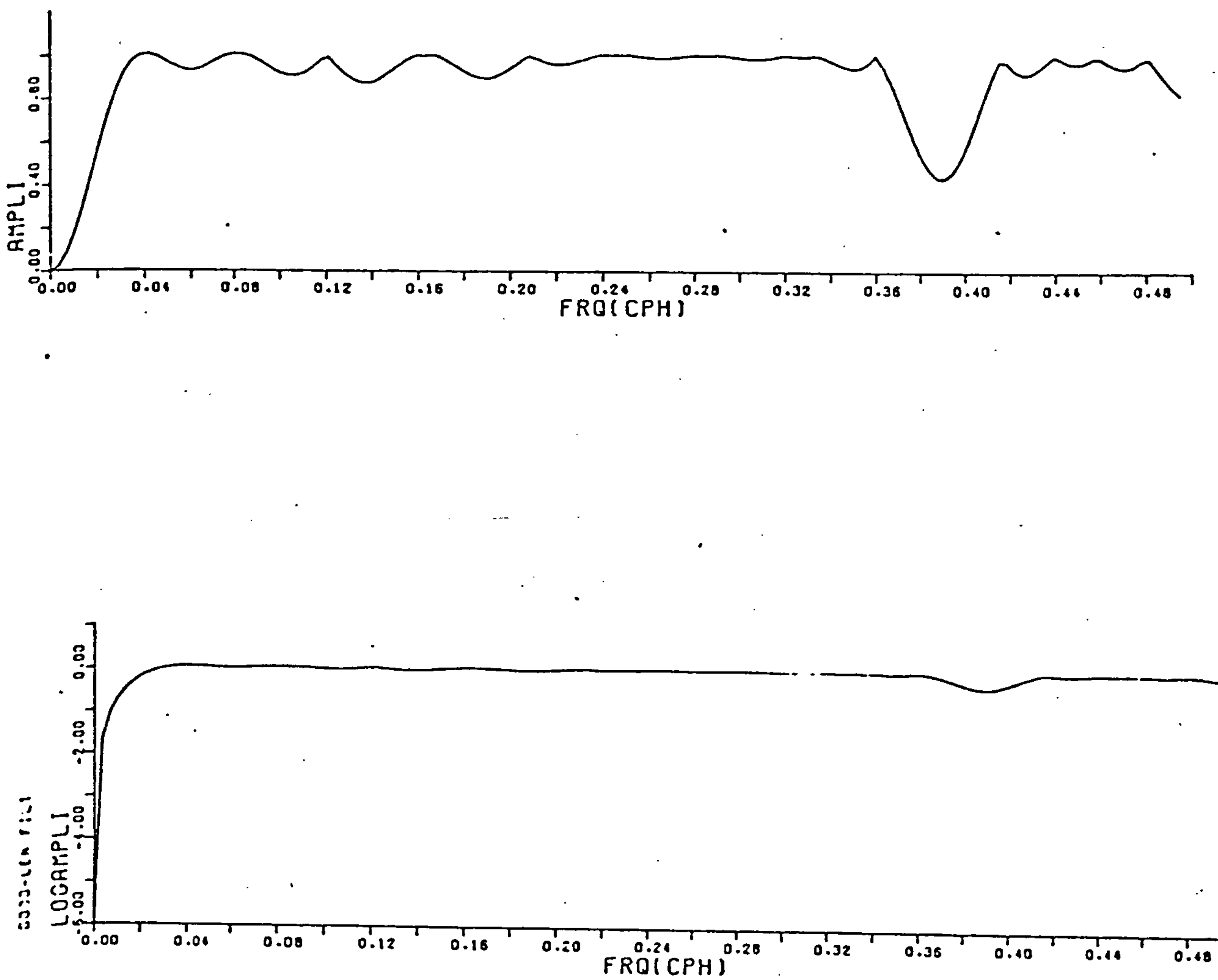



Figure 7.7 Frequency response of Doodson-Lennon filter
Upper - linear scale, lower - logarithmic scale.
(from Yaramanchi, 1979)

## 7.6 The Observed Load

The uncertainity in the amplitude of the theoretical gravity body tide is in the order of ±0.5% (Baker 1980,Alsop and Kuo 1964) and that of the phase lag negligible ( Zschau, 1978 from Baker, 1980). The overall residual standard deviation of the analysis is 1.38μgal as compared with 0.7ugal for Baker's measurements at Bidston. Tables 7.3 and 7.4 compare the parameters obtained from the Eskdalemuir analysis with those of Baker's installations. (Dr. Baker kindly provided the theoretical $M_2$ load for the Eskdalemuir site). It can be seen that the observed load departs considerably from the model $M_2$ load apparently outside the bounds of possible error. The problem of calculating the maximum load within given error limits is non linear. Two graphs (figures 7.9,7.10) illustrate the effect on load amplitude and phase separately with differing observation errors. It appears that to obtain the derived load vector would require an error of one percent in the amplitude and $-1.5^{o}$ of phase. The uncertainity associated with the standard analysis is an order of magnitude less than this (see r.m.s. figures in Table 7.4).

Dr Agnew also supplied me with the results obtained by Farrell and also Melchior (both unpublished) studying data from the same instrument. Their results are shown in Table 7.5 , together with the results of model studies other than Baker. The model studies should be discounted in favour of Baker's as they use a comparatively coarse grid (Schwiderski, 1980 ). The results of Melchior appear to

TABLE 7.3

OBSERVED GRAVIMETRIC FACTORS (δ) AND PHASES (κ IN DEGREES)

| Station and Instrument | $M_2$ δ | $M_2$ κ | $N_2$ δ | $N_2$ κ | $S_2$ δ | $S_2$ κ | $O_1$ δ | $O_1$ κ | $K_1$ δ | $K_1$ κ |
|---|---|---|---|---|---|---|---|---|---|---|
| Eskdalemuir | 1.139 | ( 3.11) | 1.119 | ( 4.36 | 1.171 | ( 0.3) | 1.083 | (−0.5) | 1.098 | (−0.6) |
| | [±0.003 | (±0.15)] | [±0.016 | ( ±0.8)] | [±0.006 | (±0.3)] | [±0.003 | (±0.1)] | [±0.002 | (±0.1)] |
| Redruth (15) | 1.414 | (13.95) | 1.282 | ( 17.3) | 1.442 | ( 3.2) | 1.127 | (−0.44) | 1.142 | ( 0.96) |
| | [±0.001 | (±0.05)] | [±0.005 | ( ±0.2)] | [±0.003 | (±0.1)] | [±0.001 | (±0.07)] | [±0.001 | (±0.04)] |
| Taunton (15) | 1.312 | ( 6.13) | 1.264 | ( 7.5 | 1.304 | (−0.05) | 1.304 | (−0.23) | 1.138 | ( 0.24) |
| | [±0.002 | (±0.07)] | [±0.009 | ( ±0.4)] | [±0.003 | (±0.1)] | [±0.002 | (±0.09)] | [±0.002 | (±0.08)] |
| Newtown (15) | 1.246 | ( 4.72) | 1.182 | ( 6.2) | 1.252 | ( 0.6) | 1.138 | ( 0.5) | 1.148 | ( 0.7) |
| | [±0.002 | (±0.08)] | [±0.008 | ( ±0.4)] | [±0.003 | (±0.2)] | [±0.005 | (±0.3)] | [±0.004 | (±0.2)] |
| Llanrwst (13) | 1.207 | ( 1.99) | 1.170 | ( 3.6) | 1.218 | (−0.7) | 1.143 | ( 0.2) | 1.157 | ( 0.2) |
| | [±0.002 | (±0.08)] | [±0.008 | ( ±0.4)] | [±0.003 | (±0.2)] | [±0.004 | (±0.2)] | [±0.003 | (±0.1)] |
| Cambridge (721) | 1.196 | ( 3.99) | 1.136 | ( 2.7) | 1.119 | (−0.5) | 1.119 | (−0.8) | 1.118 | (−4.5) |
| | [±0.004 | (±0.2)] | [±0.02 | ( ±1.0)] | [±0.007 | (±0.4)] | [±0.009 | (±0.4)] | [±0.006 | (±0.3)] |
| London (15) | 1.186 | ( 3.08) | 1.159 | ( 3.3) | 1.196 | ( 0.9) | 1.140 | (−0.2) | 1.136 | ( 0.41) |
| | [±0.002 | (±0.08)] | [±0.008 | ( ±0.4)] | [±0.005 | (±0.2)] | [±0.002 | (±0.1)] | [±0.001 | (±0.06)] |
| Herstmon. (721) | 1.132 | ( 0.66) | 1.142 | ( 0.4) | 1.156 | ( 1.8) | 1.152 | (−0.4) | 1.146 | ( 0.09) |
| | [±0.0008 | (±0.04)] | [±0.004 | ( ±0.2)] | [±0.002 | (±0.08)] | [±0.002 | (±0.1)] | [±0.002 | (±0.08)] |
| Bidston (13) | 1.153 | ( 0.68) | 1.152 | ( 0.0) | 1.173 | ( 0.5) | 1.138 | ( 0.22) | 1.149 | ( 0.18) |
| | [±0.0008 | (±0.04)] | [±0.004 | ( ±0.2)] | [±0.002 | (±0.08)] | [±0.001 | (±0.08)] | [±0.001 | (±0.05)] |
| Bidston (15) | 1.147 | ( 0.77) | 1.140 | ( 0.7) | 1.165 | ( 0.86) | 1.132 | ( 0.13) | 1.144 | ( 0.50) |
| | [±0.0009 | (±0.04)] | [±0.005 | ( ±0.2)] | [±0.002 | (±0.09)] | [±0.001 | (±0.06)] | [±0.0008 | (±0.04)] |
| Bidston (721) | 1.148 | ( 0.68) | 1.156 | ( 0.1) | 1.174 | ( 0.6) | 1.138 | (−0.4) | 1.149 | (−0.17) |
| | [±0.001 | (±0.05)] | [±0.006 | ( ±0.3)] | [±0.002 | (±0.1)] | [±0.002 | (±0.1)] | [±0.002 | (±0.07)] |

Errors for Eskdalemuir are r.m.s. values; other stations are taken from Baker (1980) and errors are standard errors

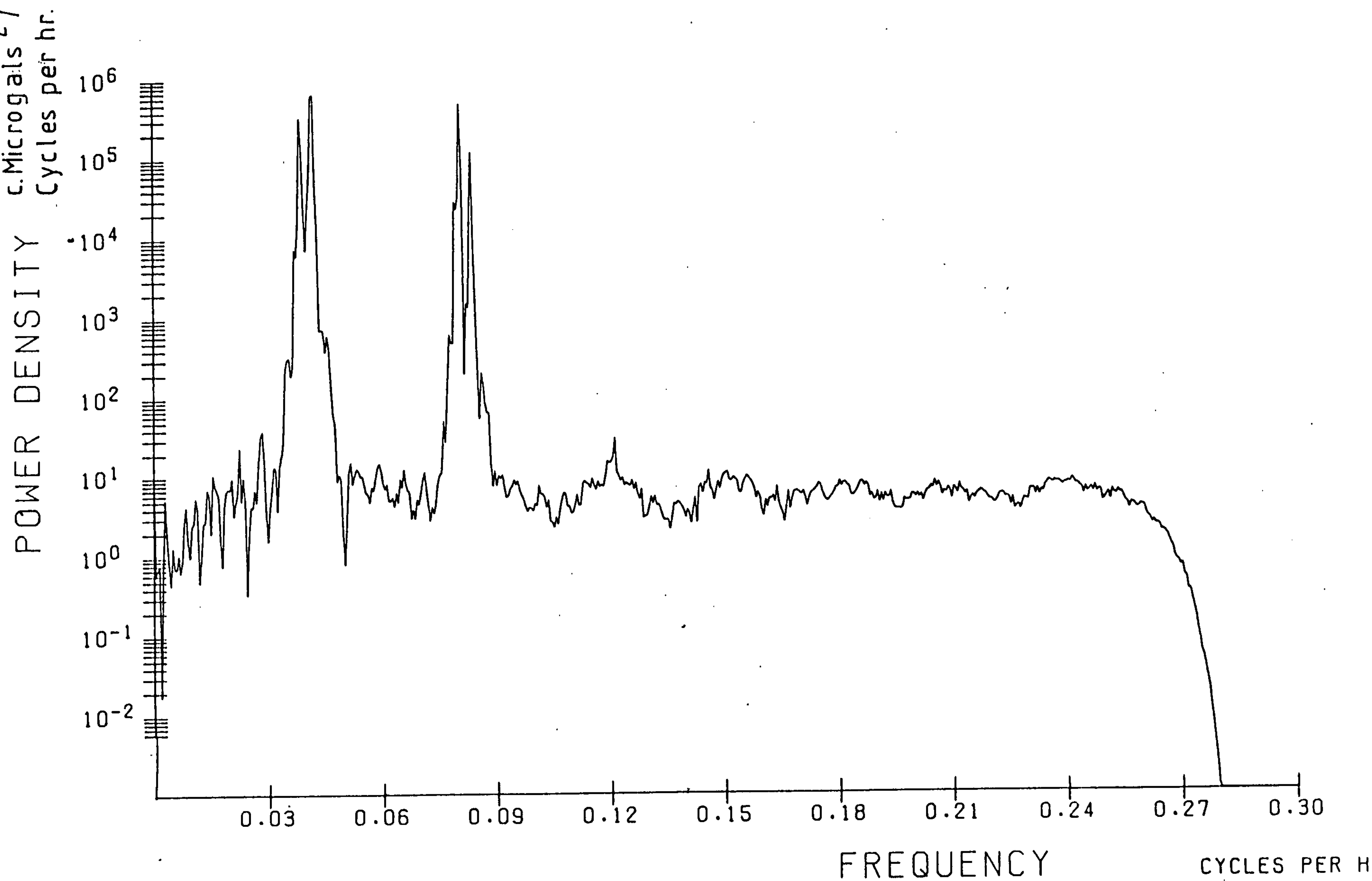



Figure 7.8 Power density spectrum of 85 days data at Eskdalemuir.

The uncertainity in the amplitude of the theoretical gravity body tide is in the order of +0.5% (Baker 1980,Alsop and Kuo 1964) and that of the phase lag negligible ( Zschau, 1978 from Baker, 1980). The overall residual standard deviation of the analysis is 1.38ugal as compared with 0.7ugal for Baker's measurements at Bidston. Tables 7.3 and 7.4 compare the parameters obtained from the Eskdalemuir analysis with those of Baker's installations. (Dr. Baker kindly provided the theoretical $M_2$ load for the Eskdalemuir site). It can be seen that the observed load departs considerably from the model $M_2$ load apparently outside the bounds of possible error. The problem of calculating the maximum load within given error limits is non linear. Two graphs (figures 7.9,7.10) illustrate the effect on load amplitude and phase separately with differing observation errors. It appears that to obtain the derived load vector would require an error of one percent in the amplitude and $-1.5^{o}$ of phase. The uncertainity associated with the standard analysis is an order of magnitude less than this (see r.m.s. figures in Table 7.4).

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TABLE 7.4

$M_2$ OBSERVATIONS AND THEORETICAL CALCULATIONS (AMPLITUDES IN μGALS AND GREENWICH PHASE LAGS IN DEGREES)

| Station | Observed (O) Amp. Phase | Theoretical Body (B) Amp. Phase | Observed Load (L') Amp. Phase | Theoretical Load (L) Amp. Phase | Observed - total theoretical (R = L' - L) Amp. Phase |
|---|---|---|---|---|---|
| Eskdalemuir | 27.63 ( 3.30) | 28.24 ( 6.41) | 1.63 (253.07) | 2.26 (288.7) | 1.74 (325) |
| Redruth | 43.49 (-3.48) | 35.67 (10.47) | 12.35 (312.4) | 12.31 (312.0) | 0.10 ( 17) |
| Taunton | 39.01 ( 0.00) | 34.50 ( 6.13) | 5.98 (321.9) | 6.28 (322.2) | 0.30 (147) |
| Newtown | 34.68 ( 1.91) | 32.29 ( 6.63) | 3.64 (315.1) | 3.81 (316.3) | 0.19 (161) |
| Llanrwst | 32.68 ( 5.64) | 31.40 ( 7.63) | 1.70 (325.6) | 1.92 (317.0) | 0.35 ( 91) |
| Cambridge | 33.77 (-4.22) | 32.75 (-0.23) | 2.53 (291.5) | 2.44 (305.2) | 0.60 (217) |
| London | 34.53 (-2.81) | 33.78 ( 0.27) | 1.98 (290.8) | 1.88 (302.2) | 0.40 (221) |
| Herstmonceux | 33.88 (-1.33) | 34.72 (-0.67) | 0.93 (204.3) | 0.82 (170.6) | 0.52 (266) |
| Bidston (13) | 30.80 ( 5.46) | 30.99 ( 6.14) | 0.42 (248.4) | 0.64 (253.6) | 0.23 ( 83) |
| Bidston (15) | 30.65 ( 5.37) | 30.99 ( 6.14) | 0.54 (236.3) | 0.64 (253.6) | 0.20 (126) |
| Bidston (721) | 30.67 ( 5.46) | 30.99 ( 6.14) | 0.49 (234.8) | 0.64 (253.6) | 0.24 (115) |

| RESULTS FOR ESKDALEMUIR | M2 THEORY GREENWICH | M2 THEORY LOCAL | M2 OBSERVED GREENWICH | M2 OBSERVED LOCAL | M2 LOAD GREENWICH | M2 LOAD LOCAL | O1 THEORY GREENWICH | O1 THEORY LOCAL | O1 OBSERVED GREENWICH | O1 OBSERVED LOCAL | O1 LOAD GREENWICH | O1 LOAD LOCAL | Installed 10-09-79 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lyness | | 28.235 | | 27.6212 | | 1.62 | | 33.745 | | 31.478 | | 2.29 | 230 days |
| | | 0.00° | | -3.11° | | 113.77 | | 0.00° | | -0.50 | | 186.96° | 25-09-78<br>12-05-79 |
| Farrell | | | | | | 2.16 | | | | | | 1.8 | 118 days |
| | | | | | | 120° | | | | | | 178° | 23-12-78<br>10-05-79 |
| Melchior | | | | 27.5 | | 3.71 | | | | 31.45 | | 7.48 | Same Data Set as Farrell |
| | | | | - 7.49° | | -104.5° | | | | -12.56° | | -114° | Melchior notes a timing problem |
| Baker (Model) | | 28.235 | | | 2.26 | 2.26 | | | | | | | Fine mesh ocean |
| | | 0.0° | | | 288.7* | 77.7° | | | | | | | model with refinements |
| Ducarme and Melchior (Model) | | | | | | 4.1 | | | | | | 0.41 | Schwiderski |
| | | | | | | 62° | | | | | | 151° | Ocean Model |
| Agnew (Model) | | | | | | 3.8 | | | | | | 0.39 | " |
| | | | | | | 57° | | | | | | 154° | |

* Phase lags positive

Table (7.5) Comparison of results obtained by different workers analysing Eskdalemuir I.D.A. Data (Duncan C. Agnew, personal comm.) Upper figure is vector magnitude, lower is phase in degrees.

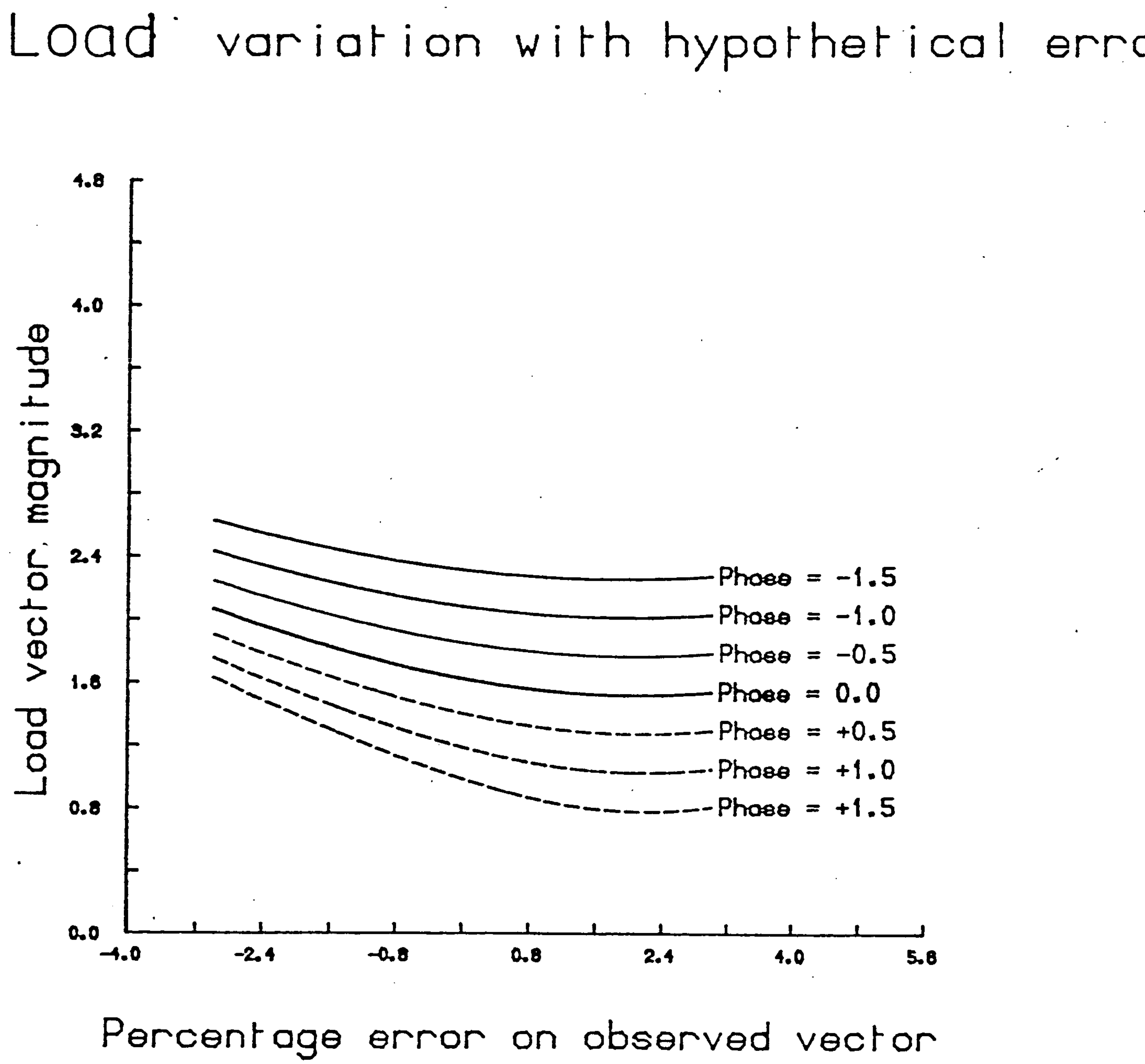



Figure 7.9 Possible load vector amplitude error.
Observed vector error ranges $\pm$ 3% magnitude, $\pm$ 1.5$^{o}$ phase.

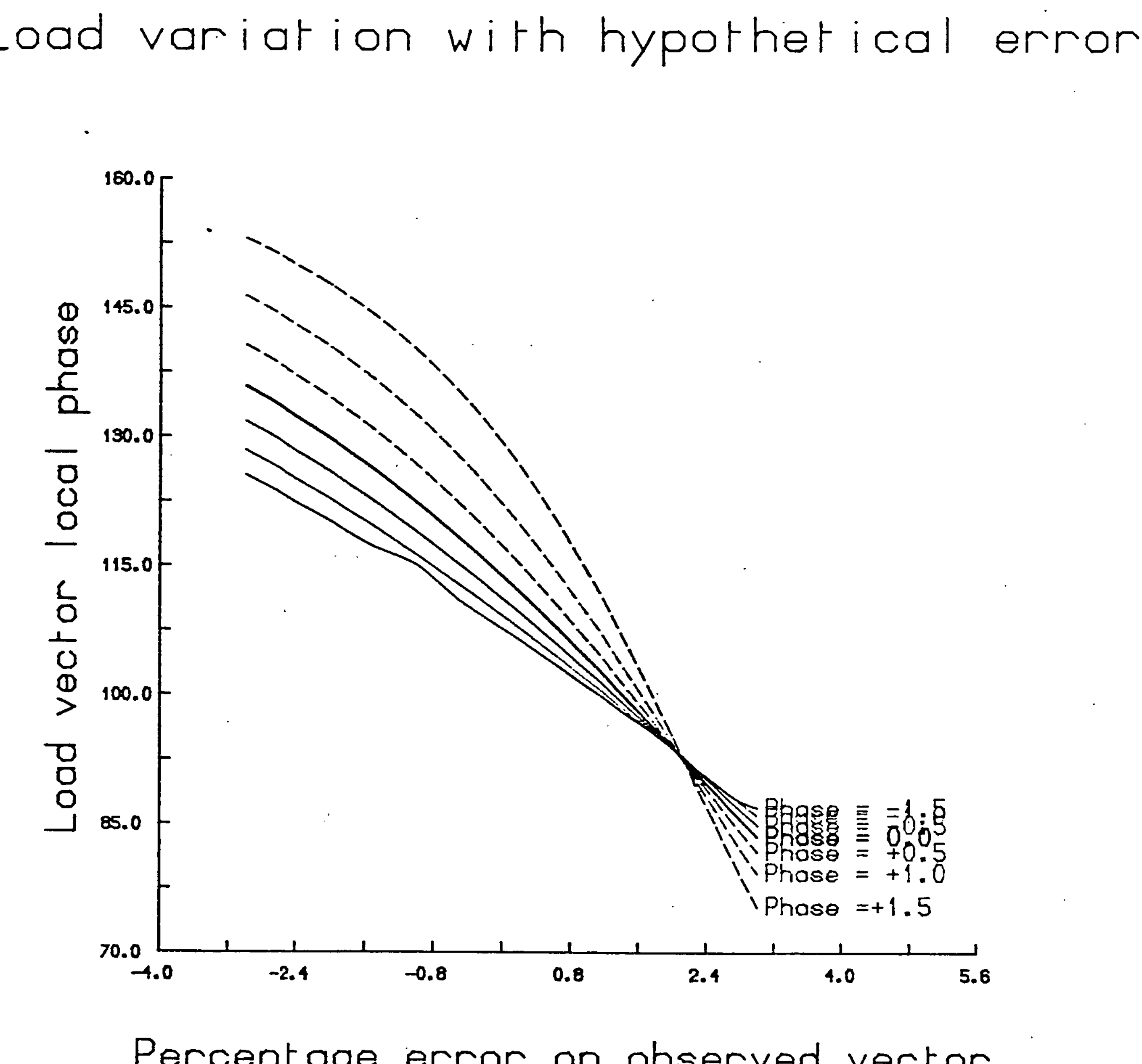



Figure 7.10 Possible error on local phase estimate of the load vector. Observed vector error ranges $\pm$ 3% magnitude, $\pm$ 1.5$^{o}$ phase.

be in error and Agnew notes that there is the possiblity of a timing error. Agreement with Farrell is moderate but there is a significant discrepancy when compared to the $M_2$ model of Baker which has been shown to be consistent elsewhere. Furthermore the $O_1$ gravimmetric factor of $1.083 \pm 0.003$ is significantly lower than all other $O_1$ values shown on Table 7.4 or any published values for western Europe (eg. Melchior, p.376).

One is forced to conclude that the Eskdalemuir instrument is currently operating with an error unacceptably high for the purposes of Earth tide registration. The probable error magnitudes involved are not sufficient to concern most users of this instrumentation; seismologists studying free oscillations of the Earth. Errors could be due to, off levelness, a build up of charge on the position sensor plates or thermal drift in the electronics. The large variation in derived tidal parameters obtained by different workers may be due to different analysis techniques ( the figures of Melchior are particularly perplexing, though he does note a timing problem) or an unstable instrument response rather than a simple systematic error.

The results of this analysis indicate that the I.D.A. determined gravimetric factor and phase lag are not suitable for use in tidal prediction programs. The analysis of the Scottish secular variation sites was carried out using gravimmetric factors and phases derived from Baker (1980).

# CHAPTER EIGHT

# SECULAR GRAVITY STUDIES IN SCOTLAND

## 8.1 Introduction

Laboratory tests indicate that it may possible to succesfully evaluate gravity diferences in the order of a few microgals. Field measurements do not generally attain this degree of precision but Hipkin (1978) describes a field measurement (using G-275) with a standard error of 0.018 gravity units. This link between Ordnance Survey fundamental bench marks at Edinburgh and Linlithgow was the pilot study for the establishment of a larger network of secular gravity sites in Scotland. This link was expanded to the stations shown in figure 8.1 which were all measured by the author in 1980 and 1981. In addition to these measurements more limited observations took place in 1977 and 1978. The observations were made under a strictly controlled regime of symmetry from year to year to eliminate random factors. The measuring technique is identical to that described in section 5.3; it makes use of well determined instrument response of G-275 and requires a large number of readings (c. 20) over a period of 80 minutes at a single site.

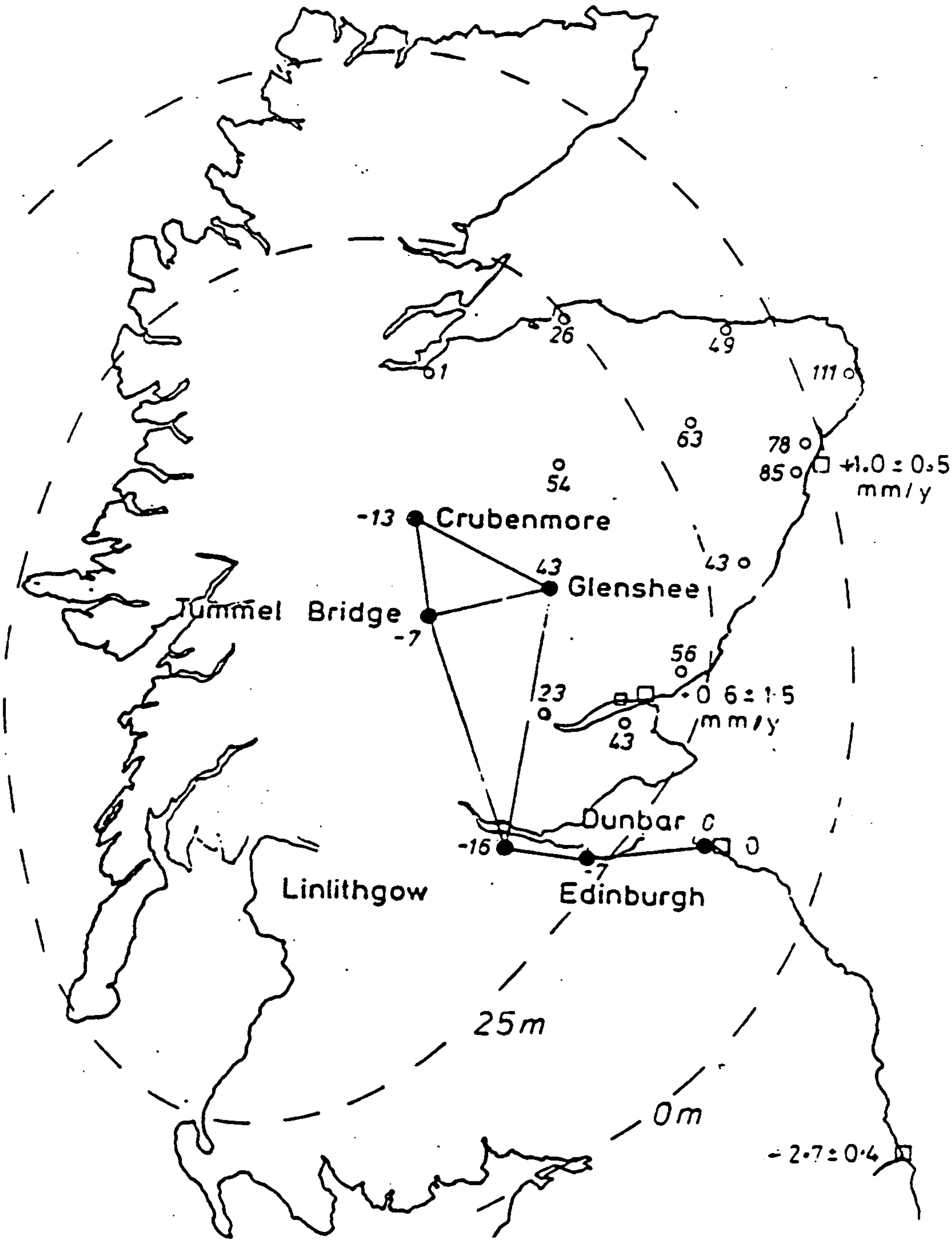



Figure 8.1 Scottish secular variation network

- ● Station locations
- o Fundamental bech marks with uplift (mm.) between second and third geodetic levellings realitive to Dunbar.
  Uplift since the last ice age derived from geomorphological studies. (Sissons, 1967).
- ◻ Tidal guages (relative uplift rates from Rossiter, 1972)

## 8.2 Scotland as a Test Bed

All the stations are located on fundamental bench marks. These form part of the Ordnance Survey geodetic levelling network and provide uniquely stable and permanent monumentation of a very high quality (Figure 8.2) together with well determined positions. The primary constraint was that the stations should form a network with gravity differences lying almost within a single dial turn. Additionally stations are a reasonable driving distance from one another (maximum two and a half hours). All the stations are situated on low permeablity metamorphic or igneous rocks to minimise the affects of ground water variations.

Secular gravity studies in Scandanavia suggest a cumultative gravity difference of 0.35 g.u. in five years (Kivinemi, 1974; Petterson, 1974). Mareographic evidence from the Gulf of Bothnia indicates contemporary rates of uplift as high as 10mm. per annum. This is at the centre of a rebounding depression resulting from the removal of the load of the last ice sheet. Geomorphological data ( Sissons ,1976) presents a similar picture for the Holocene in Scotland as shown by the dashed contours in figure 8.1 Other studies; mareographic, archaelogical and geodetic agree qualitatively that Northern Britain is rising relative to Southern Britain.

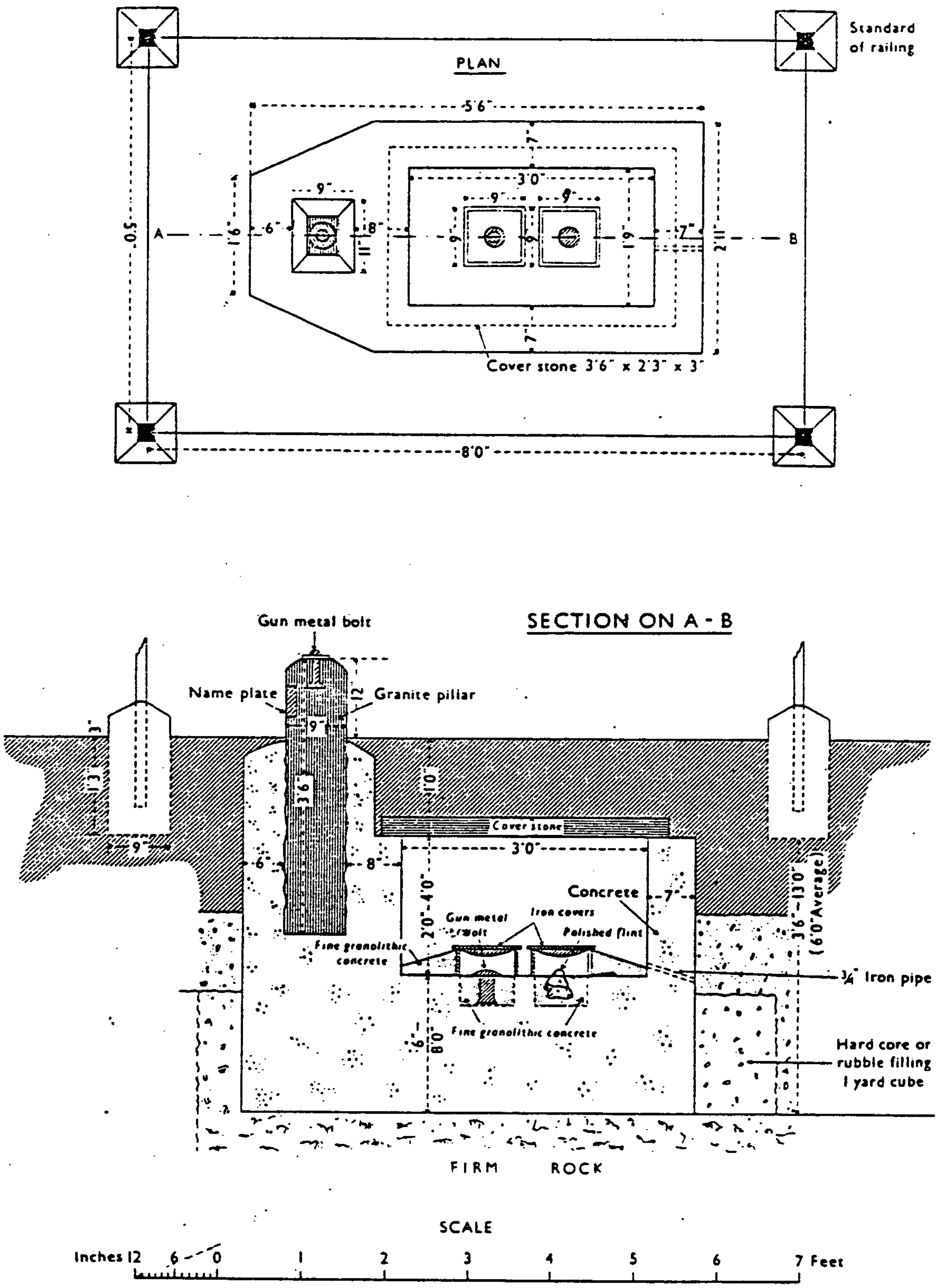



Figure 8.2Fundamental Bench Mark

Rossiter (1972) has examined all the available tide guage records for Great Britain up to 1970. The observations are of extremely variable quality and continuity, the longest record dates back to 1830 (Sheerness) but even this has considerable gaps. Aberdeen and Dunbar are amongst the most consistent stations and Rossiter suggests an uplift in eastern Scotland of the order 0.5mm. per annum. This is compared to an observed subsisdence of the order 1mm. per annum in southern England and along the French and Dutch coasts.

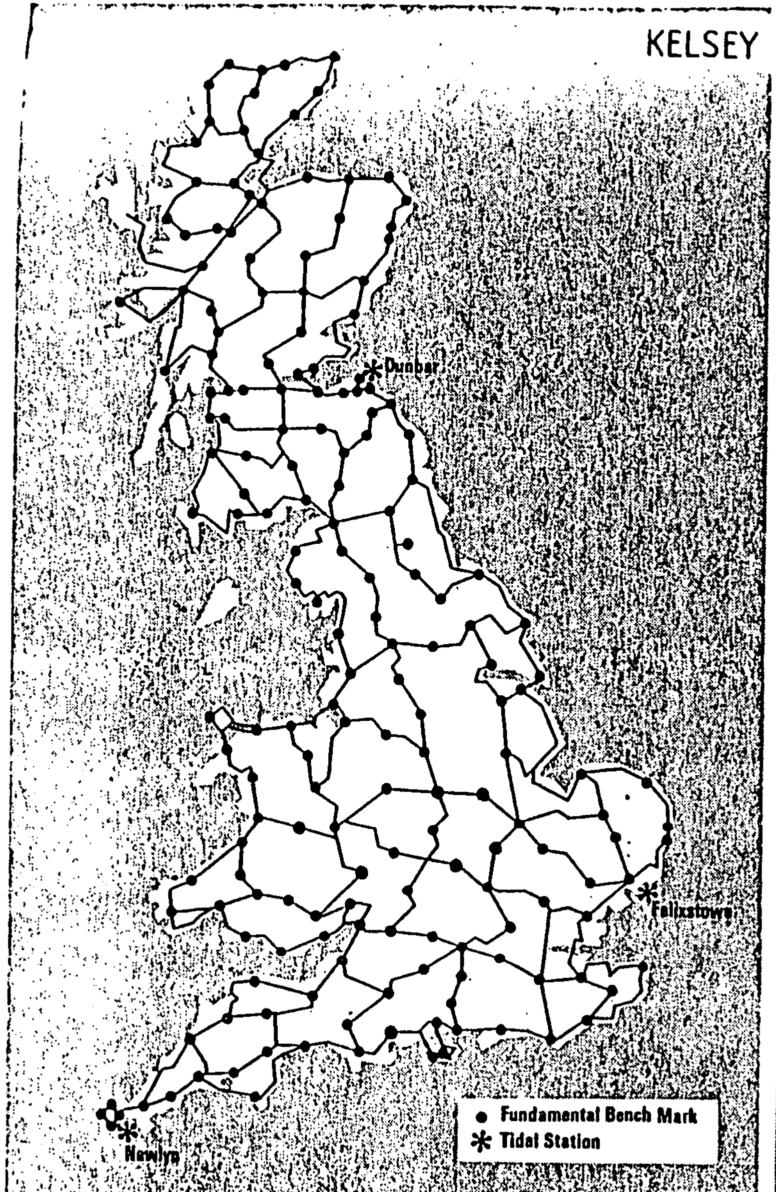
Three geodetic levellings of Great Britain have taken place. The first geodetic levelling of Great Britain was carried out during 1840 - 1860 (Jolly and Wolff, 1922). The datum for this survey , mean sea level at Liverpool derived from a ten day tide guage record is unfortunately inadequate for comparison with subsequent levellings. The second geodetic levelling took place between 1912 and 1921 in England and Wales (including Dunbar) but was not extended to the remainder of Scotland until the period 1936 - 1952. The Ordnance Survey established tidal observatories; Dunbar in 1913, Newlyn in 1915 and Felixstowe in 1917 to control the survey. (Rossiter comments that these Ordnance Survey maintained guages yeild the highest quality data in Europe .) The third geodetic levelling of England , Wales and Scotland was carried out between the years 1951 and 1959 using Newlyn mean sea level as a datum as did the second levelling. Figure 8.3 is taken from Kelsey (1972) and presents the difference between third and second levellings. The probable error of each levelling is given as 1.8mm. km.for the second and 1.2mm./$\sqrt{km}$. for the third geodetic levellings. The observed uplift in Scotland exceeds the probable error and the values for the bench marks common to the gravity network are listed below.

| | |
|---|---|
| Dunbar E. | 149 mm. |
| Edinburgh | 142 mm. |
| Linlithgow | 133 mm. |
| Crubenmore | 192 mm. |
| Tummel B. | 142 mm. |
| Glenshee | 203 mm. |

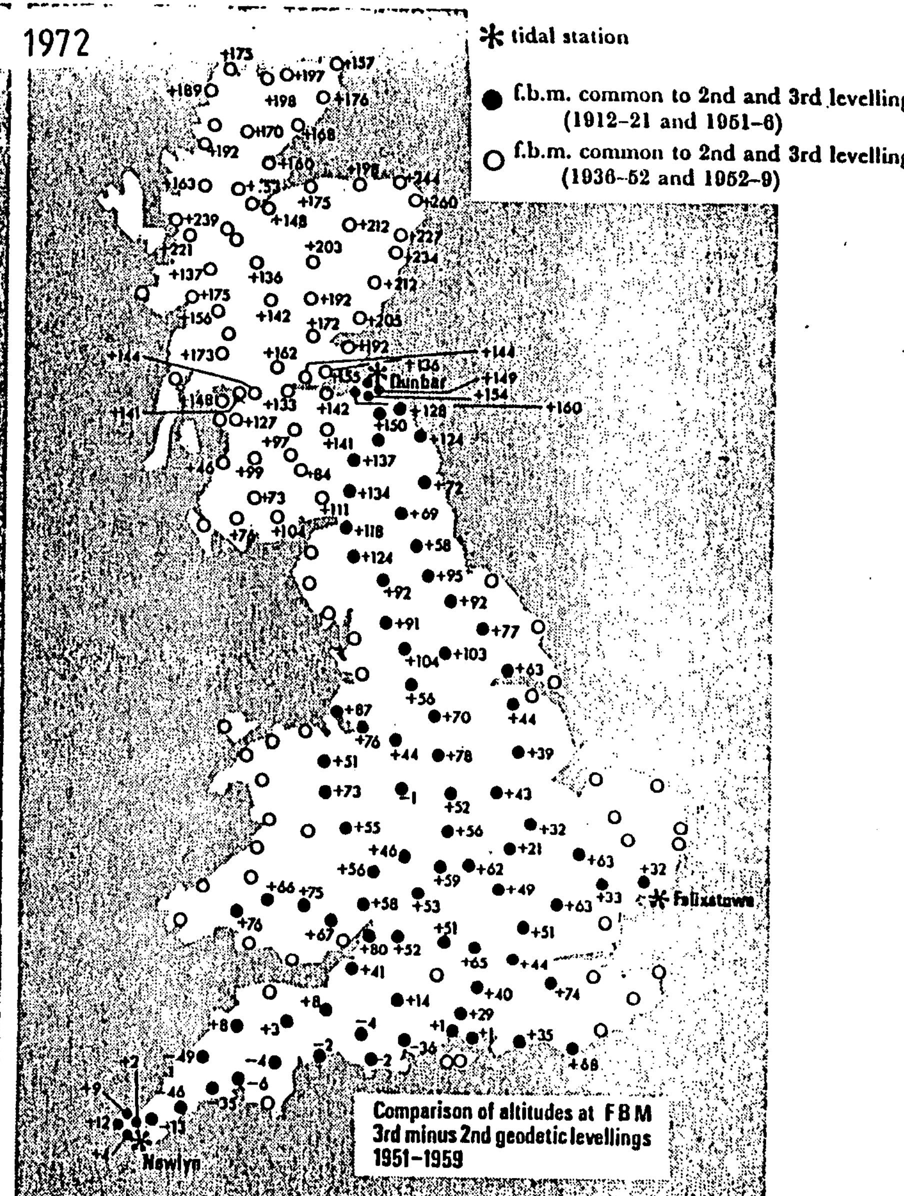
These represent a rate of uplift between four and five millimetres per year for Scottish stations. Differential rates of uplift for the Grampians with respect to southern Scotland are in fact greater than this based on an examination of the exact acquistion dates.

Geodetic data would therefore seem to suggest rates of uplift of an order of magnitude greater than mareographic analysis. Thompson (1980) analyses the data from 29 tide guages evenly spaced around the British Isles, for the period 1960 - 1975 (here again record sections were not always complete). Thompson observes a latitudinal slope of

KELSEY 1972




Third geodetic levelling, 1951–9.




Comparison of altitudes at fundamental bench marks: third minus second geodetic levellings 1951–9 in mm.

Figure 8.3 The third geodetic levelling

5.3 ± 0.4 centimetres per degree on both the east and west coasts. This is difficult to explain oceanographically and for this reason suggests a systematic error in the third geodetic levelling. Such a sytematic error would almost eliminate the supposed uplift of northern Britain and reduce all figures to less than the probable error.

Mareographic and geodetic observations are the only available sources for the derivation of modern uplift rates. This recent evidence suggests a maximum rate of uplift of five millimetres per year and probably much less than this figure. The Scottish network is therefore located in a tectonically stable area suitable for studying temporal gravity variations with the hypothesis of zero change. Archeological and geomorpholical (river terraces, peat dating etc.) agree than Scotland has risen in the Holocene period but are also inconsistent quantatively.

## 8.3 The Observations

Observations were made between the fundamental benchmarks shown in figure 8.1 over the period 1976 - 1981 as follows:

| | |
|---|---|
| 1976 | E-L |
| 1977 | E-L |
| 1978 | E-L,E-D,T-L |

1980 E-L,E-D,T-L,C-G,C-T,T-G,T-L,L-G

1981 E-L,E-D,T-L,C-G,C-T,T-G,T-L,L-G

E:Edinburgh, L:Linlithgow, D:Dunbar, C:Crubenmore, T:Tummel Bridge , G:Glenshee

Observations made prior to 1980 were carried out by levelling the gravity meter directly on the hemispherical surface of the bench mark. Subsequent observations were carried out using the tripod described in section 3.2. The use of the tripod as shown in plate 3.1 means that the height and orientation can be recovered with extreme accuracy from year to year. Furthermore, when in transport, the meter was suspended using elasticated cords during the 1980 and 1981 measurement sequences. During the 1976 - 1978 measurement sequences the meter sat on one observer's lap in the front passenger seat of the vehicle (a Renault 4 )whilst in 1980 - 1981 the meter was suspended as close to the vehicle's centre of gravity as possible.

Meter readings were taken alternately by one of two observers whilst the second noted the air temperature and pressure to 0.1K and 0.1mbar respectively. Twenty to twenty four readings were taken at each site over a period of approximately eighty minutes with an average reading interval of four minutes. The reading procedure is as described in section 3.2. After a sequence of readings on one fundamental bench mark, the apparatus was carefully loaded into the car and driven to the second site were the reading process was repeated. The first site was then revisited followed by the second (ie. ABAB ). Thus each day's observations is a treble link consisting of four 80 minute reading sequences and three driving sequences. Each connection can be measured in a long day (10 - 14 hours fieldwork). All the measurements to be undertaken were made in June or July when meterological conditions are fairly stable and the long days permit all the observations to be undertaken with natural light. This is particularly necessary with the use of coincident image spirit levels which were used in 1980 and 1981. The difference between the La Coste and ancillary platform levels was noted in 1981.

The meter proved trouble free during the fieldwork period and the batteries maintained their capacity despite the unusually heavy demands placed upon them. A sun shade was acquired for the 1981 fieldwork season, as direct sunlight had proved to be the major problem during the 1980 campaign. Sunlight shining directly on the level bubbles caused them to drift and some form of shading is necessary. The tripod was found to act as a stable and secure measuring base.

## 8.4 Data Reduction and Results

The data reduction procedures have already been throughly outlined in section 5.3. All data collected on Scottish fundamental bench marks, including that collected between 1976 and 1978 was reduced using spline fitting (program NSPL) and ancillary adjustment routines. Earth tide reductions were made using the program PBAS (section 5.3) using tidal parameters extrapolated from Baker (1980) as shown in Table 8.1.

The data from each day was initially adjusted individually to examine the data quality and conformablity to the classic G-275 drift pattern. Figure 8.4 illustrates the observations of the Edinburgh Linlithgow link between the year 1976 and 1982 and provide a typical example of data quality. ( The spline program parameters are shown in the inset box .) The root mean square error of these daily spline fits with two knots does not exceed 0.05 g.u. and is generally in the range 0.015 g.u. to 0.030g.u.. The daily drift curves for the 1981 survey are remarkably consistent, whereas those for 1980 exhibit some inconsistencies attributable to the inadequate shading mentioned above. Daily spline fits were found to provide robust solutions for all years. Increasing the number of nodes did not significantly alter the spline solution or reduce the root mean square error. Table 8.2 illustrates the solution variation with an increasing number of nodes for the Linlithgow - Glenshee link. Because of this , the simplest solution sets generated using two unconstrained nodes

| Station | Lat. (°) | Long. (°) | Height (m) | $M_2$ Theory (μ gals) | Load Amp. (μ gals) | Vector G. Phase (°) | Local Phase (°) | $M_2$ Observed (μ gals) | $\delta_{M_2}$ | $\kappa_{M_2}$ (°) |
|---|---|---|---|---|---|---|---|---|---|---|
| EDN | 55.953 | 3.152 | 60.05 | 27.396 | 2.8 | 285 | 81 | 27.834 | 1.179 | 5.70 |
| CRU | 56.984 | 4.216 | 318.84 | 25.953 | 2.2 | 317 | 51 | 27.331 | 1.221 | 3.59 |
| LIN | 55.956 | 3.656 | 101.55 | 27.393 | 2.6 | 295 | 72 | 28.196 | 1.194 | 5.03 |
| GLE | 56.729 | 3.405 | 296.47 | 26.308 | 2.1 | 298 | 69 | 27.061 | 1.193 | 4.15 |
| TUM | 56.708 | 4.020 | 149.60 | 26.337 | 2.3 | 310 | 58 | 27.556 | 1.214 | 4.05 |
| DUN | 55.998 | 2.499 | 5.94 | 27.332 | 2.5 | 273 | 92 | 27.245 | 1.156 | 5.26 |

Table (8.1). Position of Scottish secular variation sites and $M_2$ tidal parameters inferred from Baker (1980)

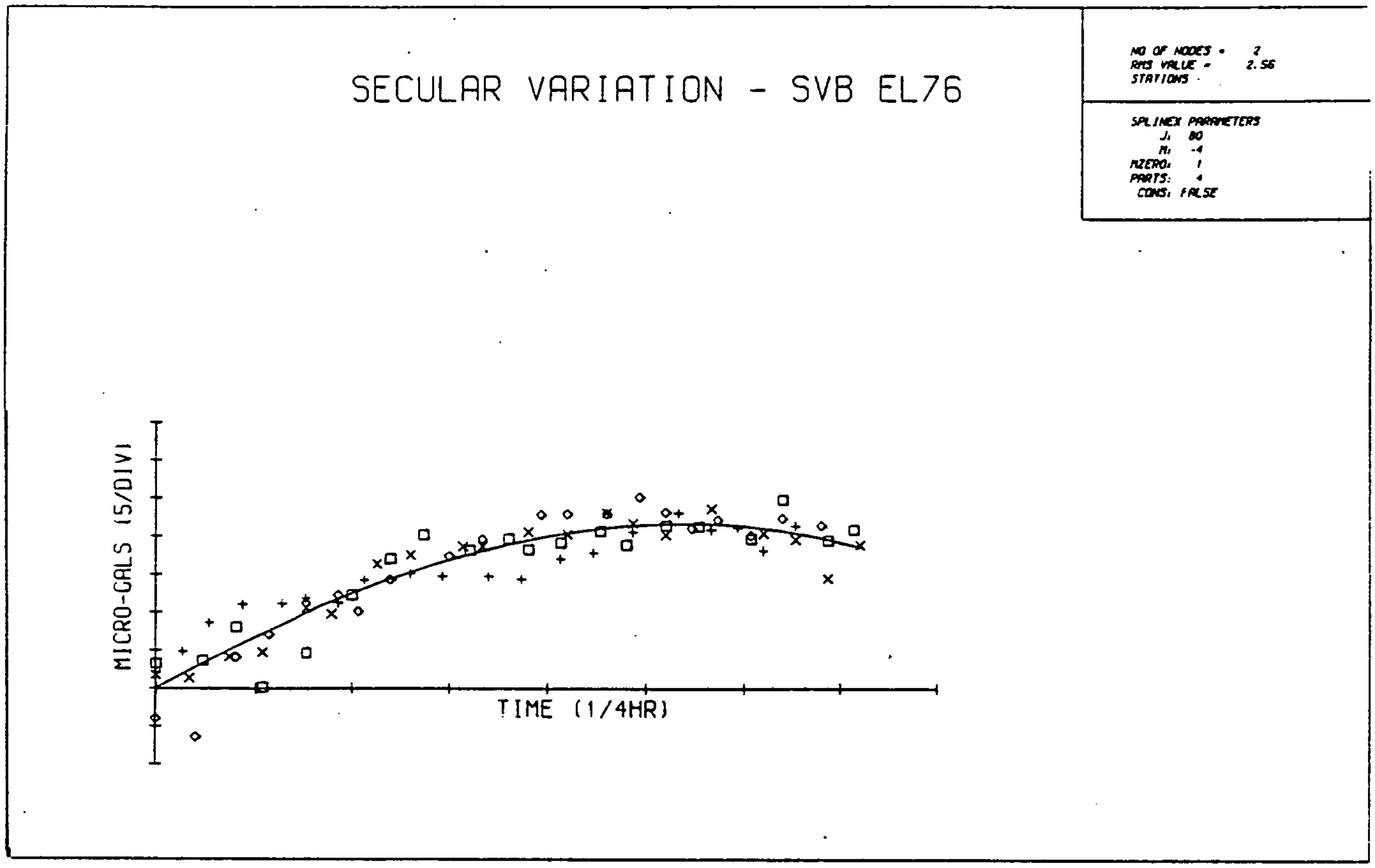



**Figure 8.4(a)** **Edinburgh - Linlithgow link, 1976**

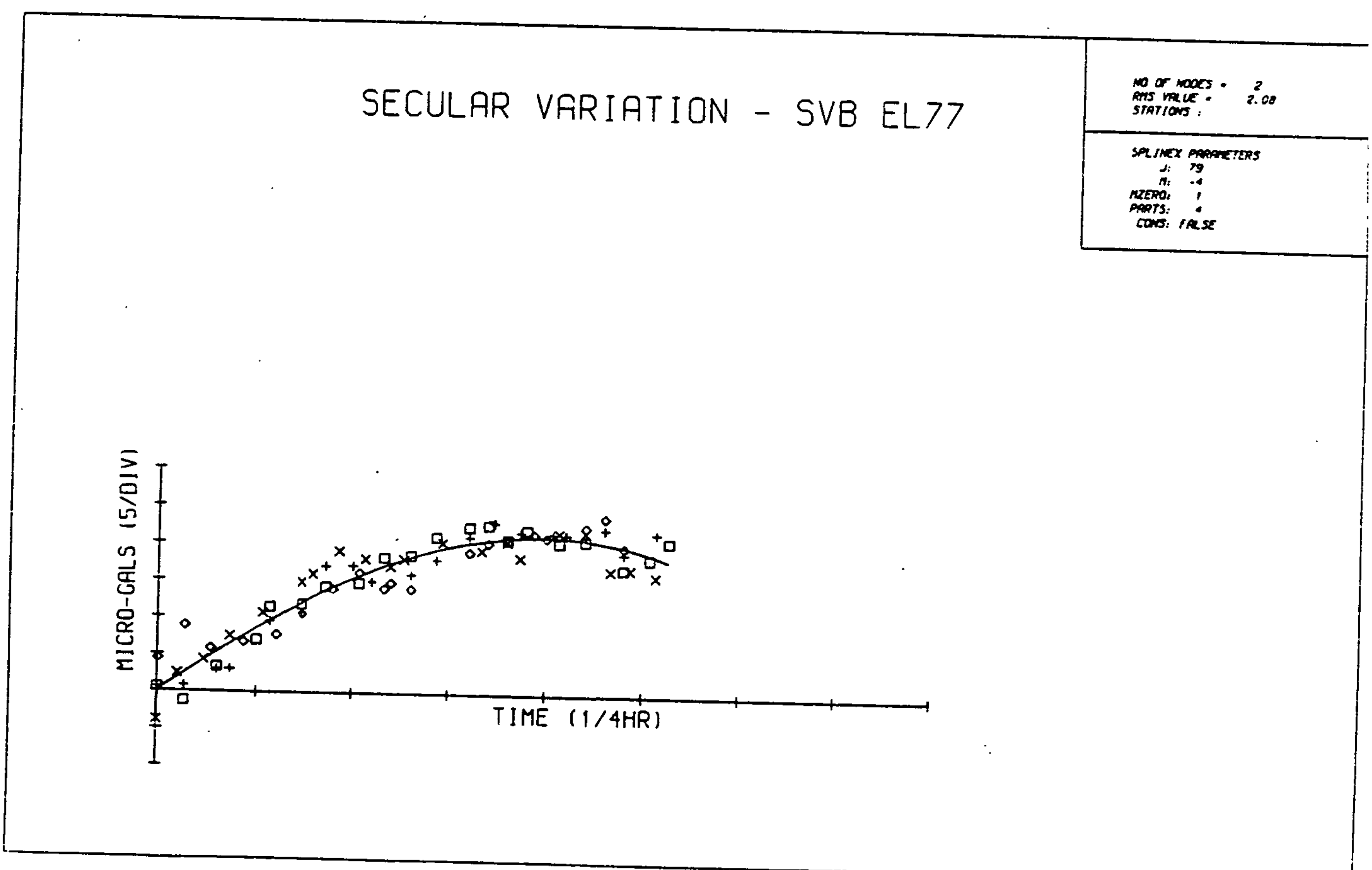
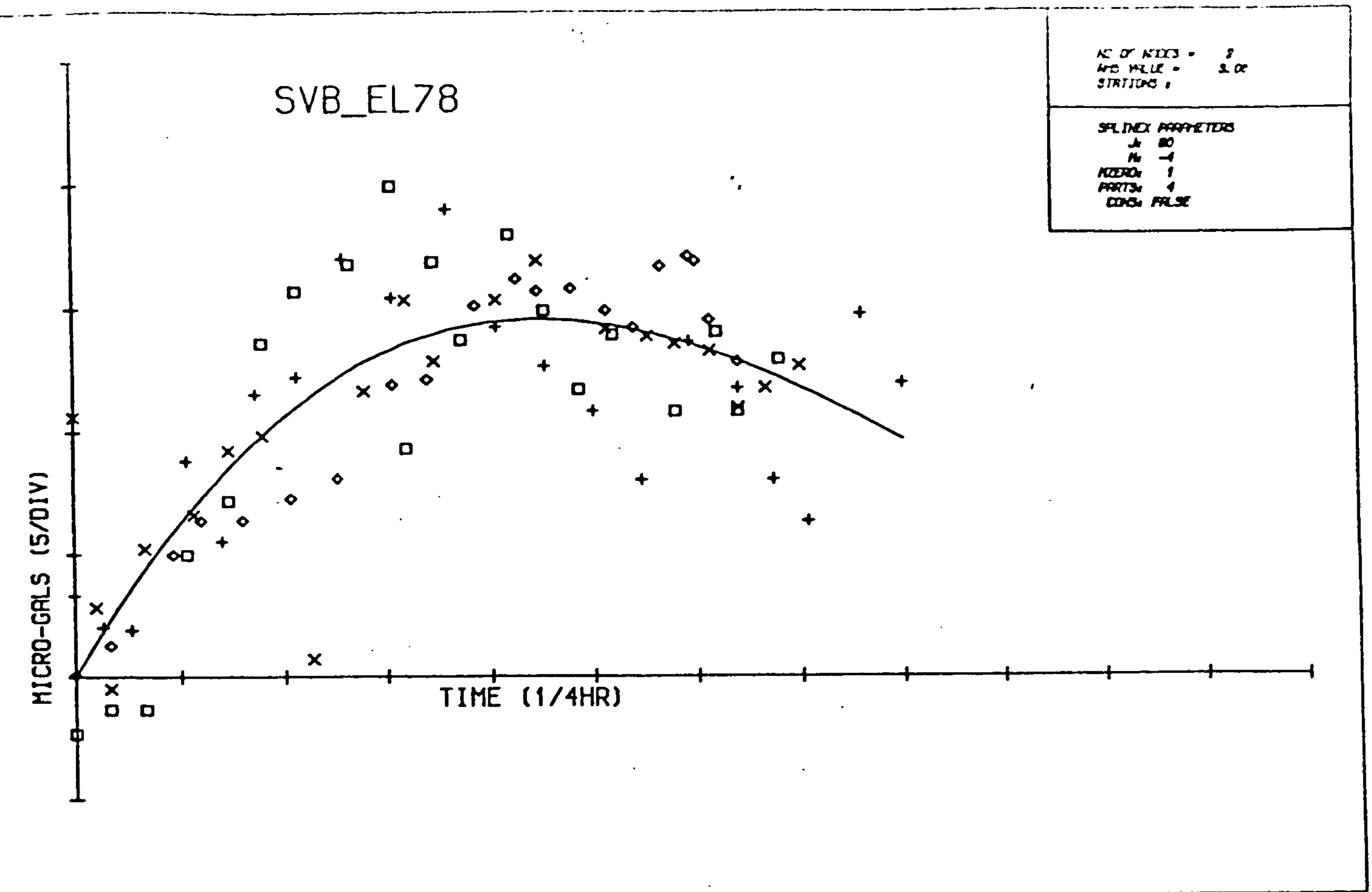



Figure 8.4(b) Edinburgh - LInlithgow link, 1977



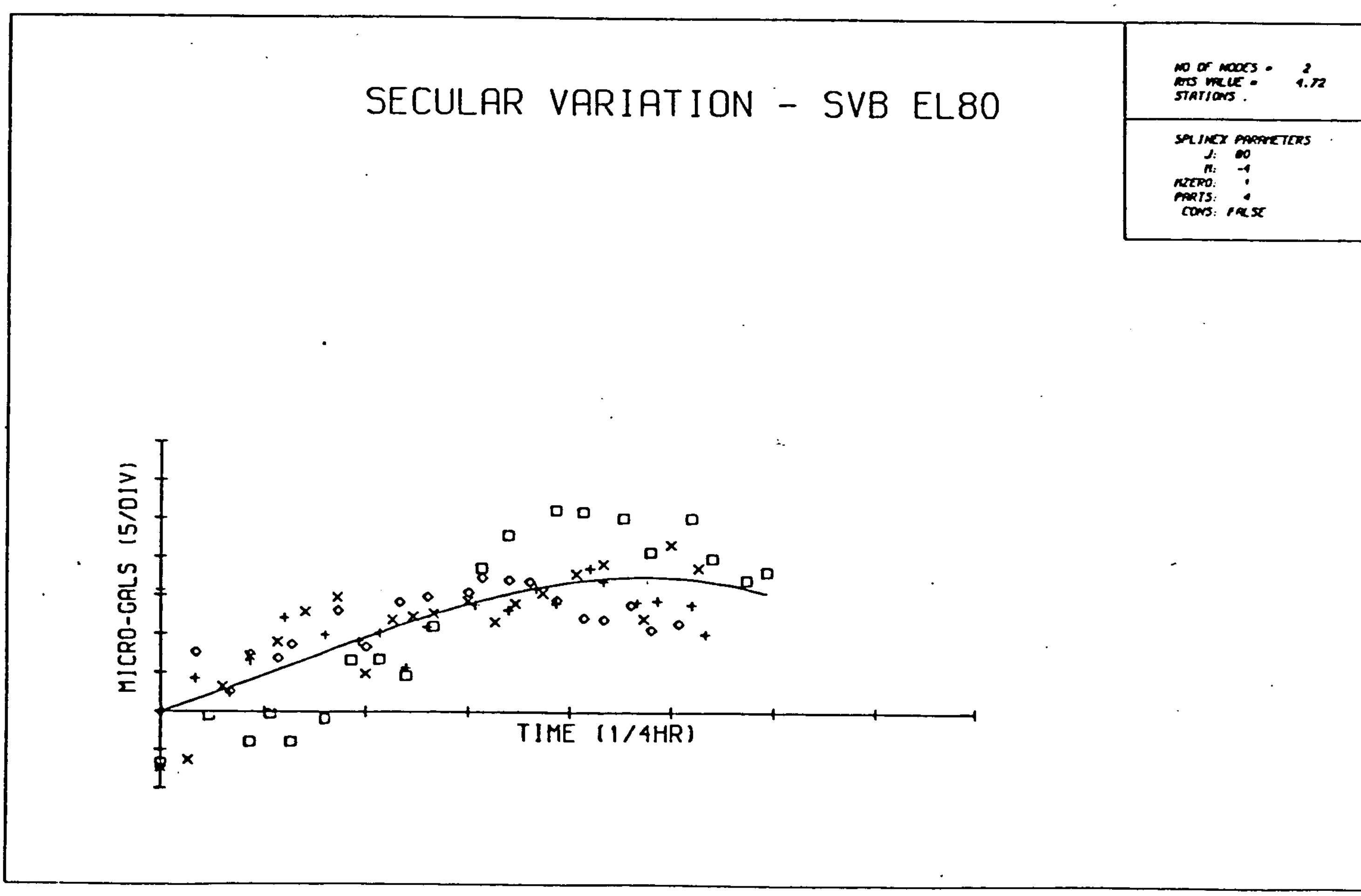




Figure 8.4(d) Edinburgh - Linlithgow link, 1980

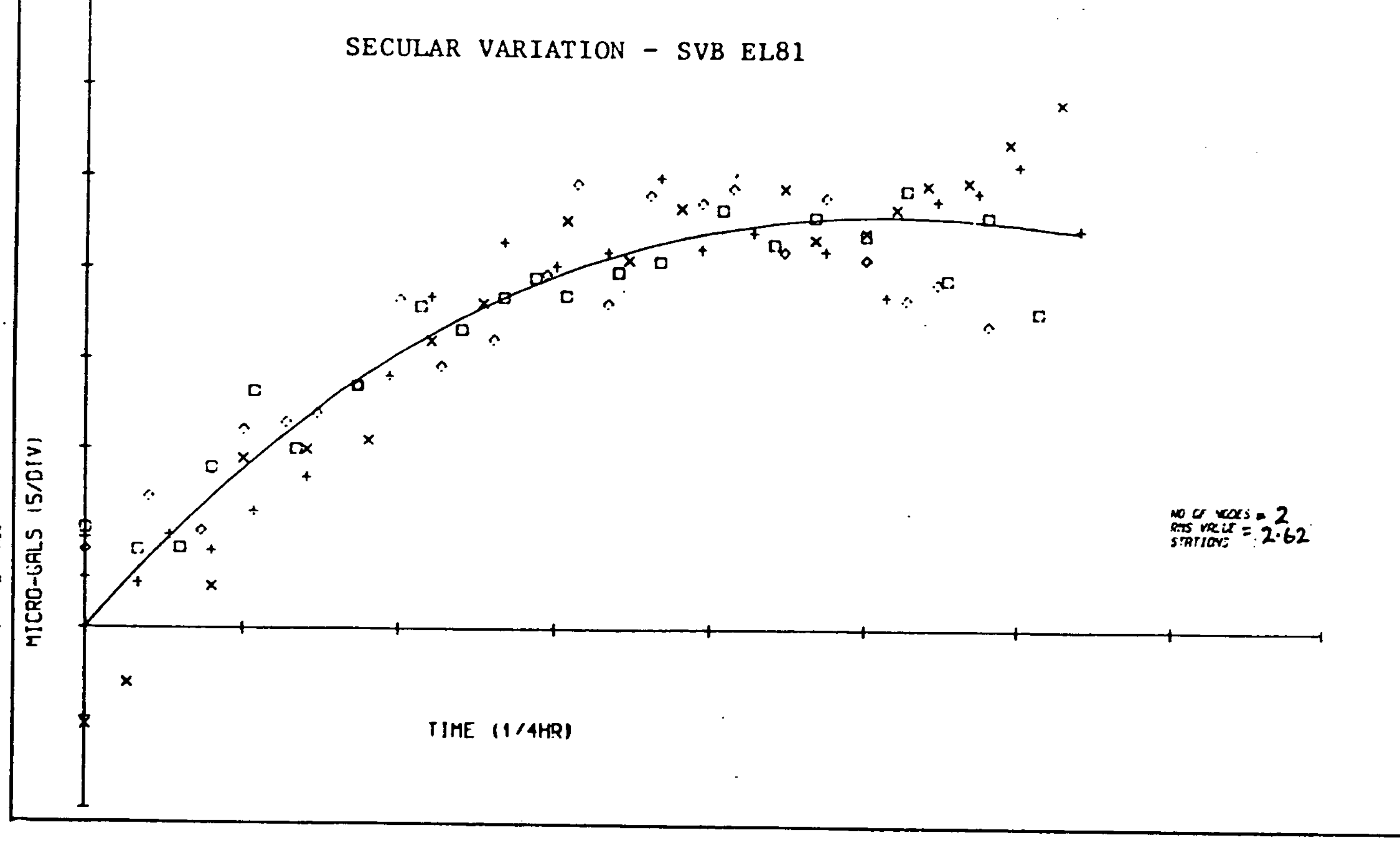



**Figure 8.4(e)** **Edinburgh - Linlithgow link, 1981**

Table 8.2

Effect of increasing number of nodes

(Spline solution with 'superimposed' data sets)

| Number of Nodes | Linlithgow–Glenshee 1980 Gravity Difference (g.u.) | rmse | Linlithgow–Glenshee 1981 Gravity Difference (g.u.) | rmse |
|---|---|---|---|---|
| 2 | 49.071 | 0.076 | 49.205 | 0.071 |
| 3 | 49.071 | 0.076 | 49.205 | 0.071 |
| 4 | 49.070 | 0.076 | 49.205 | 0.070 |
| 5 | 49.071 | 0.075 | 49.205 | 0.070 |
| 6 | 49.070 | 0.075 | 49.205 | 0.070 |
| 7 | 49.070 | 0.075 | 49.205 | 0.070 |
| 8 | 49.070 | 0.075 | 49.205 | 0.070 |
| 9 | 49.070 | 0.075 | 49.206 | 0.070 |
| 10 | 49.071 | 0.075 | 49.206 | 0.070 |
| 11 | 49.071 | 0.074 | 49.205 | 0.070 |
| 12 | 49.071 | 0.074 | 49.205 | 0.069 |

were used throughout. This avoided the possiblity of overfitting the data.

All the data from one year's field measurements were adjusted by a common drift function for all 80 minute measurement sequences solution in a least squares sense; the **a priori** assumption being that each observation sequence measured at a fundamental bench mark would conform to a similar drift response (as observed in the laboratory). Figures 8.5 , 8.6 and 8.7 illustrate the drift curves so obtained for the years 1978,1980 and 1981 respectively. Each observation sequence is represented by a different symbol. Thus if we consider the 1981 diagram of figure 8.7, 58 different measuring sequences of 80 to 90 readings are shown (a total of 598 readings). The low root mean square error and observational consistency demonstrate the validity of the model assumption.

Such a universal adjustment is independent of the site observation sequence and network. A simple weighted least squares linear fit was applied to each day's observations (weights equal to the recripocal root mean square error of the spline fit). The final solution after a daily linear fit is shown in Table 8.3. It can be seen that the observed annual gravity change is quite variable, attaining a maximum of 0.24 g.u. on the Tummel Bridge - Glenshee link. A histogram of the gravity change between consecutive years is shown in figure 8.8. This distribution with twelve

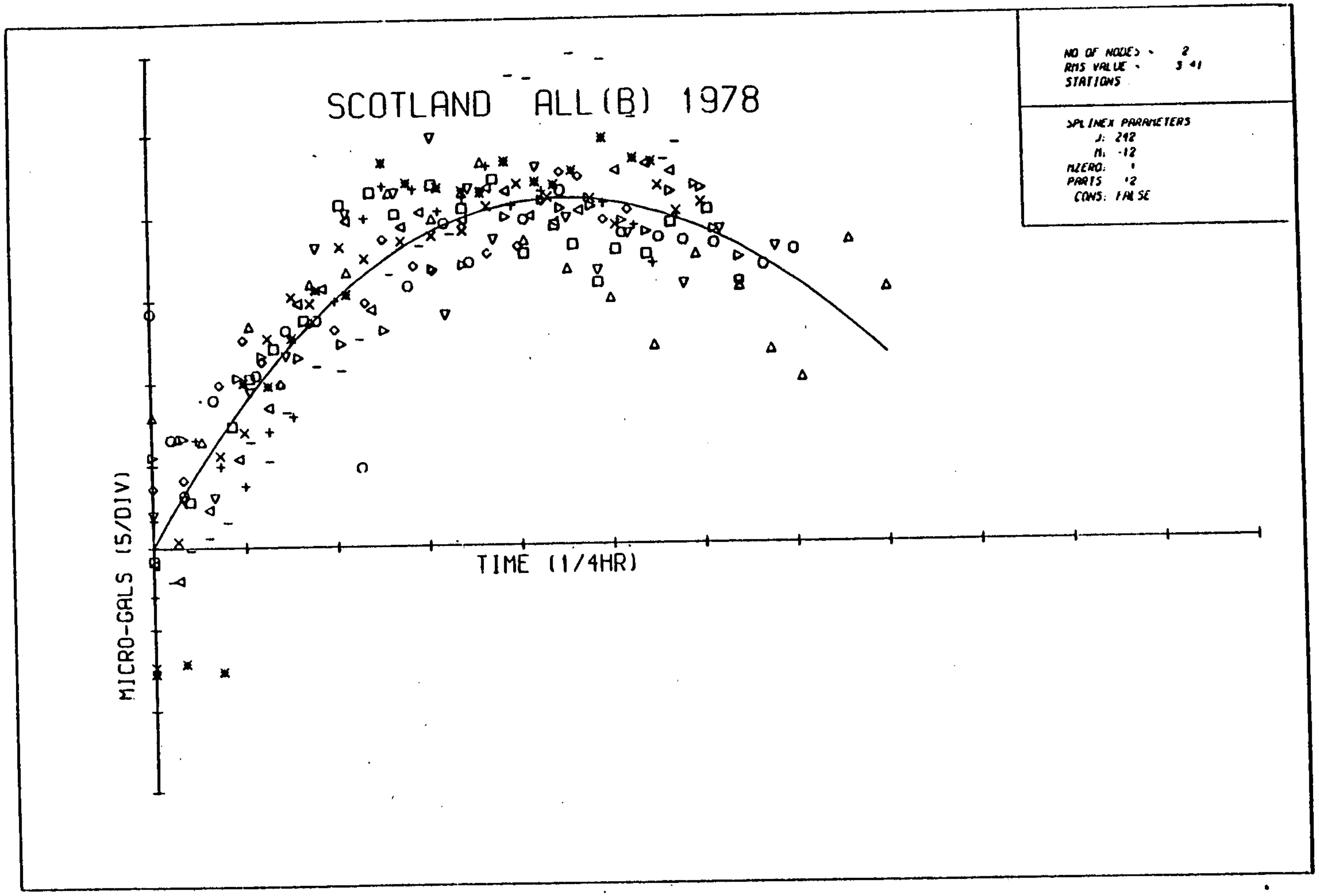



Figure 8.5 Complete 1978 data set. Station drift curves superimposed.
242 observations, 12 data sequences 4 x 3 days readings

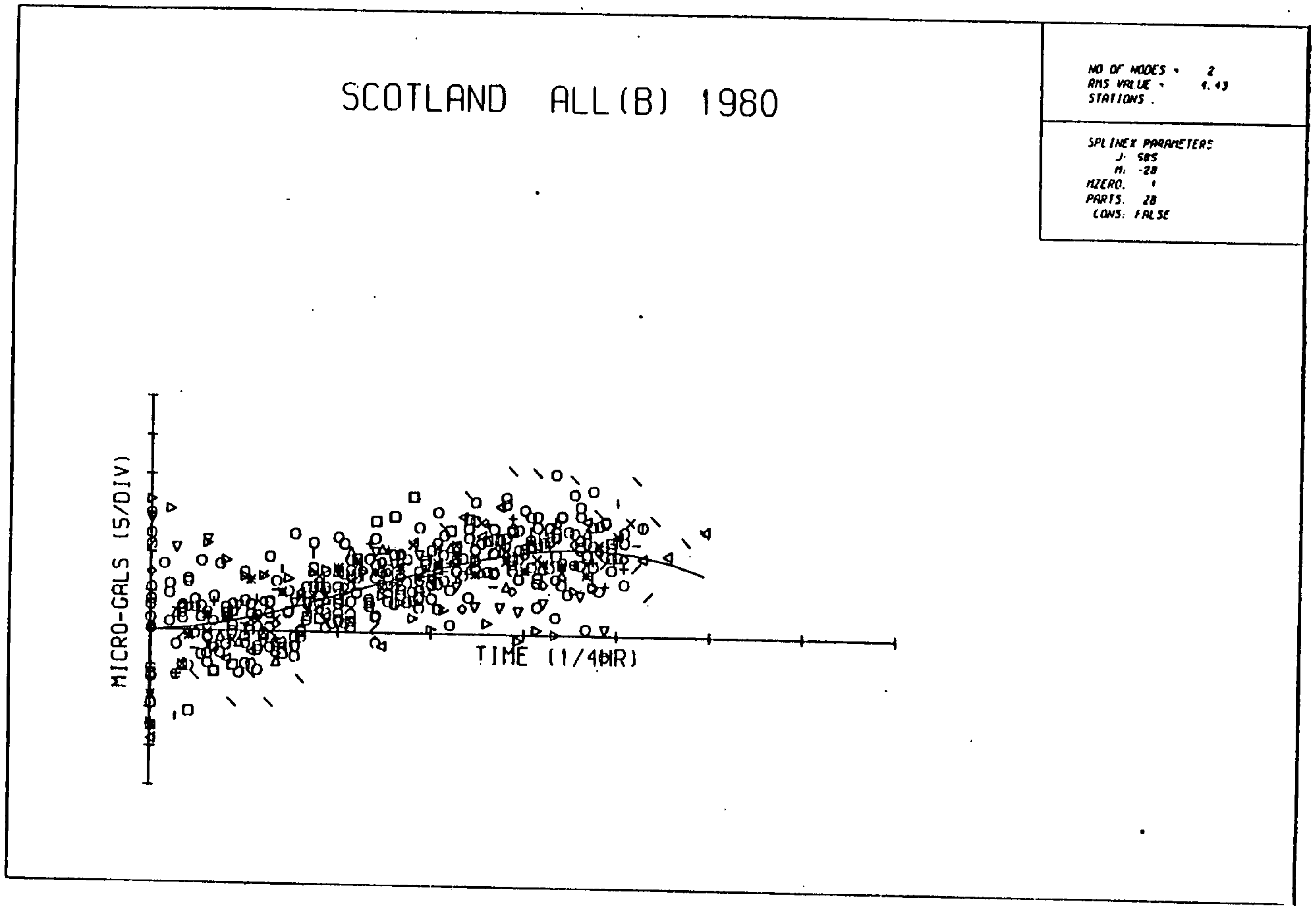



Figure 8.6 Complete 1980 data set. Station drift curves superimposed.

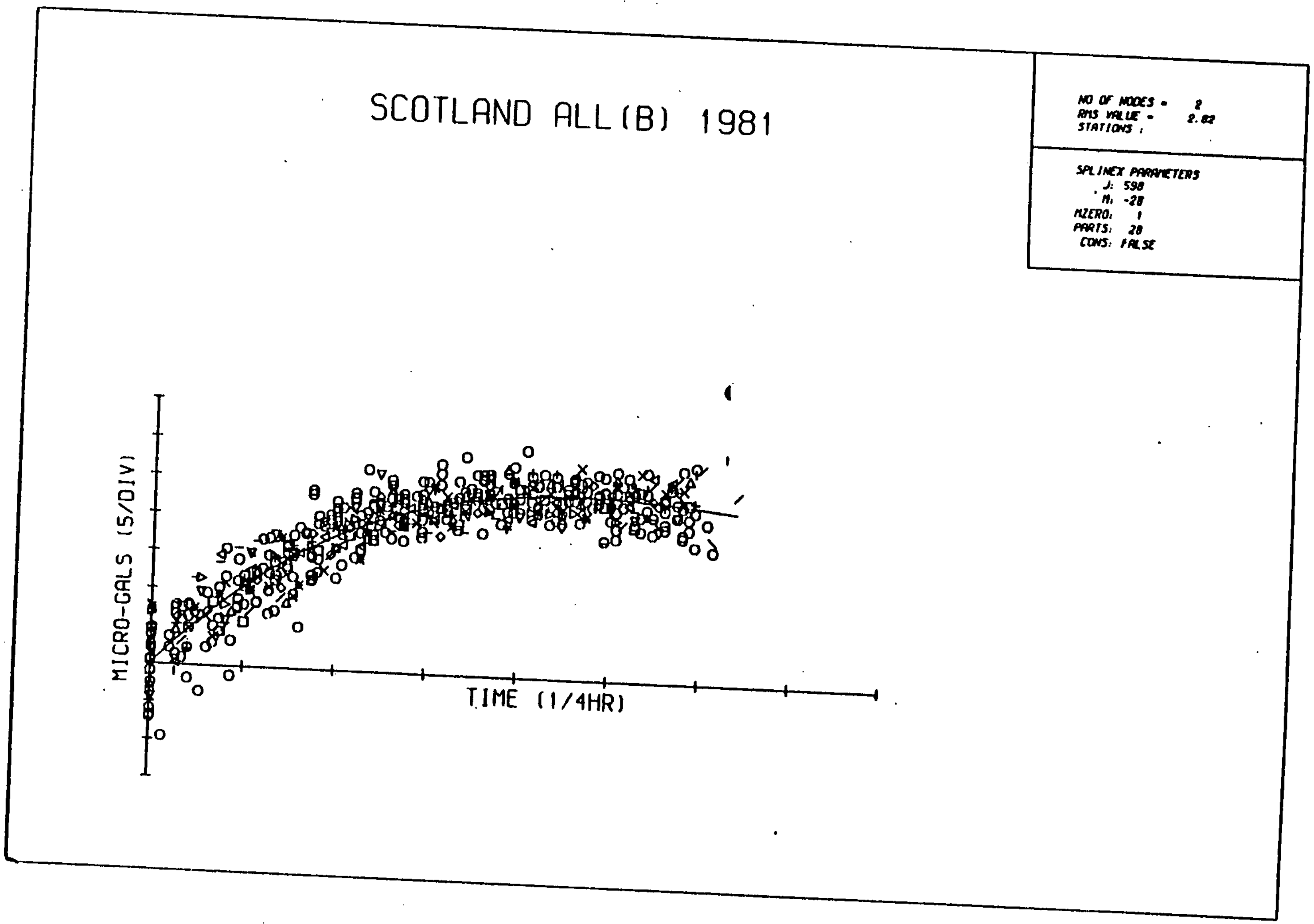



Figure 8.7 Complete 1981 data set. Station drift curves superimposed.

TABLE 8.3

Scottish Secular Variation Network - Results

| Link | Year | Gravity diff. (g.u.) | rmse (WFIT only) | rmse (NSPL only) | $(rmse_W^2 + rmse_N^2)^{1/2}$ |
|---|---|---|---|---|---|
| Crubenmore - Glenshee | 1980 | 62.295 | 0.044 | 0.081 | 0.092 |
| | 1981 | 62.316 | 0.040 | 0.042 | 0.058 |
| Crubenmore - Tummel Bridge | 1978 | 44.557 | 0.010 | 0.047 | 0.048 |
| | 1980 | 44.507 | 0.014 | 0.079 | 0.080 |
| | 1981 | 44.439 | 0.026 | 0.053 | 0.059 |
| Edinburgh - Dunbar | 1980 | -24.727 | 0.017 | 0.058 | 0.060 |
| | 1981 | -24.677 | 0.037 | 0.057 | 0.068 |
| Edinburgh - Linlithgow | 1976 | - 5.534 | 0.014 | 0.046 | 0.048 |
| | 1977 | - 5.531 | 0.011 | 0.043 | 0.044 |
| | 1978 | - 5.563 | 0.026 | 0.072 | 0.076 |
| | 1980 | - 5.439 | 0.005 | 0.090 | 0.090 |
| | 1981 | - 5.628 | 0.009 | 0.052 | 0.053 |
| Linlithgow - Glenshee | 1980 | 49.066 | 0.003 | 0.074 | 0.074 |
| | 1981 | 49.184 | 0.042 | 0.066 | 0.078 |
| Tummel Bridge - Glenshee | 1980 | 17.654 | 0.011 | 0.081 | 0.082 |
| | 1981 | 17.895 | 0.011 | 0.065 | 0.066 |
| Tummel Bridge - Linlithgow | 1978 | -31.291 | 0.051 | 0.081 | 0.096 |
| | 1980 | -31.413 | 0.006 | 0.069 | 0.069 |
| | 1981 | -31.368 | 0.009 | 0.055 | 0.056 |

rmse - root mean square error

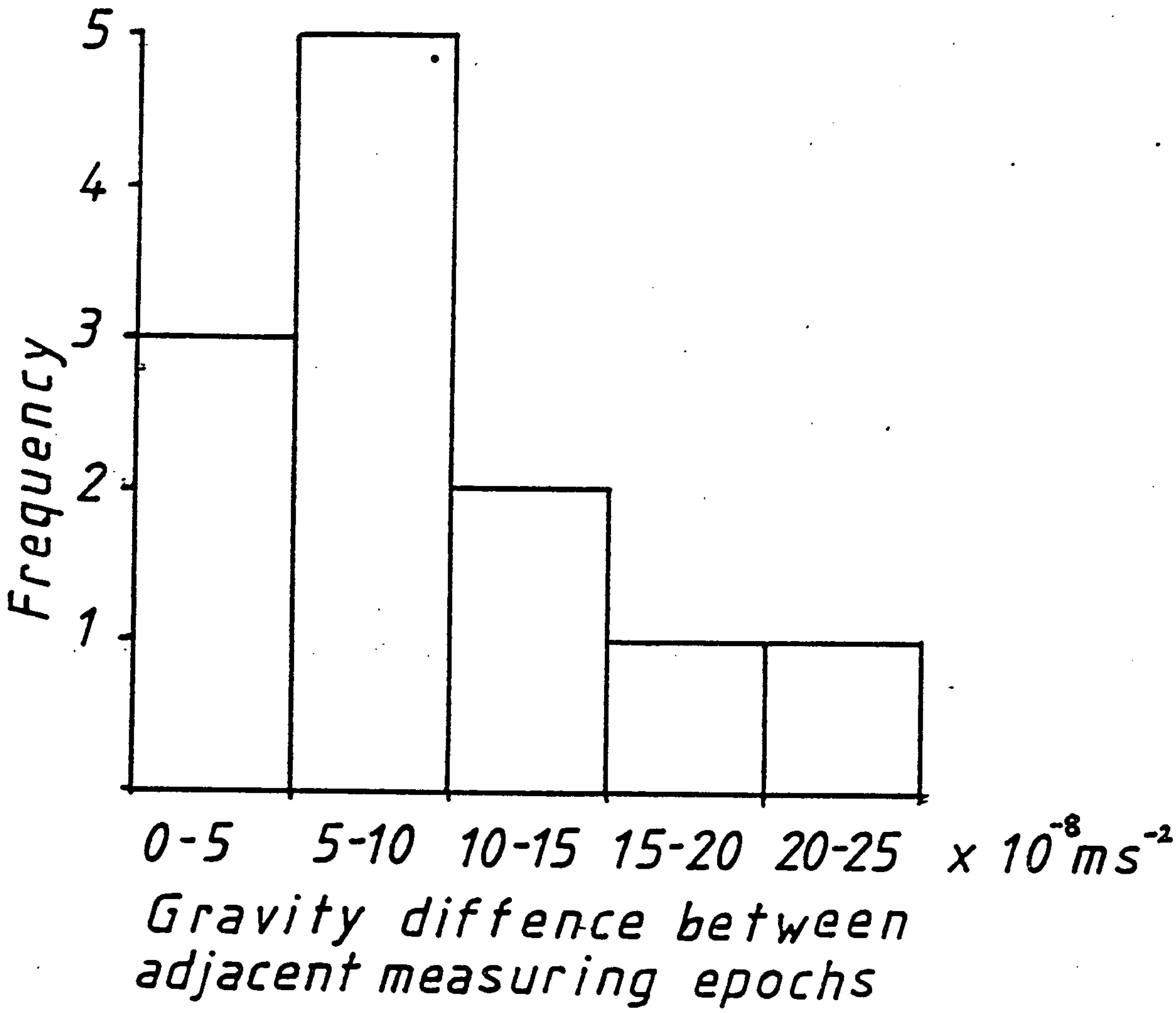



Figure 8.8 Histogram of residual frequency.

members possess a mean of 0.081 g.u. with a standard deviation of 0.073 g.u.. The last column of Table 8.3 is an estimate of the root mean square error for each individual link. This is obtained by taking the square root of the mean square error on the site drift function plus the weighted linear fit.

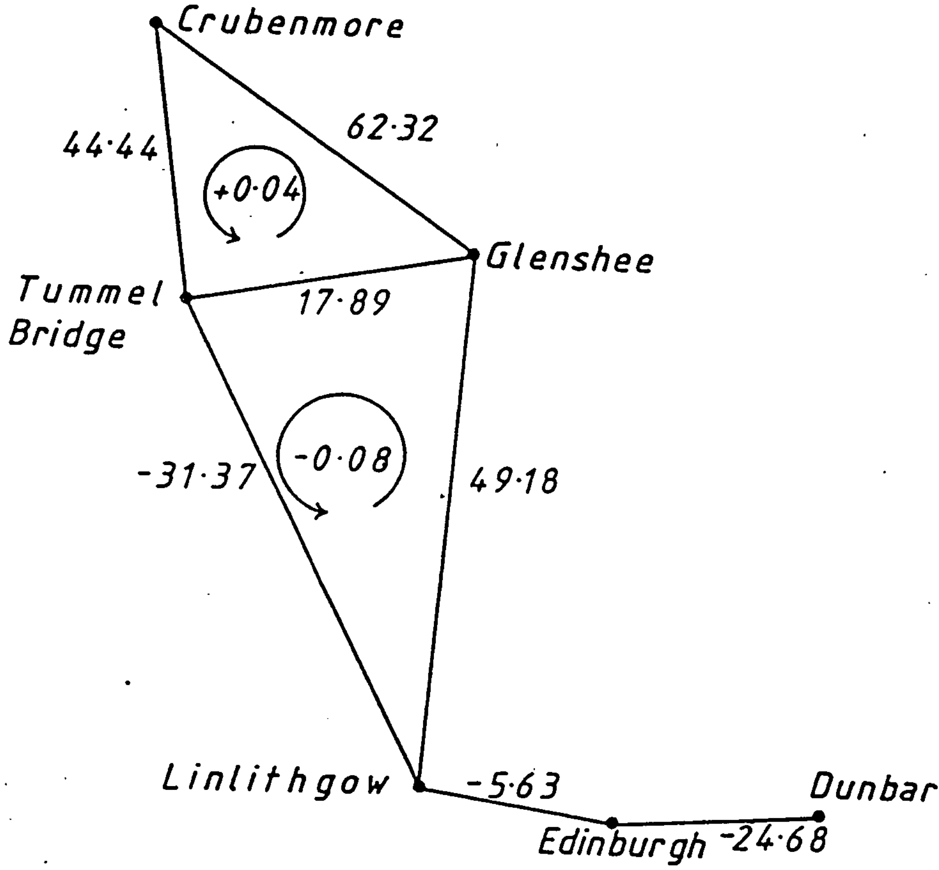
Five of the sites chosen form a simple network of two traingles with a common side. This simple network was completely measured during the 1980 and 1981 fieldwork seasons only. The misclosures are shown diagramatically in figure 8.9. The largest observed gravity change of 0.24g.u. (more than double the estimated r.m.s. error of 0.105g.u. , ie.$0.082^2+0.066^2$) is observed on the network's common link, Tummel Bridge - Glenshee.

## 8.5 Conclusions

In conclusion the Scottish gravity secular variation net has attained levels of precision comparable to but not better than conventional high precision surveys. But it has proved successful in linking distant stations precisely without a dense network. It would be particularly interesting to apply this method to the much observed Fennoscandia (figure 2.3) secular variation profile where stations are similarly separated by large distances. The time involved in measuring the network in this fashion is

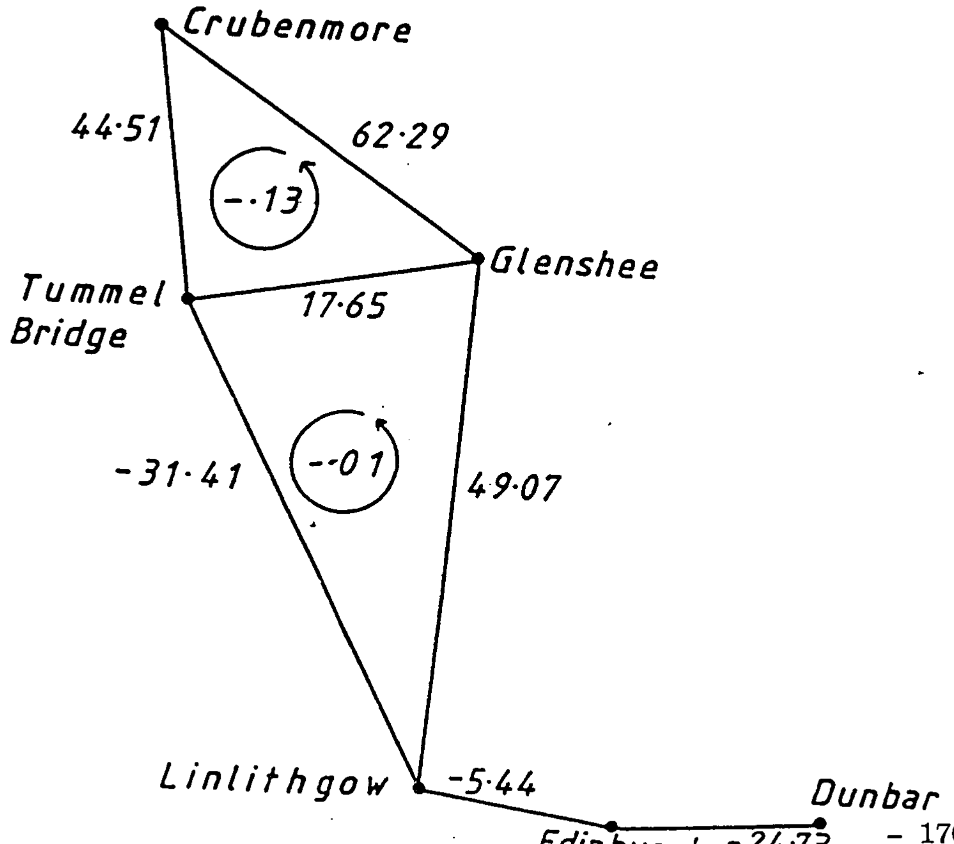
Scottish High Precision Gravity Net

1981




Scottish High Precision Gravity Net

1980



greater than conventional surveying involving forward looping or a double or treble ladder sequence. One important link (Tummel Bridge) unfortunately appears to be less accurate than the others reducing the precision of the network and increasing the network misclosures. Since this is the only common link it would be invalid to adjust it without an independent reason.

The technique of fitting a characteristic drift curve to field data has proved robust (as evidenced in figures 8.5, 8.6, and 8.7). This indicates success in overcoming time dependent environmental and time dependent systematic effects. The failure to improve the accuracy of the final solution to the level generally attained at individual sites suggest inter-site effects such as irregular transport drift (see section 5.3, Table 5.1). This could be controlled by increasing the density of the network, or reducing the areal extent of the network, hence shortening the distance between stations. But this would loose the advantage that sites are currently almost within a dial turn range.

# CHAPTER NINE

## GRAVITY MEASUREMENTS IN EAST CENTRAL GREECE

### 9.1 Introduction

A local (c.80km. x 20km.) microgravimmetric network was established in East Central Greece using two gravimeters G-275 (Edinburgh University) and G496 (Athens University) in 1981. A total of 69 stations were established with an approximate station spacing of two kilometres. This study is incorporated in a regional remeasurement of the Greek National gravity base network undertaken by members of the Seismological Laboratory of the University of Athens. The network is located in an area of potential seismic hazard and will be remeasured on an annual basis

A series of major shocks occurred in the Gulf of Corinth during February and Marh, 1981 ($M_S$ 6.7,6.4,6.4,U.S.G.S.). These shocks were followed by increased seismic activity in the area North of Thibes (max $M_S$ 4.5, Athens University). Seismic stations were immediately installed in the area using Sprengnether drum recording instruments which were withdrawn with the introduction of a local telemetred network. (VOLOSNET, installed and maintained by members of the Global Seismology Unit, Institute of Geological Sciences, using Willmore Mark III seismometers and 'Geostore' analogue tape-recorders).

A map of the principle morphological trends in the Hellenides is shown in figure 9.1. The particular area that is of interest gravimetrically is the coastal strip west of the island of Evia centred on the Atalanti Fault. It is firstly necessary to consider the tectonic background of the region.

## 9.2 Greek Tectonics

Greece and Turkey are the most seismically active counties in Europe (Karnik,1969), the annual earthquake energy release in Greece accounting for two per cent of the world's total and equivalent to a single event of magnitude 7.2. The most probable annual mode is $M_S$ = 6.4±0.1 with an upper bound of 8.7±0.6 for surface wave magnitude (Makropolous 1979,Galanopolous 1960,1961; Richter 1958). Because of this, the area has been the subject of much study including a UNESCO multidisciplinary group during the period 1972-1976. Figure 9.2 illustrates the spatial distribution of all Greek earthquakes compiled by Makropolous and Burton (1981) on the basis of UNESCO and other data.

Examination of this figure in conjunction with figure 9.3 illustrates the main tectonic structures of the region. The Mediterranean ridge is an irregular feature stretching from the Ionian Sea to Cyprus but is not thought to be a

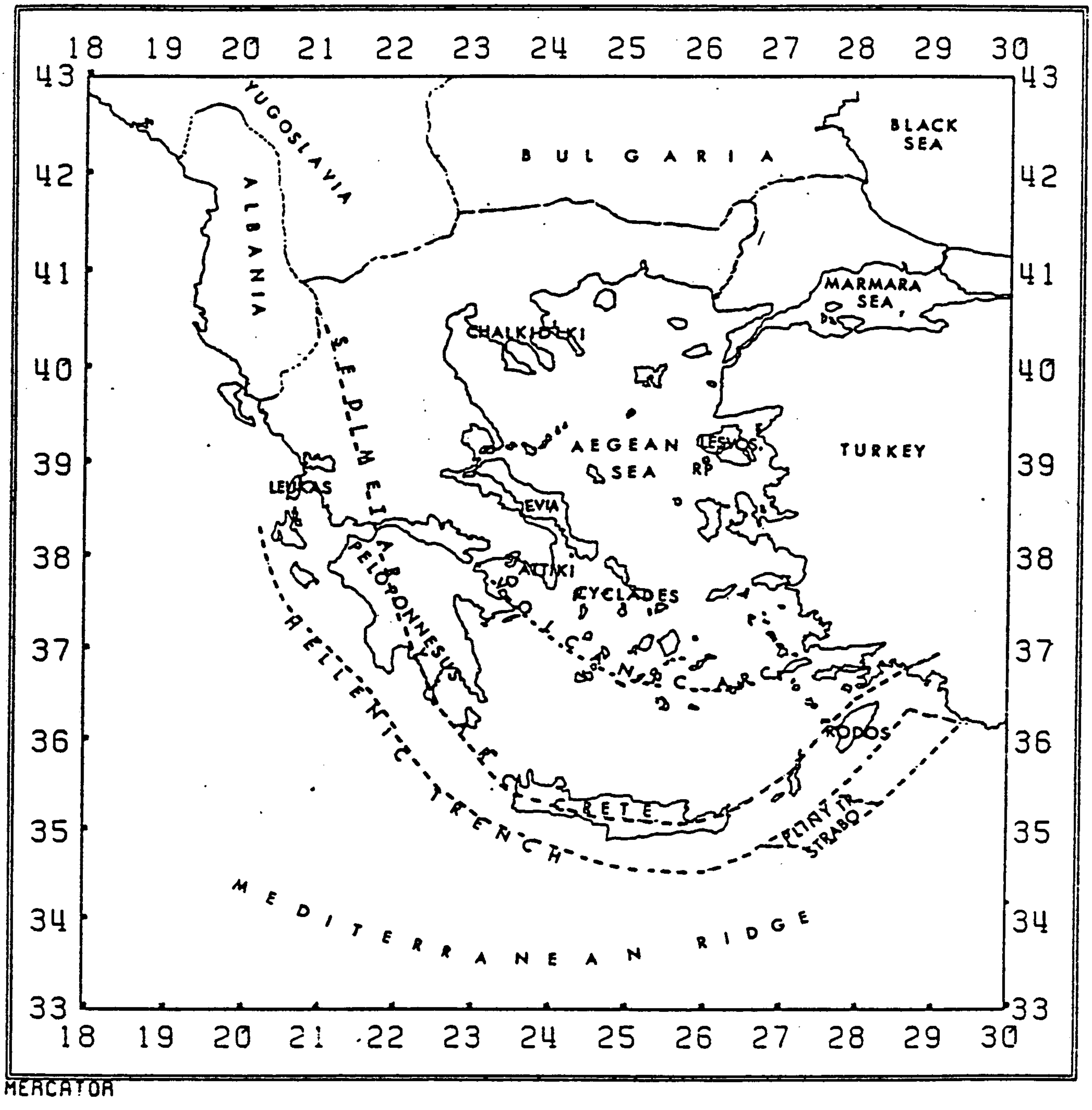



Figure 9.1
Summary map of the Aegean region, showing morphologic and geologic trends in a schematic way.
(from Makropolous, 1978)

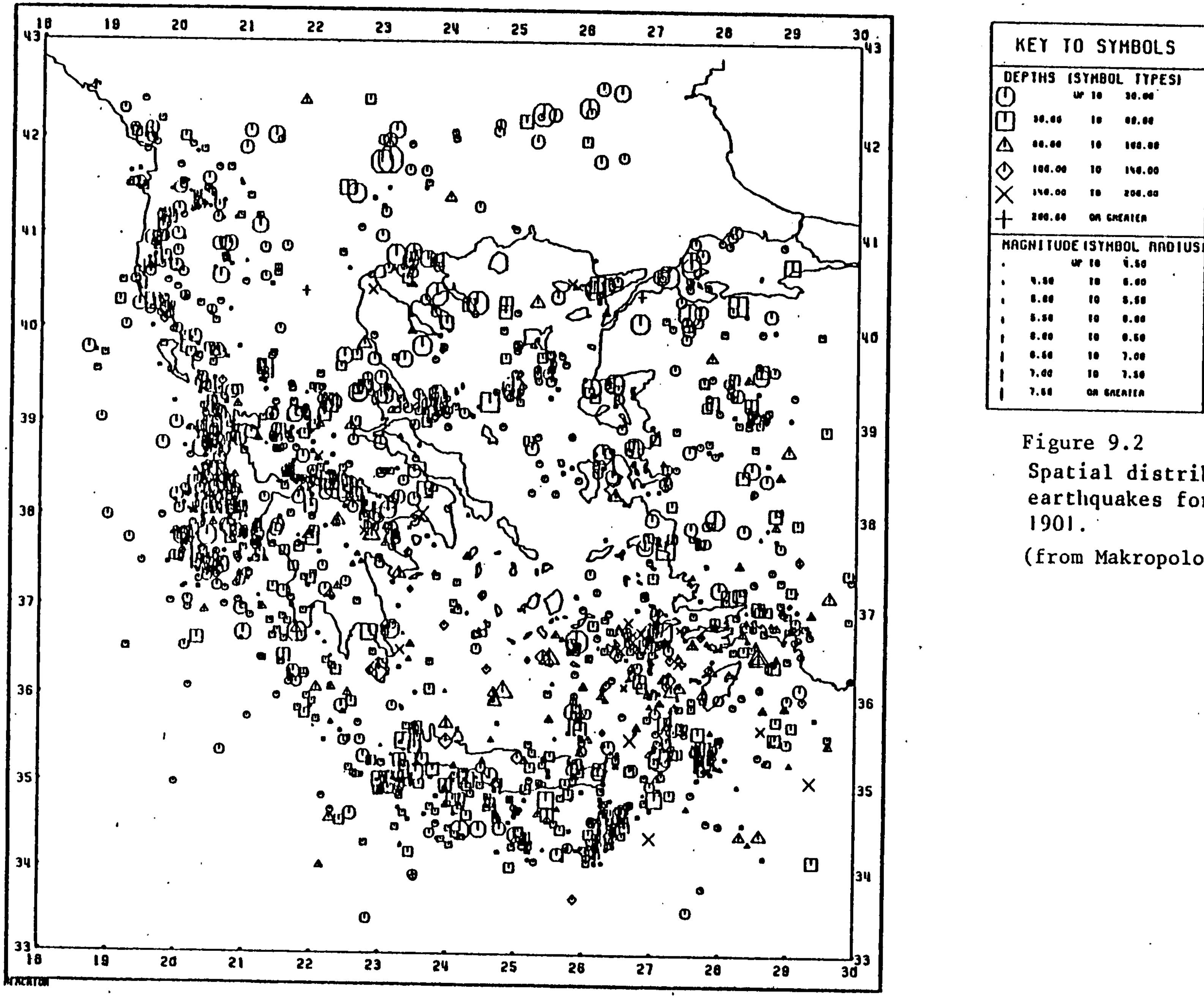


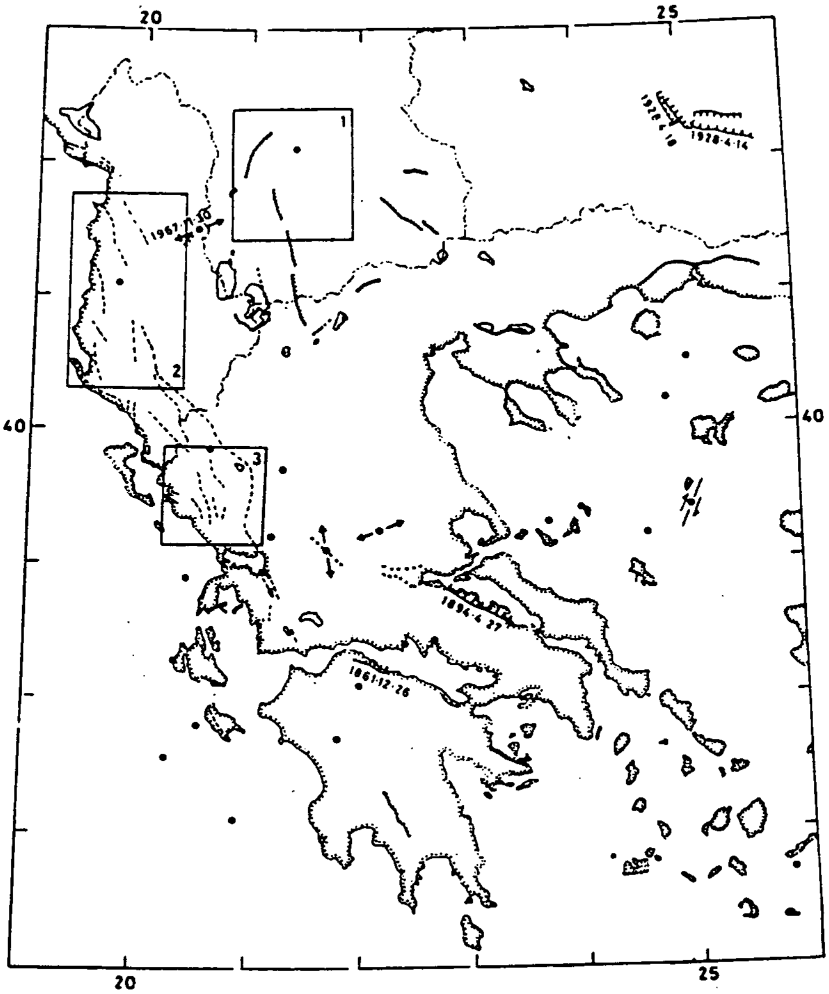

Figure 9.2
Spatial distribution of all earthquakes for Greece since 1901.
(from Makropolous and Burton, 1981)


Fig 9.3 Summary of the present deformation of theAegean area after McKenzie (1978). (Long curved lines show normal faults. Lines with open semicircles show thrust faults. Solid dots mark epicentres of shocks for which mechanisms are used. Arrows show the direction of motion obtained from fault plane solutions. The long heavy arrow shows the direction of relative motion between the Aegean and Africa. Heavy Vs mark sites of recent volcanism.)

mid-ocean ridge (Finetti, 1976). The Hellenic trench consists of a series of depressions to a depth of 5100 metres paralleling a sedimentary (Hellenic) arc. Between the Hellenic and volcanic arcs lies the Cretan Trough where the water depth attains a maximum of 2000 metres.

Seismic refraction studies (Makris, 1977) have shown the crustal thickness in the Aegean to be 22 to 32 km. , whereas the thickness beneath Greece and Turkey is between 40 and 50 km.. Several tectonic models for this complex region have been proposed. A common feature of the models is the underthrusting of the African plate along the Hellenic arc with a dip of c.35$^{o}$. Figure 9.4 is taken from McKenzie (1978), and demonstrates the major fault lines as determined from Landsat images, refraction studies and fault plane solutions. McKenzie postulates that the crustal thinning beneath the Aegean is evidence of stretching by a factor of about two and the direction of relative motion between the Aegean region (microplate) and Africa is 211$^{o}$.

The extensional deformation in Northern Greece is evidenced by diffuse normal faults characterised by shallower dips at depth than those at the surface (McKenzie, 1977). One such feature trending NWW - SEE is clearly seen West of Evia in the Atalanti region (Figure9.3, and 9.4 ). Figure 9.5 shows the region in greater detail, and the epicentres of large magnitude events which




. Surface breaks and faults visible on the *Landsat* images (see Fig. 10 for details). Projection that of Fig. 14. The fault breaks are taken from 1861.12.26 Richter (1958), 1894.4.27 Richter (1958) 1928.4.14 and 1928.4.18 Richter (1958), 1967.11.30 Sulstarova & Kociaj (1969) and Ambraseys (private communication).

Figure 9.4 Landsat lineaments from Mckenzie, 1978

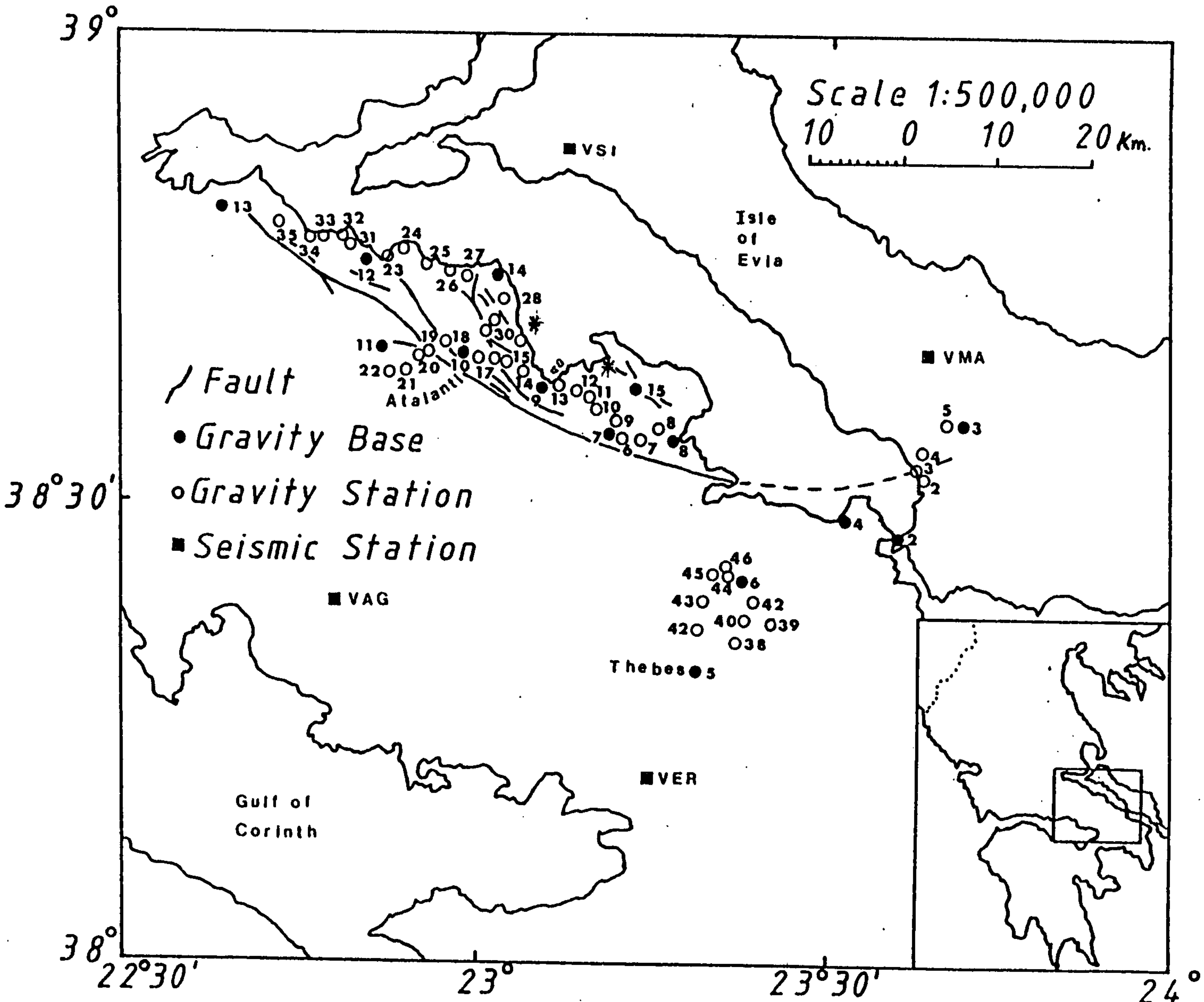



Figure 9.5 Station location map. * 1894 earthquake epicentres.

occurred in 1894. These earthquakes caused much loss of life (greater than 300, Karnik 1969) and several villages where submerged following subsidence. The small islands just North of Scala(s) were once mainland.

Following the Gulf of Corinth earthquakes several rough hewn stone buildings collapsed during shocks centred around the hamlet of Ψπατον. This is slightly south of the Atalanti Fault but led to fears it may be reactivated. The 1894 shocks were the last major events and the elapsed time of 89 years exceed the return period (82 years, Makropolous, 1979 ) of a magnitude 6.5 event for this locality. Figure 9.6 is taken from Makropolous (1979), and illustrates the most probable annual maximum earthquake magnitude using the Extreme Value method (Gumbal, 1966), based on a catalogue of 1860 events. A peak is quite apparent in the Atalanti area.

## 9.3 The Atalanti Network

A Network of 68 stations , with a total of 370 observations of two La Coste and Romberg 'G' meters was established by the author and Dr. E. Lagios. These stations were first occupied in September 1981, (Table 9.1 lists collection dates), and have been remeasured during July 1982. The stations were observed using G-275 (Edinburgh University) and G-496 (Athens University) during

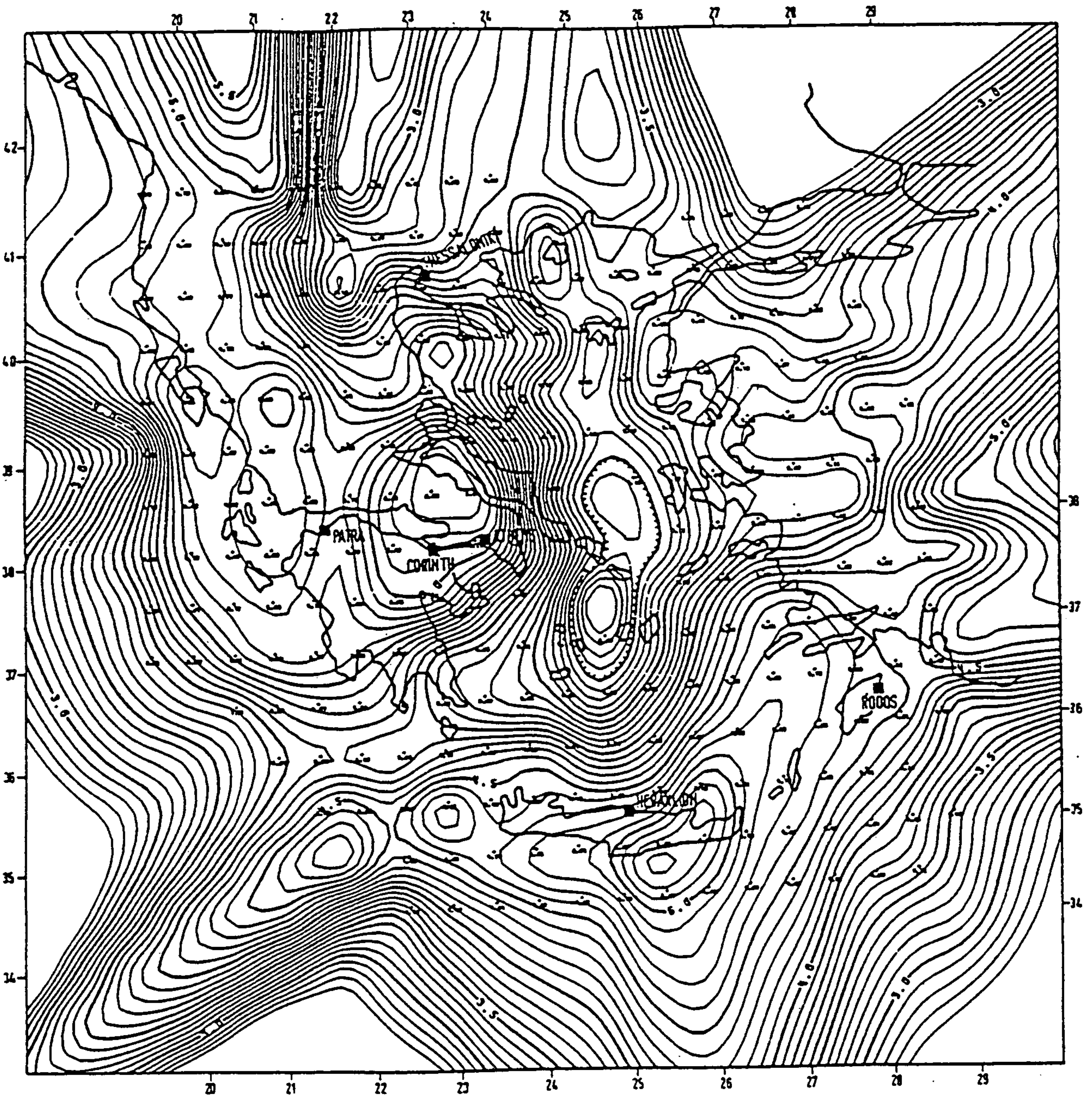



Fig 9.6 Most probable annual maximum earthquake magnitude (mode)
for Greece.

(from Makropolous, 1978)

# APPENDIX 7

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A micrograviometric network in East Central Greece -

an area of potential seismic hazard

| | B0 | B1 | B1A | B2 | B3 | B4 | B5 | B6 | B7 | B6 | B9 | B10 | B11 | B12 | B13 | B14 | B15 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 | S12 | S13 | S14 | S15 | S16 | S17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5-09 | 1,15 | 2,14 | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6-09 | 1 | | | 3,14 | 8,9 | | | | | | | | | | | | | 2,15 | 4,13 | 5,12 | 6,11 | 7,10 | | | | | | | | | | | | |
| 7-09 | | | | 1 | | 2 | 3 | | 5,14 | 9,10 | | | | | | | 4,15 | | | | | | 6,13 | 7,12 | 8,11 | | | | | | | | | |
| 8-09 | | | | | | | | | 2,25 | | 8,19 | 13,14 | | | | | 1,26 | | | | | | | | | 3,24 | 4,23 | 5,22 | 6,29 | 7,20 | 9,18 | 10,17 | 11,16 | 12,15 |
| 20-09 | 12 | 11 | | | 10 | 9 | | | 2,7 | 1,8 | 3,6 | 4,5 | | | | | | | | | | | | | | | | | | | | | | |
| 22-09 | 1 | 2 | | | | | | | | | | 1,16 | 9,10 | | | | | | | | | | | | | | | | | | | | | |
| 24-09 | | | | | | | | | | | | 11,12 | | 1,22 | | 7,16 | | | | | | | | | | | | | | | | | | |
| 25-09 | | | | | | | | | | | | | | 1,16 | 7,10 | | | | | | | | | | | | | | | | | | | |
| 26-09 | | | | | | | | | | | 4,11 | 6,9 | 7,8 | 2,13 | 1,14 | 3,12 | | | | | | | | | | | | | | | | | | |
| 27-09 | | | | | | | 2,11 | | 7 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 28-09 | | | | | | | 1,14 | | 7,8 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 01-10 | | 1,14 | 2,13 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

| | S18 | S19 | S20 | S21 | S22 | S23 | S24 | S25 | S26 | S27 | S28 | S29 | S30 | S31 | S32 | S33 | S34 | S35 | S36 | S37 | S38 | S39 | S40 | S41 | S42 | S43 | S44 | S45 | S46 | GNCL1 | GNCL2 | GNCL3 | G4 | G5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5-09 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 4,13 | 5,12 | 6,11 | 7,10 | 8,9 |
| 6-09 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7-09 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8-09 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 20-09 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 22-09 | 4,15 | 5,14 | 6,13 | 7,12 | 6,11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 24-09 | | | | | | 2,21 | 3,20 | 4,19 | 5,18 | 6,17 | 8,15 | 9,14 | 10,13 | | | | | | | | | | | | | | | | | | | | | |
| 25-09 | | | | | | | | | | | | | | 2,15 | 3,14 | 4,13 | 5,12 | 6,11 | 8,9 | | | | | | | | | | | | | | | |
| 26-09 | | | | | | | | | | | | | | | | | | | | 5,10 | | | | | | | | | | | | | | |
| 27-09 | | | | | | | | | | | | | | | | | | | | | 3,10 | 4,9 | 5,8 | 6,7 | | | | | | | | | | |
| 28-09 | | | | | | | | | | | | | | | | | | | | | | | | | 2,13 | 3,12 | 4,11 | 5,10 | 6,9 | | | | | |
| 01-10 | | | | | | | | | | | | | | | | | | | | | | | | | | - | | | | 3,12 | 4,11 | 5,10 | 6,9 | 7,8 |

Table 9.1 Atalanti network measurement timetable. Stations measured in double ladder sequence.

the 1981 field campaign and using G-496 and G-478 (National Technical University of Greece) during 1982. The stations will continue to be occupied annually or more frequently depending on seismic activity.

The station locations are shown on Figure 9.5 They are situated in the the area of faulting stretching from Larymna (B8) to Molos (B13), and on the island of Evia where the main Atalanti fault terminates. A group of ten stations are located a few kilometres North of Thibes where the tremors mentioned in section 9.2 were felt. Few stations exist West of the main fault because of logistic difficulties; here the terrain is rugged and only one minor road to Zelion (B11) traversed the fault line. (Fault location derived from Philipson(1930) and Mercier(1977)).

The measurements were made in a ladder sequence with base stations (marked '●' in figure 9.5) occupied on more than one ladder circuit and also measured on a seperate base station only circuit. Car transport was used throughout with G-275 resting on the operator's lap in the rear passenger accomodation and G-496 secured with a safety belt in the front passenger seat. Station positions can be relocated from a large masonry pin and a circle of red paint, together with photographs. The height and latitude were taken from 1:50,000 maps supplied by the Hellenic Military Geographic Service. The resurvey of 1982 failed to locate station 'S7' and only station 'B14' had been destroyed.

In addition to the stations located in the study area measurements were taken on the Greek National Calibration Line before and after the field campaign. The calibration line consists of five stations ascending Mount Parnis , near Athens. This calibration line overlaps only part of the gravity range of the network. It serves to demonstrate possible variations in the scale factor before and after the field campaign and to relate different measuring epochs.

## 9.4 Data Analysis

The general procedure is similar to that outlined in section 5.3. Pressure and temperature were taken during the 1981 survey but not during the 1982 survey,(because of the lack of a suitable barometer). Therefore no pressure corrections were were applied but it should be noted that pressure systems in Greece during the summer months are extremely stable. The pressure difference upon return to a station during the 1981 survey was often less than one millibar.

The data were first corrected for earth tides using the harmonic expansion of Cartwright and Tayler (1971) as ammended by Cartwright and Edden (1973), using the computer progam PBAS (Appendix (4) ), with standard gravimmetric factors. The data were examined as separate daily sequences using the spline fitting program (NSPL) to construct daily drift curves, for each instrument. A typical set of curves with two nodes is shown in Figure 9.7. This daily analysis was performed to identify tares, misreadings and observation sequences with anomalous drift. In general the root mean square error of a daily linear fit was less than two microgals. A total of 370 readings were taken with each instrument during 1981 , but less than ten were excluded. In the case of G-275 one day, the first observation of the calibration line, exhibited a very high drift rate caused by battery failure during the ladder sequence. In the case of the 1982 readings the observations using G-496 were similar to the previous year but those observations taken with G-478 were of very poor quality. This instrument had presented difficulties in the field with the beam sticking firmly in the mid position. The readings of this instrument were rejected and the data for 1982 consists solely of that collected using G-496.

In addition to an appraisal of the daily drift characteristics the splining program was used to obtain graphs of the complete data set as shown in figure 9.8 . Low order spline solutions were very similar to those obtained using the multi-linear technique but suffered from instablity with decreasing nodal intervals.

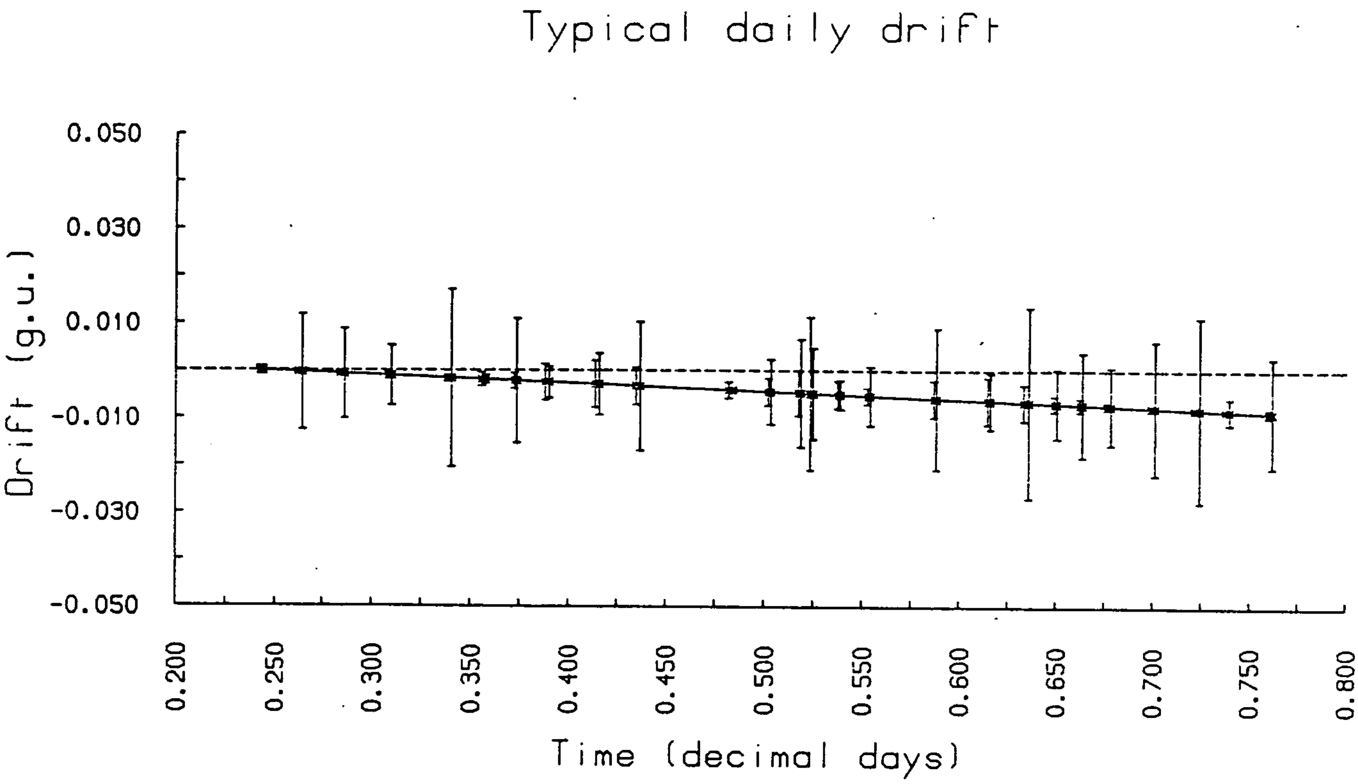



Figure 9.7 Typical double ladder sequence drift.

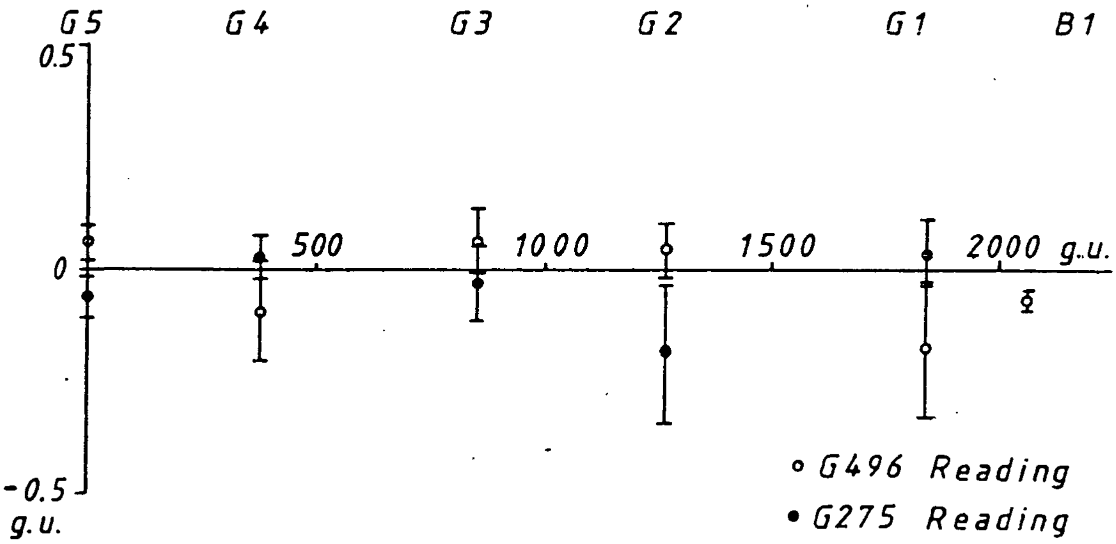



Figure 9.9 Difference between calibration line observations before and after field campaign.

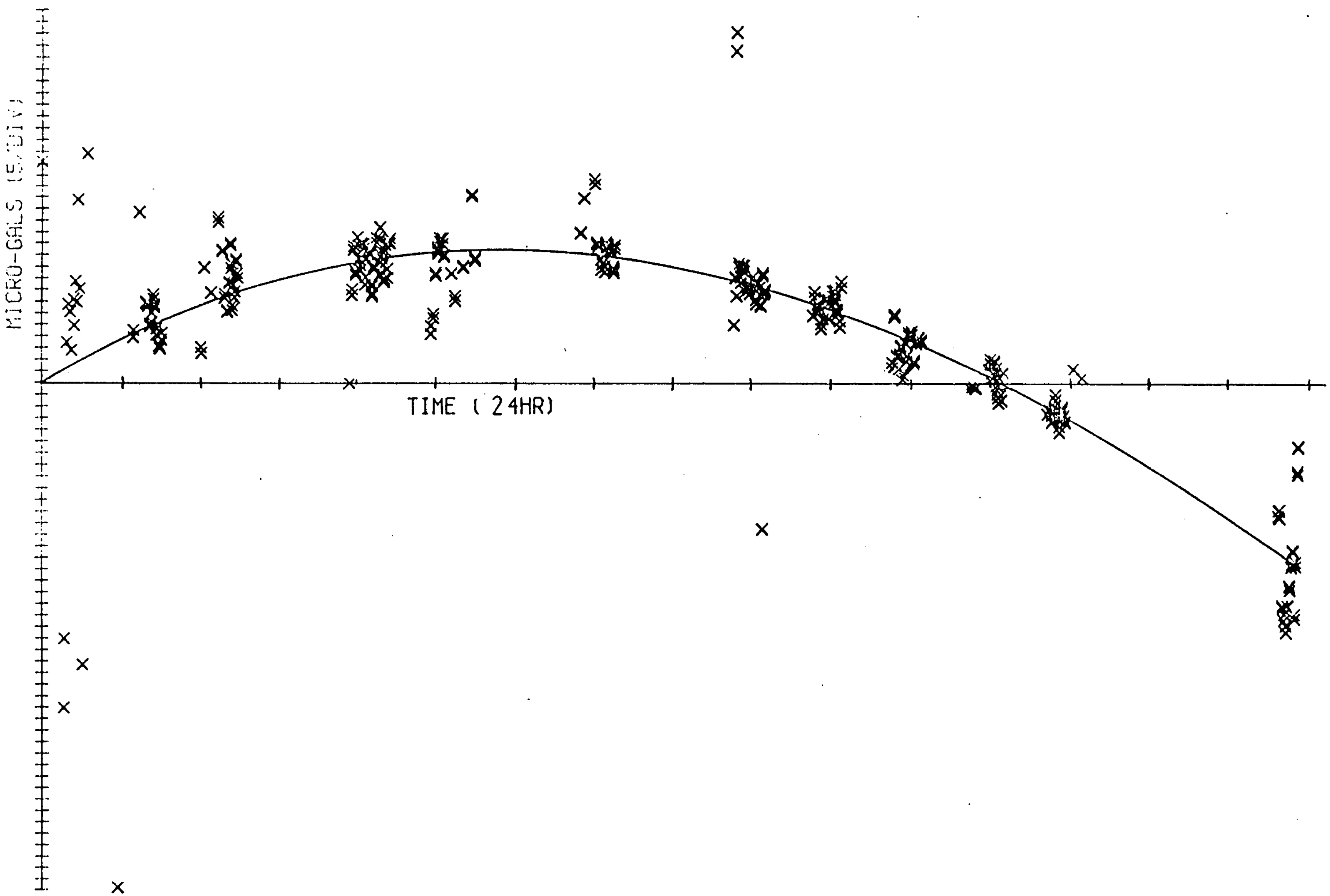



Figure 9.8 Complete Atalanti observation sequence (instrument - G275,1981) . Unconstrained 2 node cubic spline fit.

The network adjustment program was now applied to the culled data sets in order to obtain a comparison of the 1981 and 1982 data. More than half the total observations are repeat readings at a base station (i.e. stations occupied on more than one day) and every third day includes a remeasurement of base stations only. These repeat measurements control the long term drift and strengthen the network adjustment.

## 9.5 Data Results

The difference between the calibration line observation before and after a fieldwork perion of ten days is shown in figure 9.9. The gravity values are obtained from a straight line fit to each days' observations. The residuals have a standard deviation of nine microgals and do not appear to exhibit any systematic trend. The instruments' calibration has remained stable throughout the fieldwork period and a constant calibration factor adopted. The manufacturer's calibration tables were used since there are few well observed gravity stations in Greece with which to observe the stated scale factors. (The established values on the calibration line have yet to be released by the military authorities). The values derived from the combined 1981 adjustment solution are shown in Table 9.2. A histogram of the adjustment residuals compared with the

TABLE 9.2
Network adjustment values for 1981, combined instrument data set (G275 and G496)
Gravity values are with respect to station GNCL5 (Mount Parnis summit).

NETWORK ADJUSTMENT USING MULTILINEAR DRIFT

| BASE | NO. | GRAVITY | R.M.S. | NUMBER OF OBSERVATIONS |
|---|---|---|---|---|
| B0 | 1 | 2217.7047 | 0.0948 | 9 |
| B1 | 2 | 2027.1463 | 0.0479 | 12 |
| B1A | 3 | 2025.8122 | 0.0984 | 5 |
| B2 | 4 | 2506.1729 | 0.1180 | 6 |
| B3 | 5 | 2462.7353 | 0.0742 | 6 |
| B4 | 6 | 2443.0636 | 0.0659 | 6 |
| B5 | 7 | 1884.7906 | 0.0987 | 12 |
| B6 | 8 | 2129.8871 | 0.0849 | 4 |
| B7 | 9 | 2030.2629 | 0.1418 | 14 |
| B8 | 10 | 2659.0361 | 0.0864 | 8 |
| B9 | 11 | 2592.0611 | 0.0961 | 12 |
| B10 | 12 | 2383.1582 | 0.0797 | 20 |
| B11 | 13 | 1405.9868 | 0.0959 | 9 |
| B12 | 14 | 2249.9390 | 0.0947 | 12 |
| B13 | 15 | 2057.3322 | 0.0390 | 8 |
| B14 | 16 | 2441.3197 | 0.0592 | 8 |
| B15 | 17 | 2158.4494 | 0.2683 | 8 |
| GNCL1 | 18 | 1819.4743 | 0.1398 | 6 |
| GNCL2 | 19 | 1249.4719 | 0.1530 | 6 |
| GNCL3 | 20 | 846.1349 | 0.1132 | 6 |
| GNCL4 | 21 | 379.1207 | 0.1187 | 6 |
| GNCL5 | 22 | 0.0000 | 0.1165 | 6 |
| S1 | 23 | 1536.7090 | 0.1148 | 2 |
| S2 | 24 | 2462.1675 | 0.0114 | 4 |
| S3 | 25 | 2532.4780 | 0.0268 | 4 |
| S4 | 26 | 2529.3812 | 0.0741 | 4 |
| S5 | 27 | 2542.7419 | 0.0357 | 4 |
| S6 | 28 | 2164.5282 | 0.0343 | 4 |
| S7 | 29 | 2482.2106 | 0.0735 | 4 |
| S8 | 30 | 2508.9265 | 0.0474 | 4 |
| S9 | 31 | 2129.4279 | 0.1112 | 4 |
| S10 | 32 | 2110.1665 | 0.0850 | 4 |
| S11 | 33 | 2428.2421 | 0.0605 | 4 |
| S12 | 34 | 2558.1029 | 0.0313 | 4 |
| S13 | 35 | 2546.4565 | 0.0669 | 4 |
| S14 | 36 | 2554.5499 | 0.0838 | 4 |
| S15 | 37 | 2530.5140 | 0.0882 | 4 |
| S16 | 38 | 2464.7316 | 0.0343 | 4 |
| S17 | 39 | 2450.0753 | 0.0596 | 4 |
| S18 | 40 | 2221.5581 | 0.0435 | 4 |
| S19 | 41 | 2044.1075 | 0.0506 | 4 |
| S20 | 42 | 1555.5728 | 0.0624 | 4 |
| S21 | 43 | 1901.3959 | 0.1052 | 4 |
| S22 | 44 | 1709.4675 | 0.0770 | 4 |
| S23 | 45 | 2285.9367 | 0.0882 | 4 |
| S24 | 46 | 2283.7400 | 0.0579 | 4 |
| S25 | 47 | 2386.0833 | 0.0604 | 2 |
| S26 | 48 | 2411.5037 | 0.0794 | 4 |
| S27 | 49 | 2448.3446 | 0.0612 | 4 |
| S28 | 50 | 2483.0587 | 0.0860 | 4 |
| S29 | 51 | 2503.7961 | 0.0328 | 4 |
| S30 | 52 | 2479.4364 | 0.0537 | 5 |
| S31 | 53 | 2258.3677 | 0.0941 | 4 |
| S32 | 54 | 2210.5666 | 0.0613 | 4 |
| S33 | 55 | 2228.5183 | 0.0057 | 4 |
| S34 | 56 | 2233.4579 | 0.0615 | 4 |
| S35 | 57 | 2032.6949 | 0.0795 | 4 |
| S36 | 58 | 1909.0742 | 0.1164 | 4 |
| S37 | 59 | 2638.6121 | 0.1347 | 4 |
| S38 | 60 | 2002.1738 | 0.0716 | 4 |
| S39 | 61 | 1598.6606 | 0.0270 | 4 |
| S40 | 62 | 2116.9104 | 0.0913 | 4 |
| S41 | 63 | 1534.3864 | 0.0501 | 4 |
| S42 | 64 | 2025.1805 | 0.0686 | 4 |
| S43 | 65 | 2143.6459 | 0.0190 | 4 |
| S44 | 66 | 2192.9777 | 0.0075 | 4 |
| S45 | 67 | 2220.8270 | 0.0379 | 4 |
| S46 | 68 | 2176.5633 | 0.0579 | 4 |

HISTOGRAM 1

Standard Deviation of best fitting NormalDistribution 0.083 g.u.

Number of Degrees of Freedom 9

Chi squared is 5.01977

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NORMAL | 0 | 0 | 0 | 0 | 2 | 6 | 16 | 34 | 55 | 70 | 70 | 55 | 34 | 16 | 6 | 2 | 0 | 0 | 0 | 0 |
| FREQUENCY | 0 | 0 | 0 | 1 | 2 | 5 | 20 | 29 | 47 | 74 | 80 | 53 | 30 | 15 | 6 | 3 | 0 | 3 | 0 | 0 |

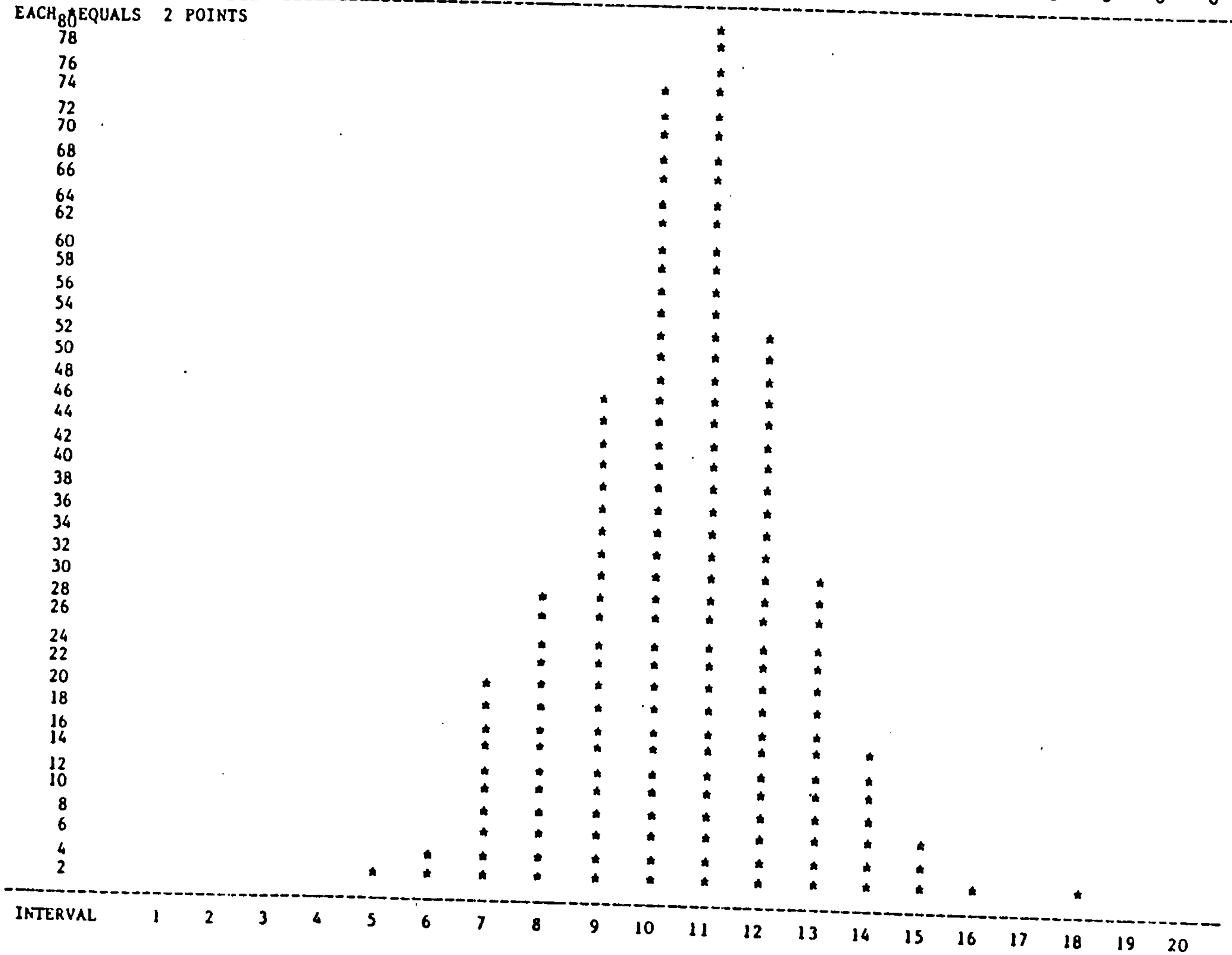



Figure 9.10 Histogram of residuals ; least squares network adjustment , 1981

best fitting normal curve is shown in figure 9.10 . This yields a standard deviation of 8.3 mcrogals and the chi-squared test ( $P(X_9^2<5.02) = 0.84$) indicates that the residuals are normally distributed . Similarly the 1982 adjustment given in Table 9.3 and figure 9.11 yields a standard deviation of 7.7 microgals and a high probablity of normality ( $P(X_8^2<3.5) = 0.93$)

These two solution sets were differenced to assess if any change in gravity greater than the limits of accuracy had taken place. A graph of the differences, adjusted with zero change in the mean is shown in figure 9.12. Some individual measurements, with their associated error bars appear to exhibit a significant gravity change. However analysis of the total data suite reveals that these are normally distributed random fluctuations with the anticipated standard deviation for the differenced data set. A histogram of the difference distribution (Figure 9.13) indicates a high probabilty of normality and $P(X_4^2,0.21) =$ 0.97. The data set has a standard deviation of 11 microgals. This figure is in agreement with the combination of standard deviations of the 1981 and 1982 adjustment solutions, $(8.3^2 + 7.7^2)^{1/2} = 11.3$ microgals.

Therefore the residuals of the differenced adjustment solutions are strongly consisted with the hypothesis of no change in gravity over the observation period , within the limits of accuracy of the instruments. Should the

TABLE 9.3
Network adjustment values for 1982 (one instrument, G496)
Values are with respect to station GNCL5 (Mt. Parnis summit)

NETWORK ADJUSTMENT USING MULTILINEAR DRIFT

| BASE | NO. | GRAVITY | R.M.S. | NUMBER OF OBSERVATIONS |
|---|---|---|---|---|
| B0A | 1 | 1783.1309 | 0.1872 | 13 |
| B2 | 2 | 2508.1494 | 0.0780 | 5 |
| B3 | 3 | 2462.7348 | 0.0248 | 2 |
| B4 | 4 | 2443.1700 | 0.0019 | 2 |
| B5 | 5 | 1884.8924 | 0.1034 | 6 |
| B6 | 6 | 2189.8727 | 0.0644 | 4 |
| B7 | 7 | 2030.3029 | 0.1098 | 11 |
| B8 | 8 | 2659.2562 | 0.0555 | 4 |
| B9 | 9 | 2592.1728 | 0.1153 | 6 |
| B10 | 10 | 2383.2155 | 0.1009 | 13 |
| B11 | 11 | 1405.9323 | 0.0361 | 3 |
| B12 | 12 | 2250.0188 | 0.0675 | 9 |
| B13 | 13 | 2057.6007 | 0.0688 | 5 |
| B14 | 14 | 2445.0141 | 0.0394 | 4 |
| B15 | 15 | 2158.5636 | 0.0000 | 1 |
| GNCL2 | 16 | 1249.4116 | 0.0371 | 2 |
| GNCL3 | 17 | 846.0662 | 0.0397 | 2 |
| GNCL4 | 18 | 378.9722 | 0.0402 | 2 |
| GNCL5 | 19 | 0.0000 | 0.0417 | 2 |
| S2 | 20 | 2462.1121 | 0.1338 | 2 |
| S3 | 21 | 2532.2922 | 0.0775 | 2 |
| S4 | 22 | 2529.4584 | 0.0172 | 2 |
| S5 | 23 | 2542.7302 | 0.0440 | 2 |
| S6 | 24 | 2164.6837 | 0.0455 | 2 |
| S7 | 25 | 2482.3571 | 0.0206 | 2 |
| S8 | 26 | 2509.0710 | 0.0486 | 2 |
| S9 | 27 | 2129.2906 | 0.0129 | 2 |
| S10 | 28 | 2110.0377 | 0.0122 | 2 |
| S11 | 29 | 2428.2570 | 0.0226 | 2 |
| S12 | 30 | 2558.1355 | 0.0175 | 2 |
| S13 | 31 | 2546.6121 | 0.1116 | 2 |
| S14 | 32 | 2554.8588 | 0.1283 | 2 |
| S15 | 33 | 2530.7908 | 0.0247 | 2 |
| S16 | 34 | 2464.9904 | 0.1057 | 2 |
| S17 | 35 | 2450.2973 | 0.0566 | 2 |
| S18 | 36 | 2221.5656 | 0.1317 | 2 |
| S19 | 37 | 2044.0626 | 0.1115 | 2 |
| S20 | 38 | 1955.6690 | 0.0555 | 2 |
| S21 | 39 | 1501.5440 | 0.0583 | 2 |
| S22 | 40 | 1709.4970 | 0.0191 | 2 |
| S23 | 41 | 2286.0340 | 0.0161 | 2 |
| S24 | 42 | 2283.8371 | 0.0136 | 2 |
| S25 | 43 | 2386.1138 | 0.0260 | 2 |
| S26 | 44 | 2411.6521 | 0.0111 | 2 |
| S27 | 45 | 2448.4386 | 0.0380 | 2 |
| S28 | 46 | 2483.0646 | 0.0450 | 2 |
| S29 | 47 | 2503.7081 | 0.0410 | 2 |
| S30 | 48 | 2479.3901 | 0.0385 | 2 |
| S31 | 49 | 2258.4051 | 0.0181 | 2 |
| S32 | 50 | 2210.6348 | 0.0332 | 2 |
| S33 | 51 | 2228.6292 | 0.0193 | 2 |
| S34 | 52 | 2233.4803 | 0.0130 | 2 |
| S35 | 53 | 2032.8591 | 0.0253 | 2 |
| S36 | 54 | 1509.2080 | 0.0654 | 2 |
| S37 | 55 | 2638.8019 | 0.0000 | 1 |
| S38 | 56 | 2002.0920 | 0.0417 | 2 |
| S39 | 57 | 1598.5929 | 0.0565 | 2 |
| S40 | 58 | 2116.7805 | 0.0767 | 2 |
| S41 | 59 | 1934.4465 | 0.0339 | 2 |
| S42 | 60 | 2025.2360 | 0.0662 | 2 |
| S43 | 61 | 2143.8366 | 0.0873 | 2 |
| S44 | 62 | 2192.9331 | 0.0313 | 2 |
| S45 | 63 | 2220.8516 | 0.0408 | 2 |
| S46 | 64 | 2176.5271 | 0.0128 | 2 |
| B1 | 65 | 2027.1961 | 0.0366 | 2 |
| B1A | 66 | 2025.7775 | 0.0081 | 2 |

Each class interval is half the estimated standard deviation of 0.0766
Result of Dagostinos test : D = 0.19673Y = -39.65202

TOTAL NUMBER OF OBS. = 193

HISTOGRAM 1

Standard Deviation of best fitting NormalDistribution 0.04
Chi squared is 3.49476

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NORMAL | 0 | 0 | 0 | 0 | 1 | 3 | 8 | 18 | 29 | 37 | 37 | 29 | 18 | 8 | 3 | 1 | 0 | 0 | 0 |
| FREQUENCY | 0 | 1 | 2 | 1 | 5 | 7 | 6 | 14 | 27 | 31 | 36 | 25 | 14 | 10 | 13 | 1 | 0 | 0 | 0 |

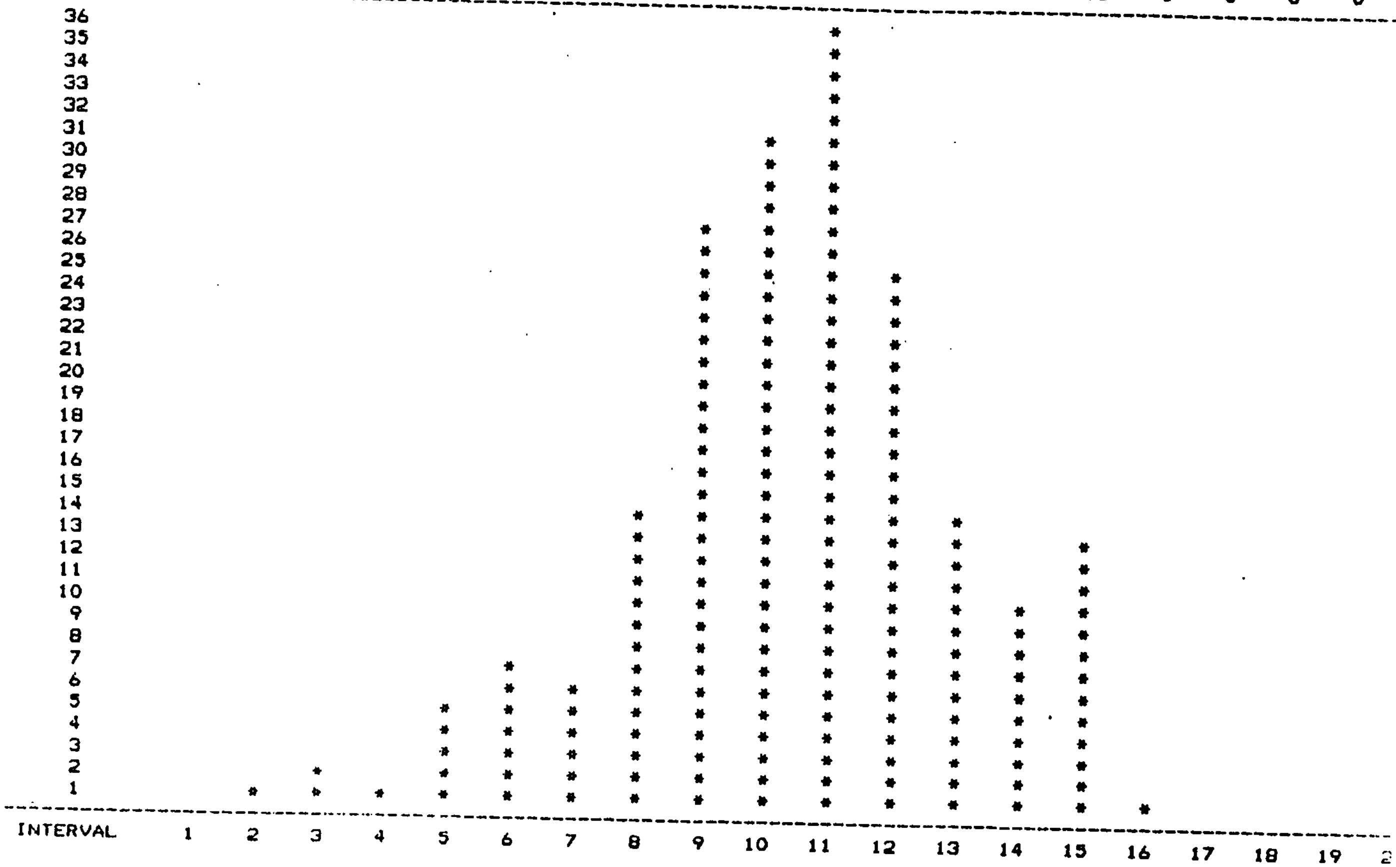



Figure 9.11 Histogram of residuals, least squares network adjustment, 1982

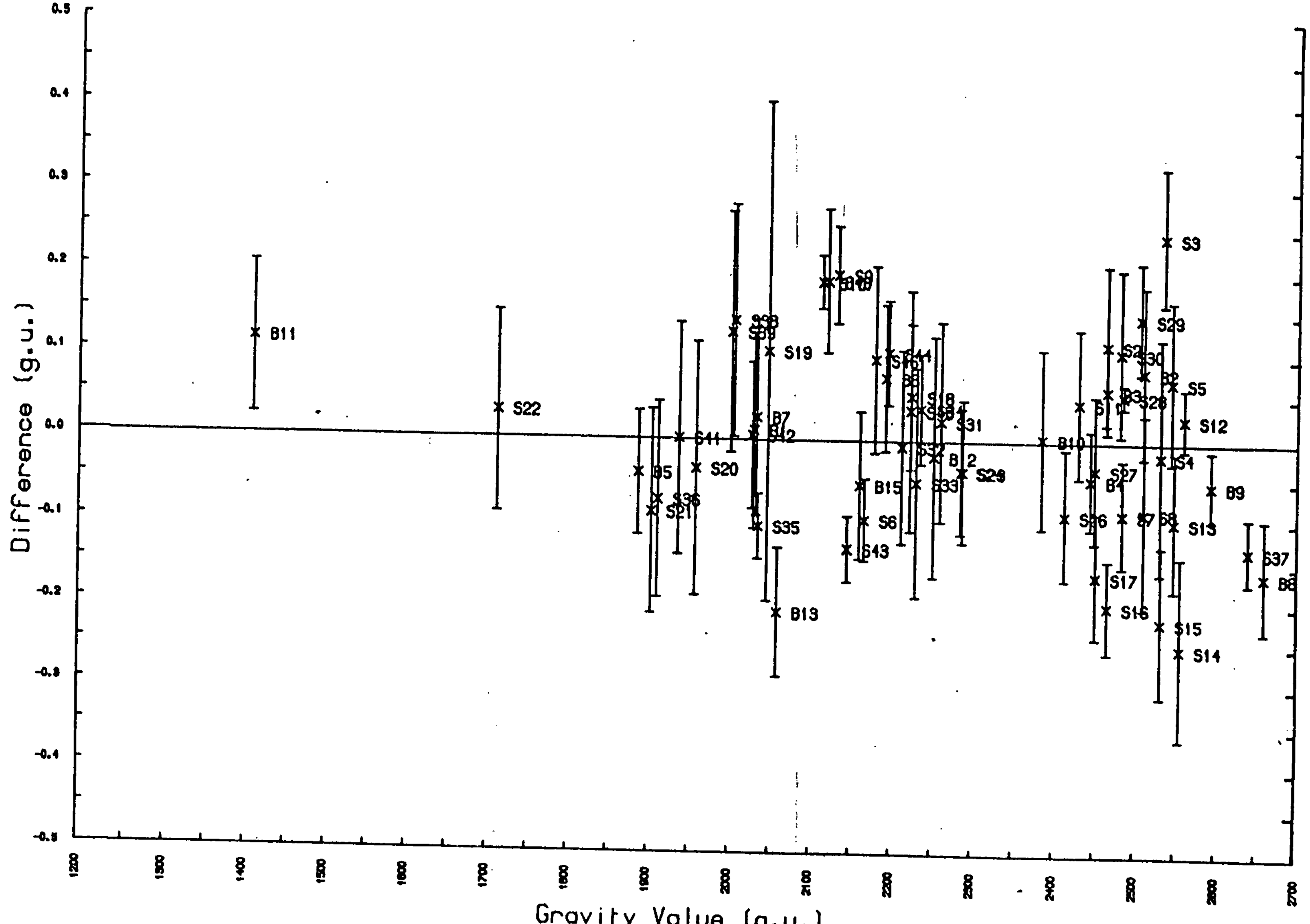



Figure 9.12  Observed gravity difference in the Atalanti region (1981 - 1982)

```
TOTAL NUMBER OF OBS. =  58
Standard Deviation   =  0.110 g.u.
Number of Degrees of Freedom    4
Chi squared is       0.23790
NORMAL       0   0   0   0   0   1   3   5   9  11  11   9   5   3   1   0   0   0   0   0
FREQUENCY    0   0   0   0   0   1   3   4   8  12  12   9   5   3   1   0   0   0   0   0
----------------------------------------------------------------------------------------------
   12
   11                                            *   *
   10                                            *   *
    9                                            *   *
    8                                        *   *   *   *
    7                                        *   *   *   *
    6                                        *   *   *   *
    5                                        *   *   *   *
    4                                        *   *   *   *
    3                                    *   *   *   *   *   *
    2                                *   *   *   *   *   *   *
    1                                *   *   *   *   *   *   *   *
                                 *   *   *   *   *   *   *   *   *   *
----------------------------------------------------------------------------------------------
INTERVAL     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
```

Figure 9.13 Histogram of gravity differences 1981-1982 difference distribution have been non normally distributed or possessed a higher standard deviation, there would be grounds for an immediate remeasurement of the network.

# CHAPTER TEN

# SUBSIDENCE MEASUREMENTS

## 10.1 Introduction

As previously discussed in Chapter Two, high precision gravity surveys have proved to be a useful technique in the detection of underground voids. A further application of the technique (with certain commercial possibilities ) is the detection of elevation changes caused by mining subsidence. This is presently carried out by conventional levelling which is costly and time consuming, particulary in the absence of thoroughfares.

Subsidence caused by underground coal workings is a common problem in Great Britain and is of two kinds:

(1) Old workings, where the subsidence is often sudden and unpredictable (2) Current workings, in which the subsidence is predictable both in time and space

Old workings may exist as voids or be infilled with uncompacted rubble. They often occur in urban areas where they present a considerable hazard to existing and planned buildings. Unfortunately locations are not well documented and often inaccurate, making a controlled survey impossible. One possible site was investigated without result and it was thought best to concentrate on current workings

Most coal seams in the United Kingdom are mined by panel working, which is suited to mechanised extraction. In this system the roof in the area of extraction is supported over the entire length of the working face by a continuous bank of hydraulic jacks. The jacks are moved forward immediately after the cutter has passed before them, allowing the goaf behind to collapse. In this way, total extraction is achieved and 90 per cent of the subsidence occurs within days (Orchard, 1964). A comprehensive study of the associated subsidence at many mines has resulted in graphical methods for the prediction of subsidence (Subsidence Engineers Handbook, National Coal Board 1975)

Fig (10.1) illustrates the standard notation for subsidence and slope. The amplitude (i.e. the vertical displacement) and shape of the subsidence profile are related to the width (w) and the depth(h) of the seam. The subsidence for a given depth of seam is found to attain a maximum when the ratio w/h is equal to 1.4 (Weir, 1969) , a situation termed 'critical' (see Fig.10.2). Figure (10.3) illustrates the relationship of subsidence to width and depth. Support by various methods of waste infill will alter the subsidence amplitude but these are

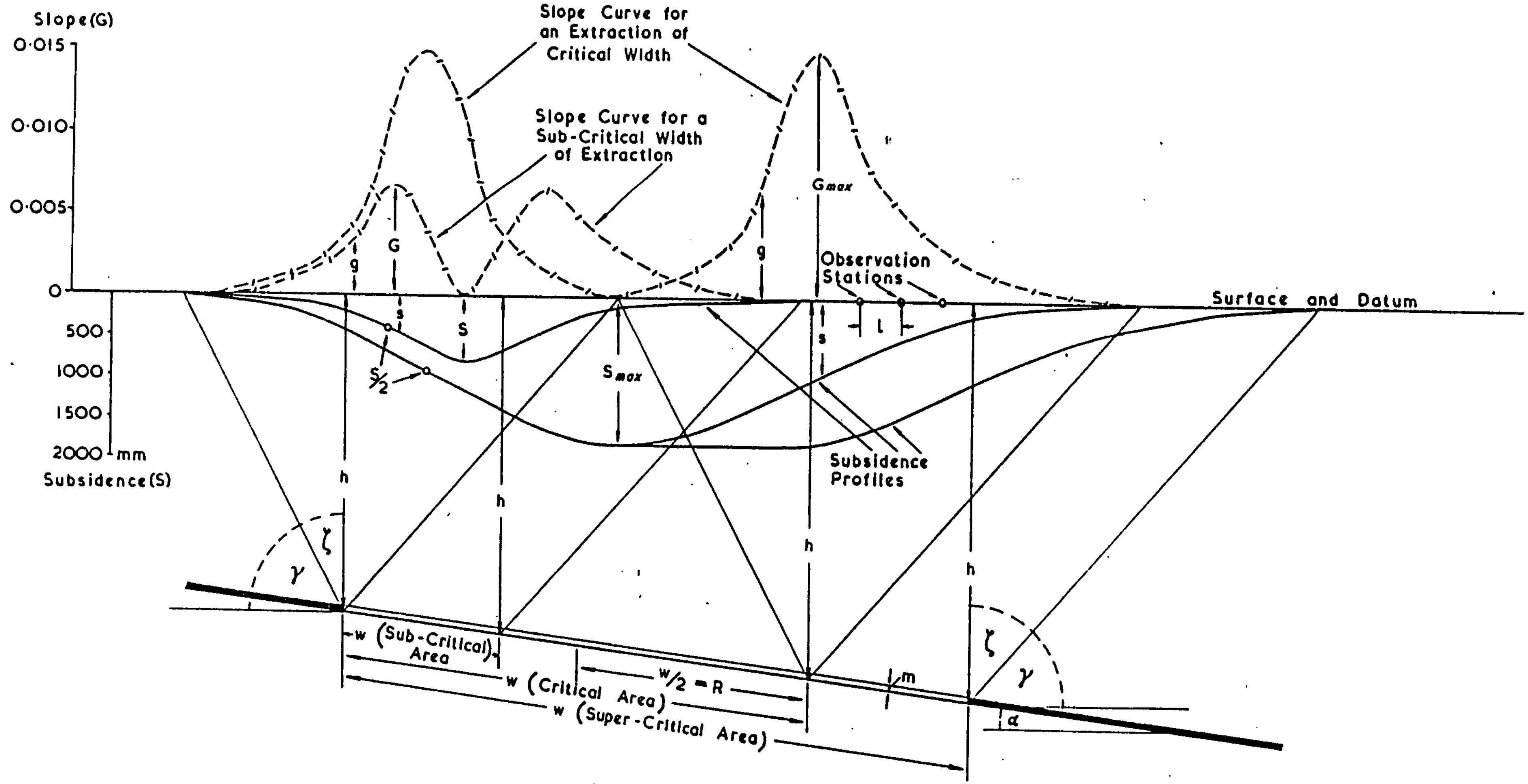



Figure 10.1 Typical section through workings, illustrating standard symbols for subsidence and slope.

(National Coal Board, 1975)

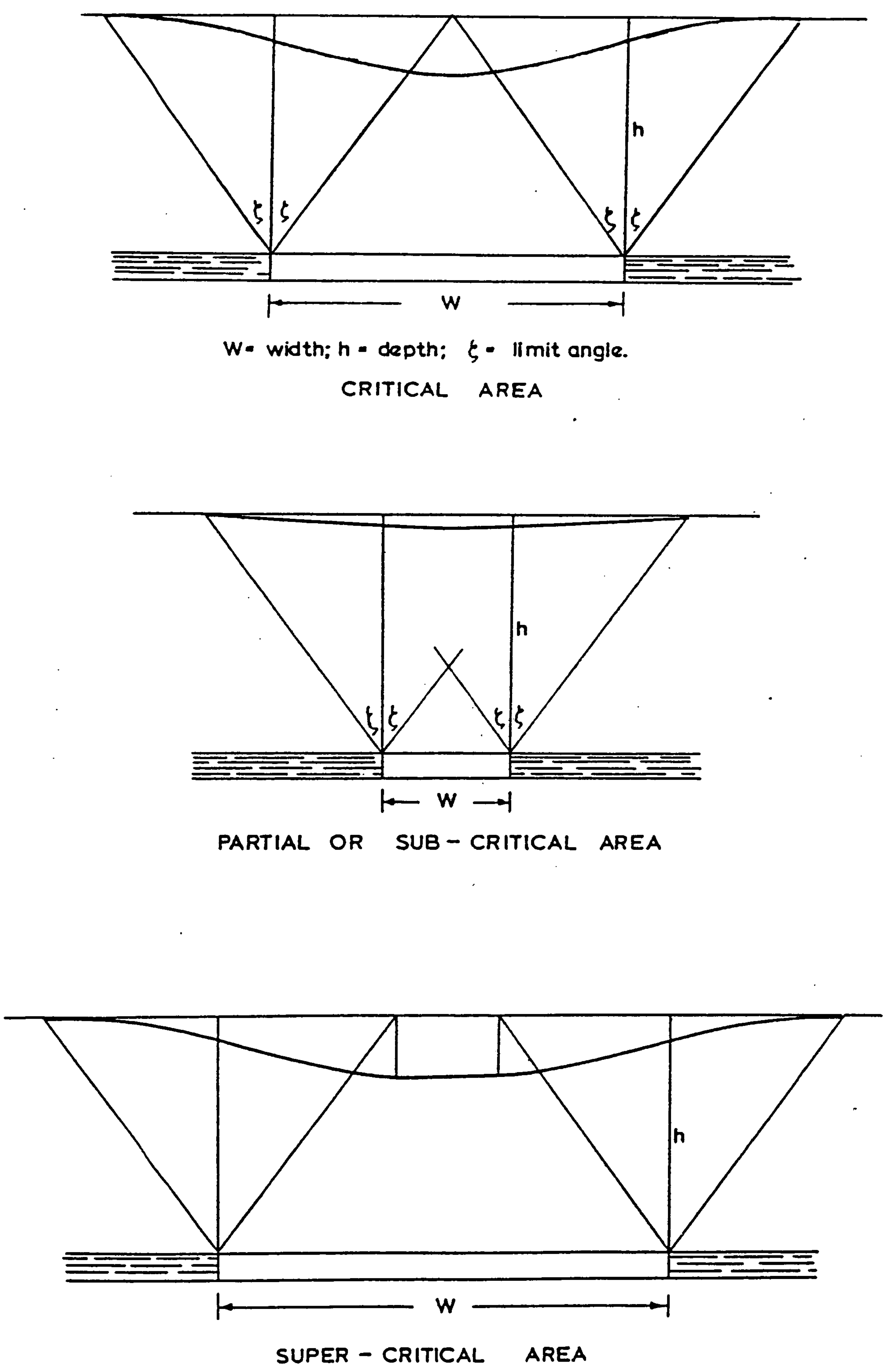



Figure 10.2 Subsidence profile with varying width.

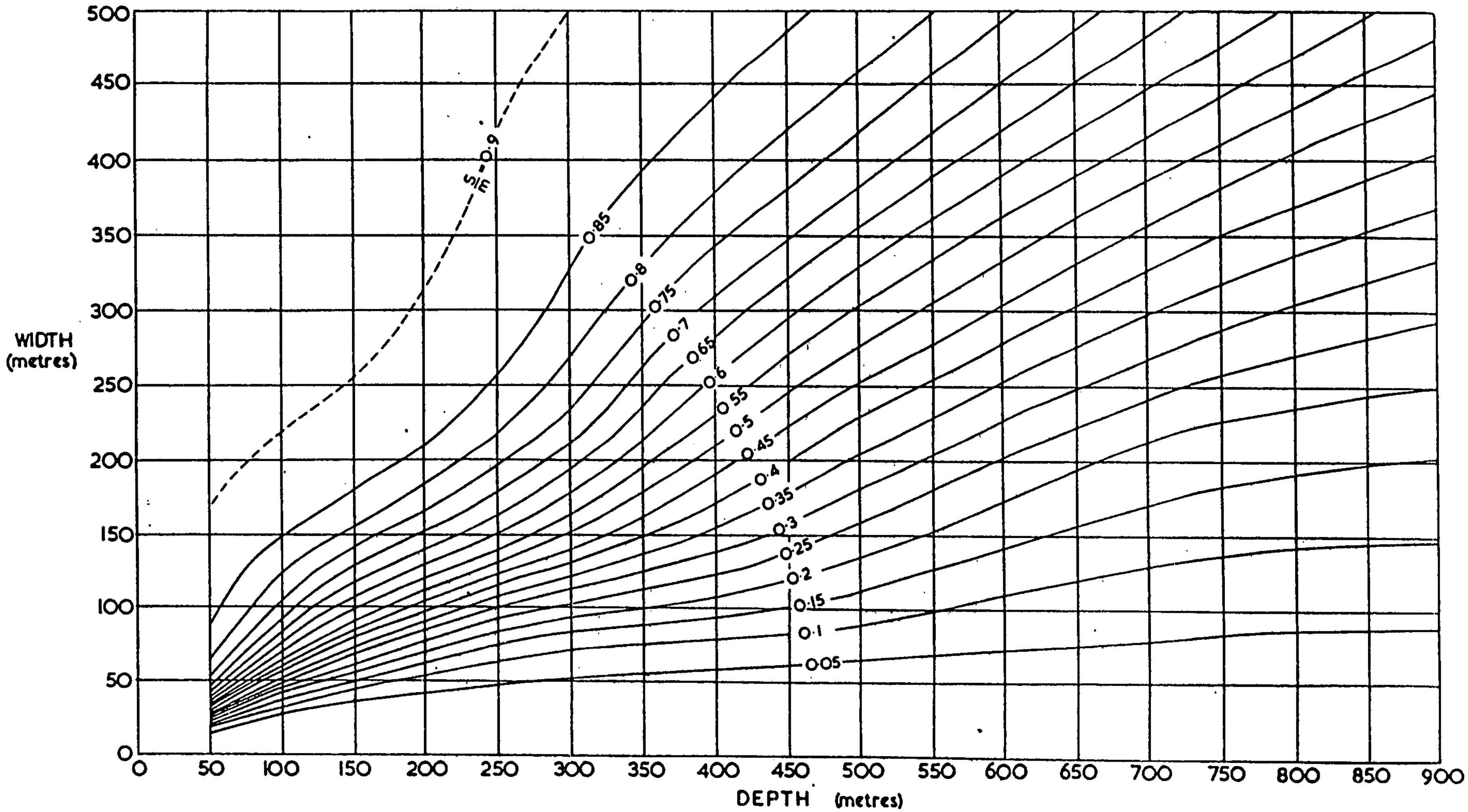



Figure 10.3 Relationship between subsidence and width and depth

expensive and only the most costly, pneumatic stowing, which can reduce subsidence by 50 per cent, has a marked effect.

## 10.2 Field area

For the purposes of this investigation it was desirable that the field area should satisfy the following conditions.

(1) Large possible subsidence to evaluate the relationship between height and gravity change with the maximimum resolution. (2) A road perpendicular to the direction of mining to ease levelling. (3) Within 100km. of Edinburgh as the site was to be visited repeatedly

A highly suitable site was selected near Saline, Fife after consultation with National Coal Board engineers (George Archibald, Robert Longmore, Green Park, Scottish Area Headquarters). Coal is being extracted,from the Solsgirth colliery, Fife at a depth of 107m.-122m. from the Upper Hirst Seam in the Upper Limestone Series of the Carboniferous. The seam is extracted in 'panels' about 200m. wide and 1.68m thick. These are shallow workings (the average depth of coal workings in Scotland is in excess of 400m.) and as a result the half width of the subsidence profile is comparatively narrow.

Figure (10.4) is a mine plan of the survey area together with some surface features. The contours show the height of the seam with reference to a datum 3048 metres ( the metric equivalent of 10,000 feet) below mean sea level. Measurements were made along the road which roughly traverses the panels.

## 10.3 Measurements

The stations marked on Figure (10.4) were levelled on four separate occasions and gravity measurements made on a total of fourteen occasions to examine the surface displacement caused by the extraction of units S27 and S29. The dates of the data acquistion are shown on Table (10.1). Each station was positioned to one side of the tarmacadammed road and located with a washer and a round headed masonry pin driven . into the surface. The pin was both the level station and the gravity site.

The first levelling sequence was completed using a Watts microptic level fitted with a parallel plate micrometer, measuring in a ladder sequence (Close, 1965). This method, though accurate was found time consuming and subsequent surveys were carried out with a Zeiss Ni02 automatic level, using forward looping.

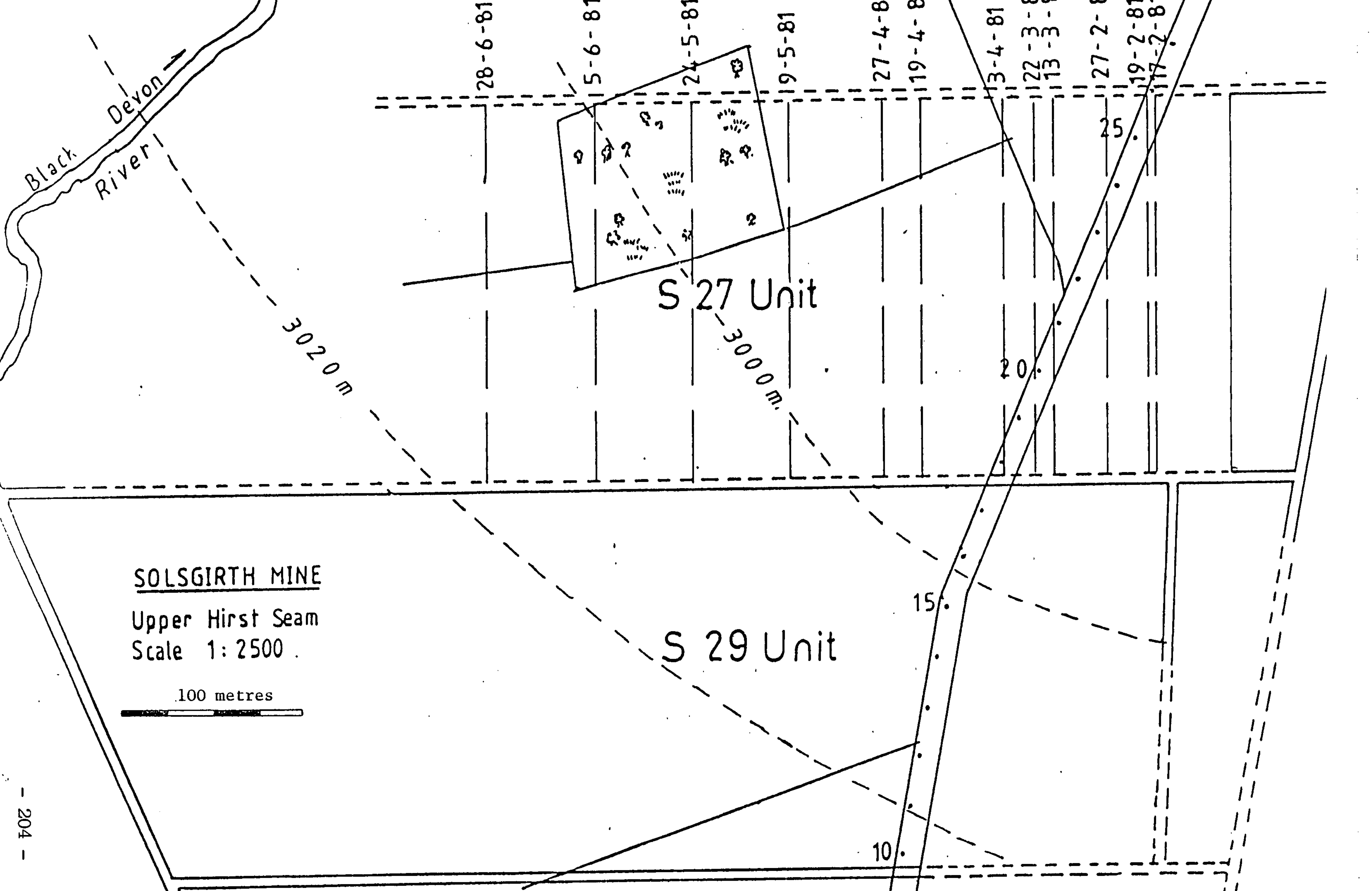



Figure 10.4 Mine plan of survey area with surface features superimposed. Dashed contours are seam base with respect to datum 10,000'(3070m.) beneath sea level.

| Data Acquisition - Solsgirth | | | |
|---|---|---|---|
| Date | Day No. | Survey Type and No. | |
| 10.02.81 | -07 | Levelling # 1 | Unit S27 |
| 17.02.81 | 00 | Gravimetric # 1 | |
| 19.02.81 | 02 | Gravimetric # 2 | |
| 27.02.81 | 10 | Gravimetric # 3 | |
| 13.03.81 | 24 | Gravimetric # 4 | |
| 22.03.81 | 33 | Gravimetric # 5 | |
| 03.04.81 | 45 | Gravimetric # 6 | |
| 19.04.81 | 61 | Gravimetric # 7 | |
| 27.04.81 | 69 | Gravimetric # 8 | |
| 09.05.81 | 81 | Gravimetric # 9 | |
| 24.05.81 | 94 | Gravimetric #10 | |
| 03.06.81 | 108 | Levelling # 2 | |
| 05.06.81 | 110 | Gravimetric #11 | |
| 28.06.81 | 133 | Gravimetric #12 | |
| 01.12.81 | 288 | Levelling # 3 | Unit S29 |
| 02.12.81 | 289 | Gravimetric #13 | |
| 27.04.82 | 438 | Levelling # 4 | |
| 28.04.82 | 439 | Gravimetric #14 | |

TABLE 10.1

Gravity observations were taken in a ladder sequence. The meter rested on the standard La Coste and Romberg concave dish with one drilled foot seated securely on the masonry pin. One levelling screw of the meter was kept at a constant height by a brass collar. The screw point was kept within a circle scribed on the dish surface and thus the maximum height variation was + 5 mm. and typically much less. Orientation was set by eye with a maximum variation of + $10^{\circ}$ .

Examination of Table (10.1) shows that gravity was measured at approximately two week intervals above unit S27 as coal was being extracted. Gravity measurements above unit S29 were made before and after subsidence. All measurements were taken with reference to a stable base approximately one kilometre from station 12; in the case of levelling this meant levelling that distance. The station spacing for unit S27 was 25m. but this was decreased to 12.5 m. for unit S29 because the predicted target area was better defined.

## 10.4 Field Results

The gravity and level changes are shown together on figure (10.5) for unit S27 and figure (10.6) for unit S29. Also shown is the predicted subsidence as determined from

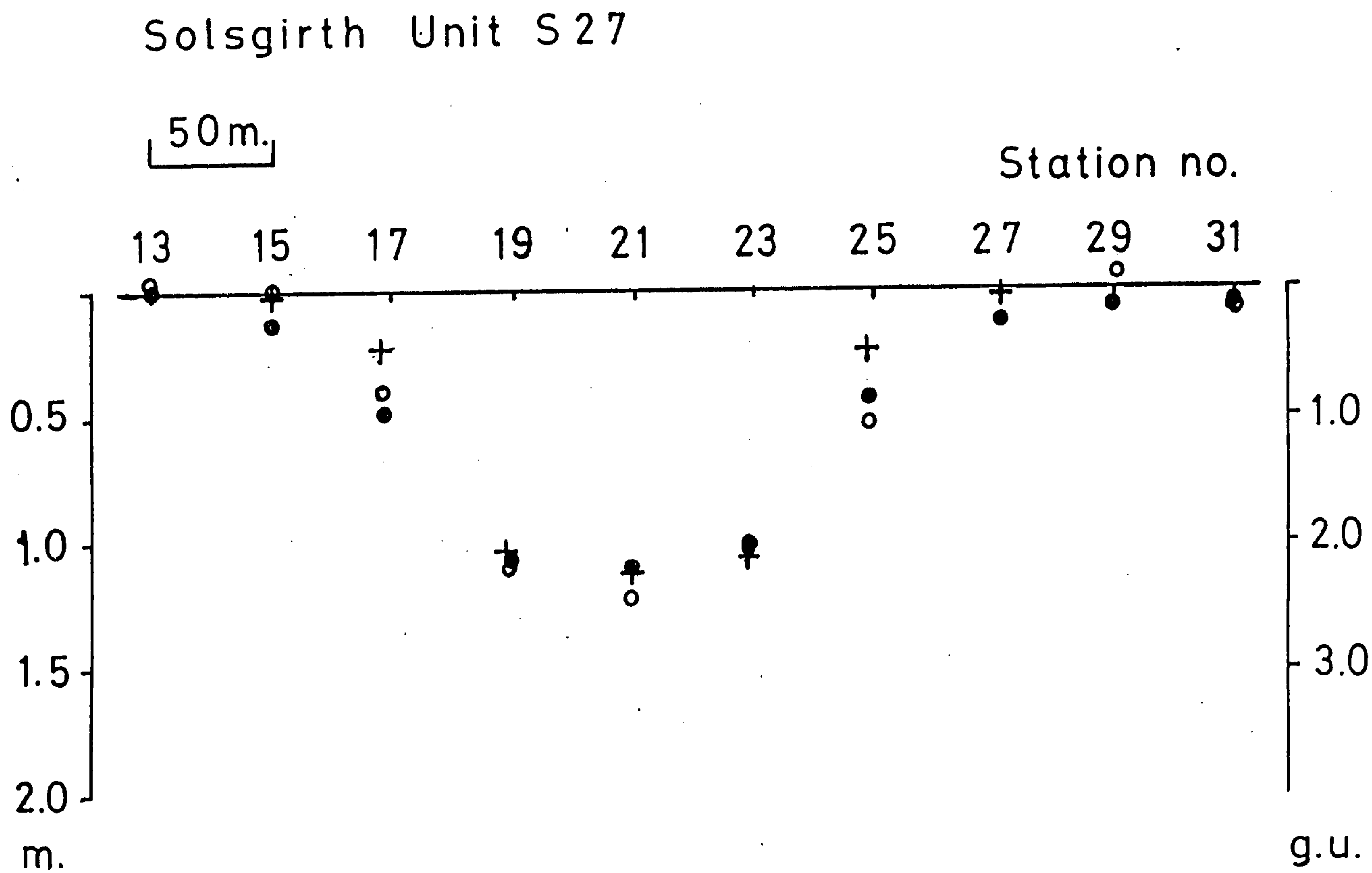



Figure 10.5 Gravity and level difference caused by extraction of unit S27 (see figure 10.7 and text for gravity-height relationship).

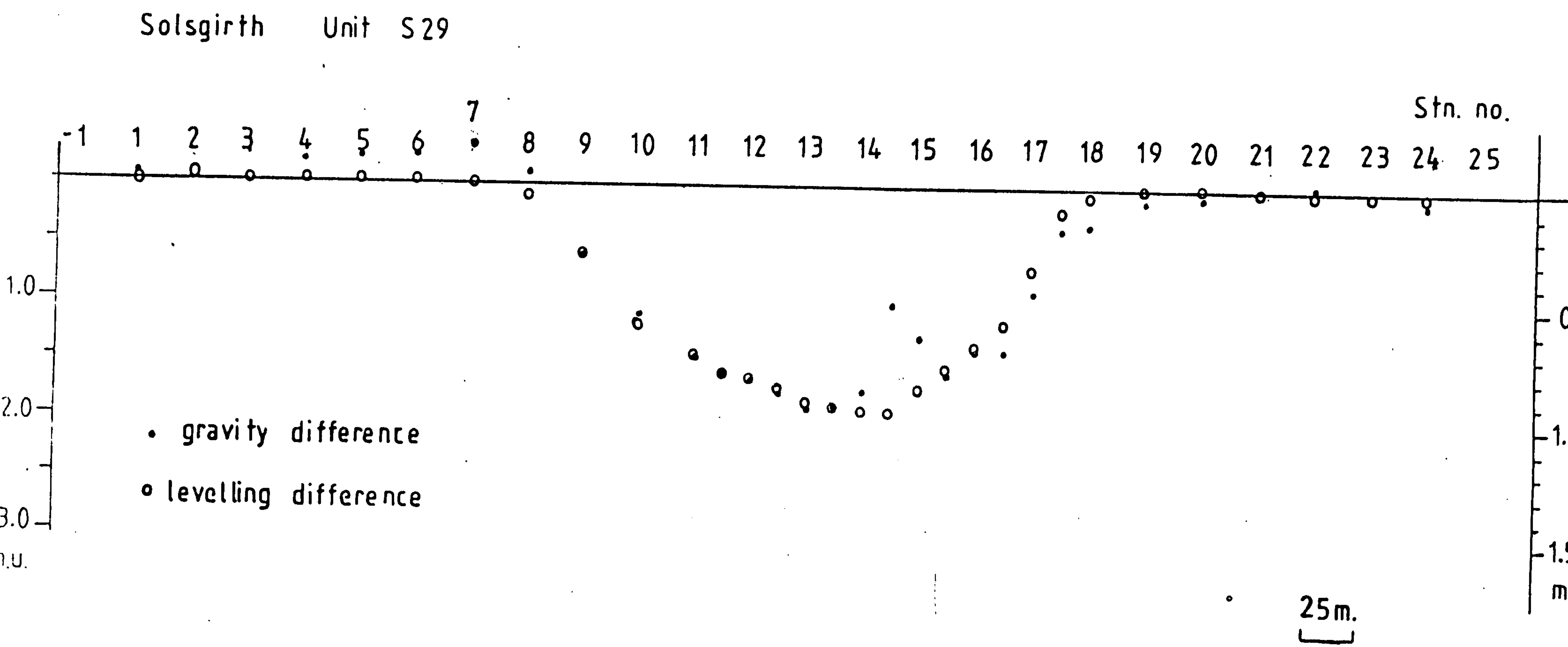



Figure 10.6 Gravity and level difference caused by the extraction of unit S29

the 'Subsidence Engineers Handbook' using the parameters shown. The predicted maximum subsidence (c.67 % of working height) is estimated on the basis of previously levelled subsidence profiles in this area (Robert Longmore, personal communication). It can be seen that the shape of the subsidence curve is in good agreement with the predicted profile . It can be seen that height and gravity are well related with the exception of a positive feature close to station 13 in the case of unit S29. A possible mechanism for this phenomenon is postulated later in this section.

The bedrock consists of cyclic sequences of sandstones, siltstones and mudstones of the Upper Limestone Series. Density measurements on comparable strata have been carried out in Ayrshire (McLean, 1965). McLean suggests a formation density of 2.54 gm/c.c. for the Limestone Series. A regression Bouger anomaly against height obtains an identical figure but with a large standard deviation ( 0.45 g.u.). A density of 2.54 gm/c.c. would imply a combined free air and Bouger gradient of 2.10 g.u. per metre. Figure (10.7) is a graph of gravity change versus height change and the best fitting straight line has a gradient of 2.05 g.u./m with a standard deviation of 0.16 g.u./m.; implying a formation density of 2.47gm./c.c.. In this analysis I have not considered the drift density which is possibly less than 2.00gm./c.c. and is of variable depth.

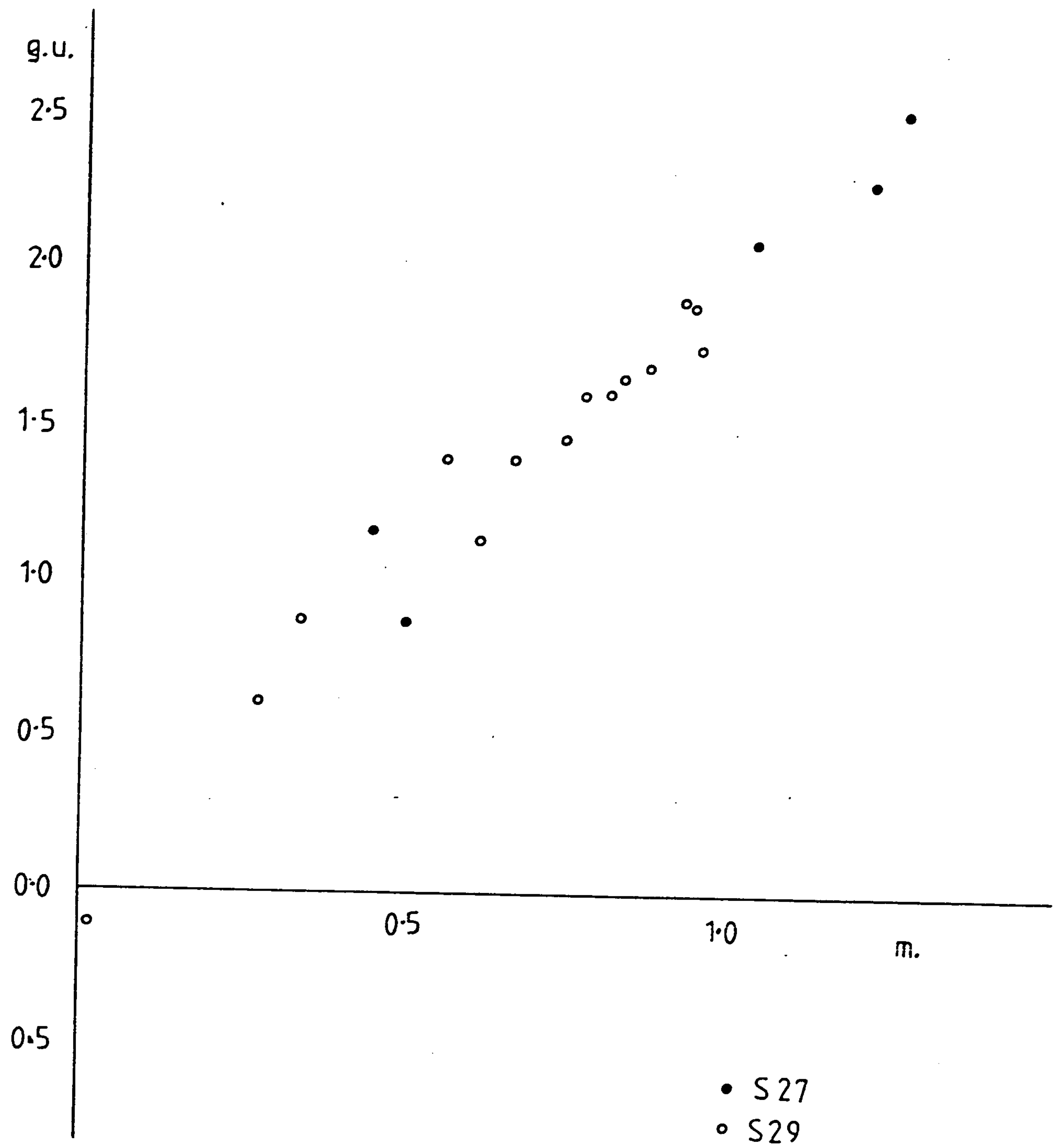



Figure (10.7)

Gravity change versus height change

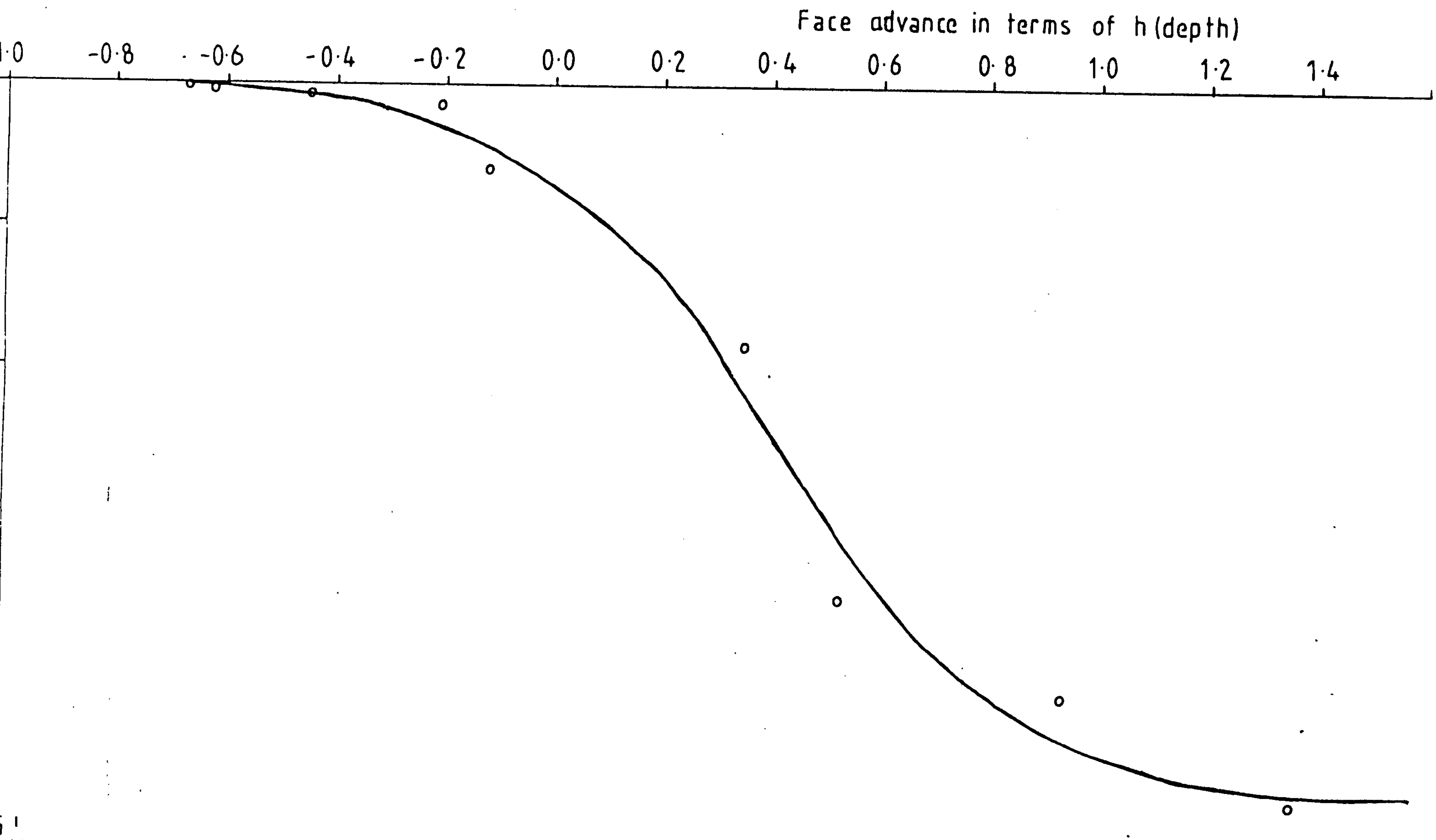
The temporal change of unit S27 was studied in detail by repeated gravity readings over a period of four months. Figure(10.8) illustrates the development of subsidence at a single surface point (station number 17) as unit S27 was extracted beneath it. All but residual subsidence (97.5%) should cease when the panel face has advanced 0.7 times the seam depth beyond the observation point (National Coal Board, 1975), in this case seventy seven metres. This factor is somewhat variable and in this instance active subsidence terminates at 1.1 times the seam depth but the curve shape is similar to the classic time development curve.

## 10.5 Model Studies

A theoretical gravity profile was calculated in which the seam extraction was numerically modelled in two dimensions following the method of Talwani ( Talwani,M et al., 1959). The two basic models before and after extracion are illustrated in figure (10.9). The coal density of 1.41 + 0.01 gm./c.c. is well determined from hand samples by the National Coal Board scientific section (personal communication via R. Longmore). A density contrast of 1.1 gm./c.c. was used in the computations. This is consistent with the previous discussion of bedrock density and gave the best fitting model.. The gravity change difference between the two models of figure (10.9) together with the

Figure 10.8

Subsidence development determined gravimetrically at station no. 17



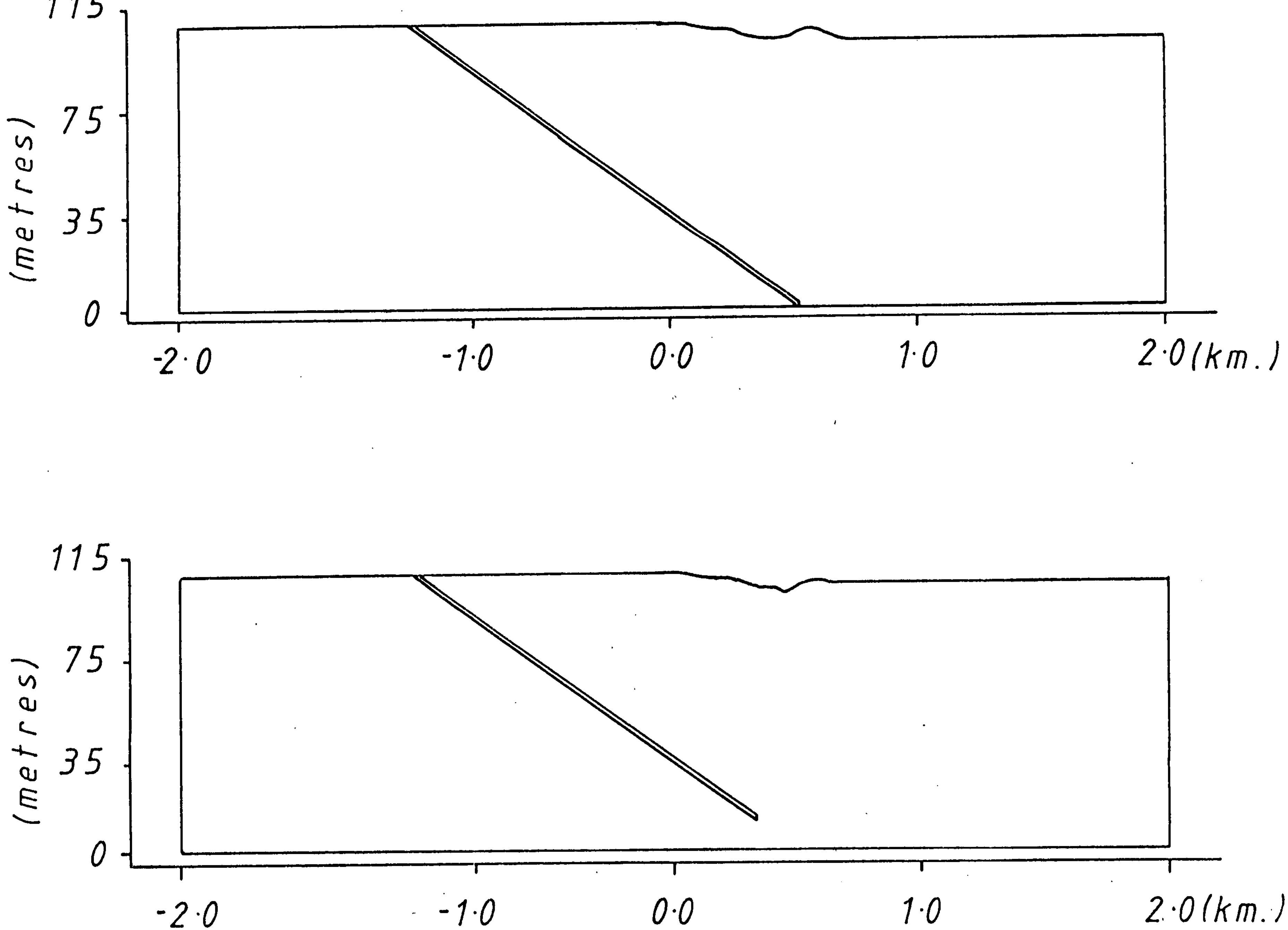



Figure 10.9 Model outline used in two dimensional gravity analysis of seam extraction. (Upper, before extraction; lower, after extraction).

observed profile are shown in figure (10.10). It is possible to estimate the contribution from the removal of the comparatively low density coal seam alone by adjustment of the second model surface.. This is illustrated in figure (10.11) and the effect can be seen to be assymetric with a maximum amplitude of 0.40 g.u.. If this effect is added to the gravity profile the corrected' gravity height relationship is 2.17 g.u./m with an improved standard devition of 0.097 g.u./m..

A possible source for the secondary peak in the observed gravity profile of S27 (see figure 10.5) is to be found upon examination the geological sheet for the area ; a simplified diagram is shown in figure (10.12). Detailed examination of the Institute of Geological Sciences sheet number 39E and 'Economic Geology of the Fife Coalfield - Area 1' (Geological Survey Memoirs, Scotland, H.M.S.O.,1930) indicate that the Number 1 Plean Limestone outcrops beneath this point. It is proposed that this local inhomogeneity causes assymetric slumping of the overburden which can be seen in the level data. Furthermore the higher density limestone may remain protuding as a unit rather than gently subsiding with the adjacent strata possibly causing a small offset fault due to localised stress concentration. Further evidence for this argument is provided by the uncharacteristing cracking of the tarmac road surface directly above this location but not visible elsewhere.

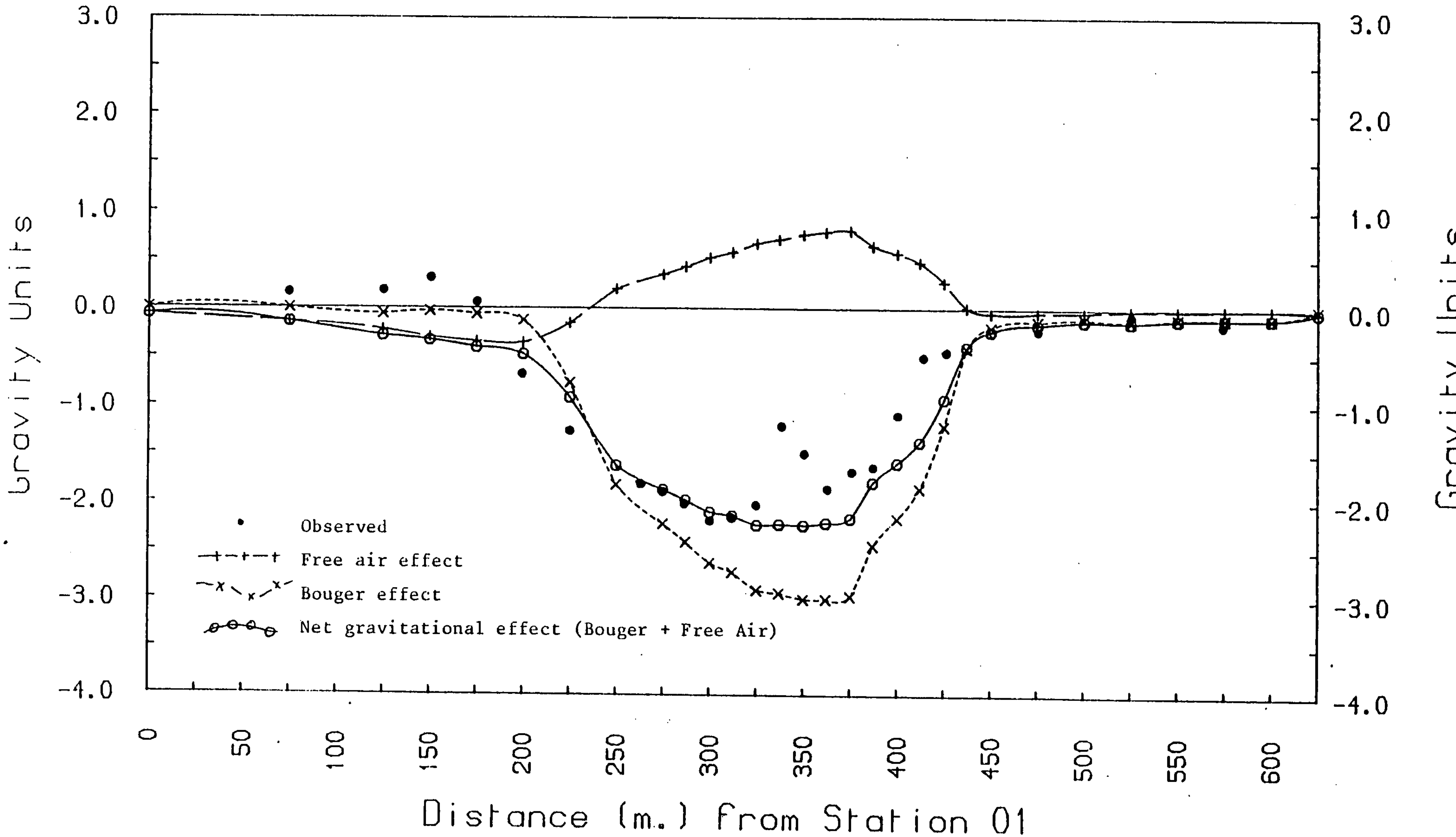



Figure 10.10 Results of two dimensional model studies

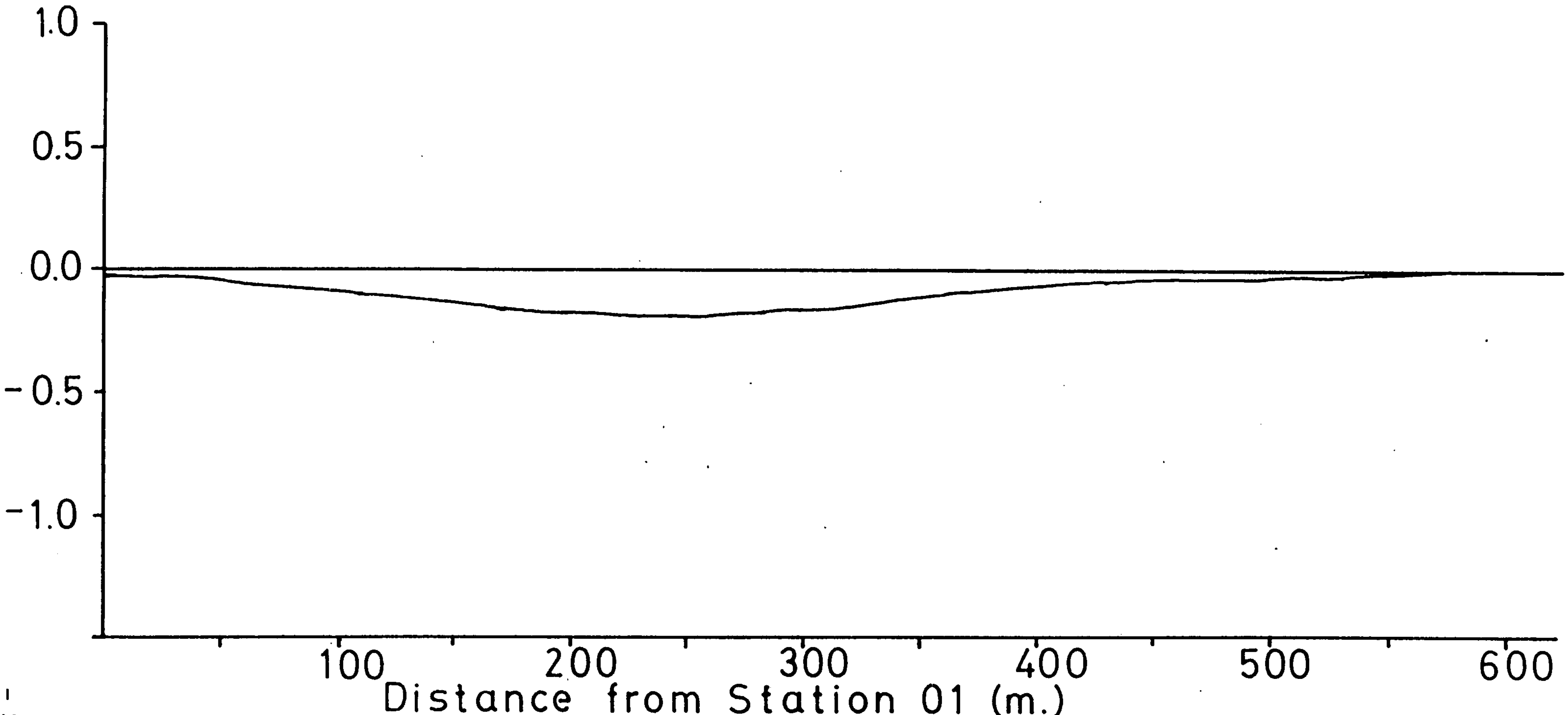



Figure 10.11 Modelled gravitational effect of seam material.

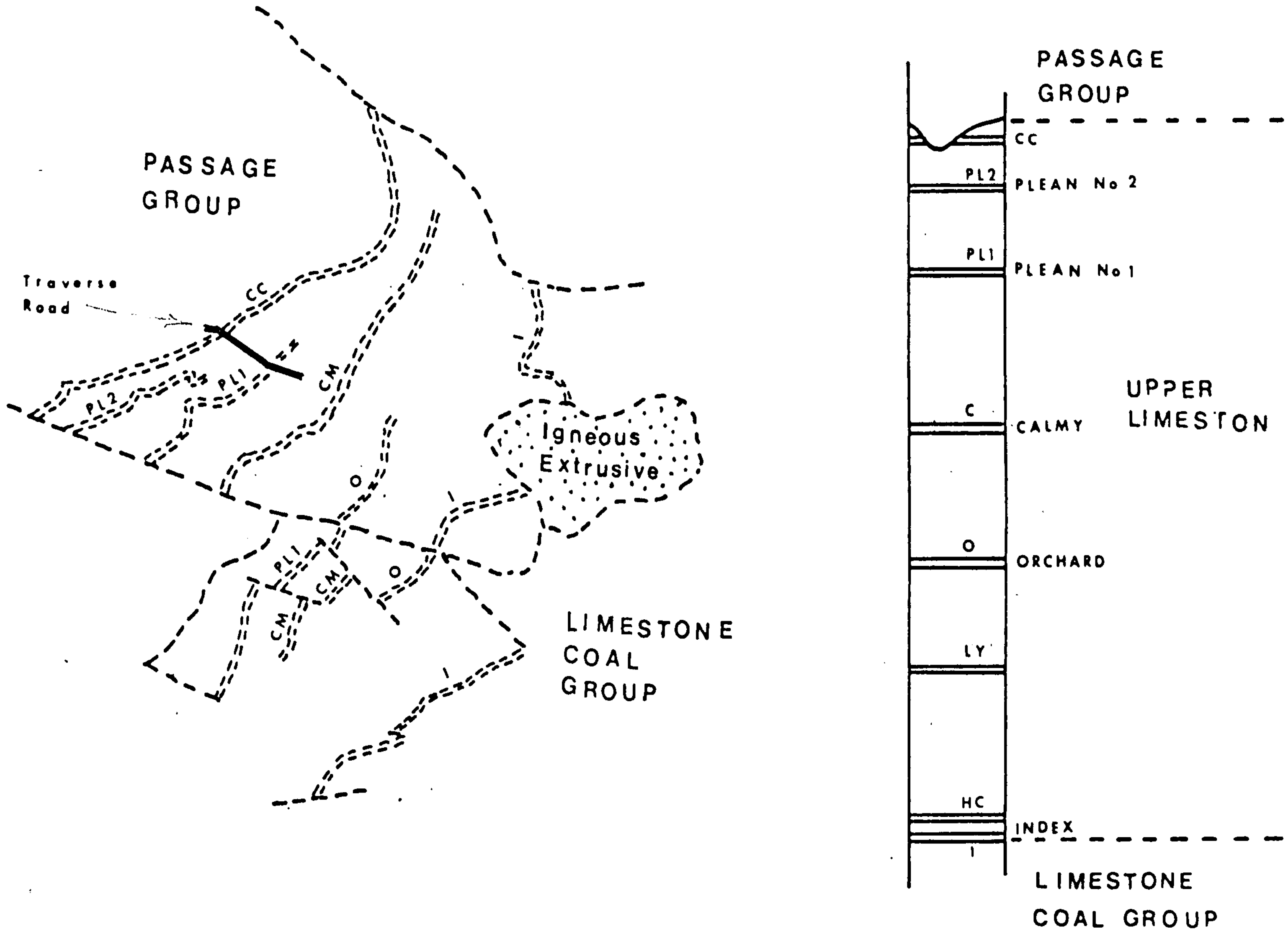



Figure 10.12 Simplified geological map of Solsgirth area.

## 10.6 Conclusions

This small scale study has demonstrated the suitablity of gravimetric surveying to the problem of mining subsidence. A gravity survey with a standard deviation of 0.1g.u. can detect elevation changes of 0.05m, which is adequate to assess changes in land drainage - a major source of compensation claims. Levelling in fields, over several kilometres is in fact often less accurate than this figure. The results are sensitive to small scale elevation changes and can be directly related to altitude. This method of inquiry would be particulary suited to subsidence, be it due to mining or say the extraction of water over a large area. The method has the advantage over levelling that observation points may be widely separated and visted in any order in most weather conditions by one person only.

## CHAPTER ELEVEN

## CONCLUSION

### 11.1 Summary

This work has successfully demonstrated the use of high precision gravimetry in several field studies. The Edinburgh gravity meter has been subject to extensive testing and ancillary equipment manufactured. The instrument testing indicated a low response to environmental effects except magnetic field variations. It also verified the existence of a characteristic drift function after unclamping for this particular instrument. Since such instrumental drift was not linked to any external phenomena it is thought to be associated with clamping induced stress and mechanical hysteresis. The auxillary platform proved useful during Scottish field data collection using the equilibrium technique because of the stable measuring base it provided in conjunction with fundamental bench marks. The attached coincident viewing levels improved the levelling accuracy, but because of the setting up time it is not thought beneficial to use the auxillary platform for other than equlibrium surveys.

Apparatus to tilt the meter, measured by laser interferometry was successfully designed and completed using the secondary plate, but the degree of accuracy is not presently adequate for the precise calibration of gravity meters. The primary United Kingdom short calibration line appears to be discrepant. Four La Coste and Romberg gravity meters of different ages and usage, independently obtain comparable correction factors, in the range 8 - 25 x $10^{-4}$. These correction factors are unexpectedly large compared to typical values in the literature (less than 6 x $10^{-4}$, Torge,1971, Nakagawa and Satomura, 1976). They are also inconsistent with observations of the second short calibration line and some stations of the long calibration line undertaken using G-275. A probable correction factor to the short calibration line Hatton Heath - Press is 0.99908, while the earlier Cat and Fiddle - North Rode line is correct.

The data quality of the Eskdalemuir I.D.A. instrument appeared to be of acceptable quality, with slightly lower accuracy than other earth tide stations in Great Britain (see Table 7.3). The standard deviation of unit weight was 1.4 x $10^{-8}\,m/s^2$ compared with values of 0.5 - 0.7 x $10^{-8}\,m/s^2$ for well maintained La Coste and Romberg Earth Tide meters. But the $M_2$ load tide is significantly different from a well proven model (Baker, 1980, though this may be attributable to a coarse local model grid), and the $O_1$ gravimetric factor is unacceptably low for Western Europe (1.083). This apparent lack of accuracy may not be true of other I.D.A.installations, and can only be determined after analysis of the data.

The results of Baker (1980) were used in the reduction of data collected using the equilibrium technique on an expanded Scottish network to study temporal gravity variations. The results of two annual surveys of the expanded network do not acheive the early promise of Hipkin (1978), but attain a level of accuracy similar to the results of convential high precision surveying (standard deviations between $5 \times 10^{-8}$ and $10 \times 10^{-8}$ $m/s^2$. The Atalanti network also reveals no significant gravity change over a period over one year. This fact combined with the recent (Jan 1983 - June 1984) lack of seismic activity (I. Main, personal communication)
implies a reduction in the probablity of immininent tectonic activity. These gravimetric surveys compare favourably with the work of other invetigators.

The mining subsidence survey was initially carried out as an experiment to observe gravity variation in a well controlled setting. The gravity-height correlation was sufficently well determined to suggest that gravity surveying would be a useful tool in the study of subsidence.

High precision gravity surveying is a neglected area of geophysical investigation. It has been shown to detect precursory tectonic activity (Whitcomb,1980) and the field measurements acquired by the author are sufficiently accurate to fulfil that role. Basic field requirements include a familarity with the individual meter, extreme care during the measuring campaign, a well devised observation and network plan. Tidal corrections (excluding the effects of ocean loading), with an accuracy more than an order of magnitude greater than reading error, can be calculated simply and rapidly by computer. Network adjustment can be similarly calculated.

## Future Work

The results of this study of high precision gravimetry suggest several topics for further work. The Hatton Heath - Prees calibration line adjustment should be examined at the earliest opportunity. Ideally a new survey should be completed using absolute gravimeters and integrated into an accurately determined multiple calibration line. (Similar to the German line with ranges of 2, 20, 200, 2,000, 20,000 g.u.. The 2,000 g.u. range is particulary important as this is just with in the range of the model D gravimeter.) This would prove useful to academic and commercial institutions alike. The proposed long calibration line (an extension of the old airport net) is unsatisfactory. Station monumentation is very poor and access is difficult. A laboratory based tilt calibration technique (perhaps based on the laser interferometric arrangement described in Chapter six ) should be developed. A possible improvement to the arrangement described here would be the ablity to determine the direction of movement of the tilt table from the fringe pattern.

The Atalanti network is currently being remeasured on at least an annual basis. It would be desirable to increase the network density and improve the monumentation. The area was carefully selected and will probably be subject to a major seismic event in the near future. Previosly published post-earthquake surveys have relied on established low order regional stations subject to large errors (eg. Barnes 1963, Oliver et al., 1976). Frequently observed precise networks will yield new information about tectonic environments. A microgravimetric network is planned for N.W. Turkey; this will benefit from the experience gained in Greece, and is a natural progression in the gravimetric study of seismic risk areas in the E. Mediterranean.

The Scottish network will be remeasured in the future on a long term basis. The existing monumentation involved is so substantial (and legally protected) there is little chance of site eradication. It should prove a valuable control to study gravimeter stablity and for the intercomparison of instruments.

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## APPENDIX 1

Computer Program: NSPL

Source: EGPH19.NSPL          Compiled: 11/06/84    10.52.12
Object: NOBJ

Parms set: FIXED

Edinburgh Fortran77 Compiler Release 3.5

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                             PROGRAM NSPL


C                       FITTING CUBIC SPLINES TO SINGLE VALUED
C                       REAL DATA WITH AN ARBITARY NUMBER AND DISPOSITION
C                       OF KNOTS IN A LEAST SQUARES SENSE WITH THE ABILTY TO
C                       'JOIN' OR 'SUPERIMPOSE' INDEPENDENT DATA SETS







C                       DECLARATIONS

      DIMENSION RMSM(130),RMSMM(130),NAME(130,4),RMSL(130),RMSLL(130)
     £   ,DRIFT(600)
      REAL*8 TIME(600),TSTART(130),GRAV(600),TNODE(130),A(130,130)
     £  ,OBSERV(600,130),ALPHA(130,130),BETA(130),H(130),AUSED(130,130)
     £  ,BUSED(130),GRAVO(130),GMAX,GMIN,HSUM,TDIFF,TGAP,TIME1,TIME2
     £  ,BN(130),TIMEF(600),GDIFF(130),DRIFTF(600),LDIFF(130),C(130)
     £  ,AL(2,2),BL(2),TSSUM,YSUM,YSSUM,TS(130),TSSQD,DETA,LLEVEL(130)
     £ ,LEVEL(130),SLOPE(4),B(130,130),AN(130),Y(130),WSPCE(130)

      CHARACTER*16  HEAD
      INTEGER NUMBM(130),NUMBL(130),SET(600,3),
     £       PDRIFT,PARTS,J,M,N,MZERO,IFNODE,PPARTS,PM
      LOGICAL L1,L2,L3

      CHARACTER  CONS(2)*15
      DATA CONS/' UNCONSTRAINED ','  CONSTRAINED  '/


C                       DATA INPUT AND ORGANISATION

C                       READ CONTROL PARAMETERS


      CALL EMASFC ('DEFINE',6,'FT01,.IN',8)
      CALL EMASFC ('DEFINE',6,'FT02,.OUT',9)
      WRITE (2,'(''  ENDS CONSTRAINED  ?   (T/F) '')')
      READ(1,'(L1)') L1
      IF (L1) CONS(1) = CONS(2)
      INAME = 0

C        J =         NUMBER OF OBSERVATIONS: (J<301)
C        M =         NUMBER OF DIFFERENT GRAVITY SITES: (M<11)
C        N =         NUMBER OF NODAL INTERVALS
C        PARTS =     NUMBER OF PARTS OF DATA SET: (PARTS<21)
```

```
      C            AN ADJUSTED DATUM "LEVEL" IS COMPUTED FOR EACH PART
      C         PARTS > 1:   PARTS SUPERIMPOSED WITH COINCIDENT INITIAL TIMES
      C         PARTS < -1:   PARTS JOINED END TO END AFTER GAPS OF TGAP
      C            WARNING! N+M+PARTS+3 < 51
      C         MZERO =      NUMBER OF GRAVITY DATUM SITE
      C         IFNODE = 0  FOR NODES AT EQUAL INTERVALS
      C         IFNODE > 10 RERUNS PROGRAM WITH DIFFERENT NUMBERS OF NODES
      C                     BETWEEN  IFNODE-10  AND  N
      C         IFNODE = 1  FOR NODES AS SPECIFIED BELOW
      C         PDRIFT = 0  NO OUTPUT OF DRFIT DATA
      C         PDRIFT = 1  OUTPUT OF DRIFT DATA TO CHANNAL 6
      C         PDRIFT = 2  OUTPUT OF DRIFT DATA TO CHANNAL 3
          1 READ (4,'(7I4)') J,M,N,PARTS,MZERO,IFNODE,PDRIFT
            PM = M
            PPARTS = PARTS

            IF (M.GT.0) GO TO 5
            M= -M
            INAME = 1
          5 CONTINUE
            MDUM = M
            IF (MZERO.LT.0) THEN
            INAME = 0
            MZERO = - MZERO
            M = 1
            END IF
            IF (J.EQ.0) GO TO 10000



      C                    READ TITLE

            READ (4,'(A16)') HEAD

      C                    READ SITE NAMES AND THEIR GRAVITY DATUMS

            READ (4,'(4A4,F11.4)') ((NAME(IM,I),I=1,4),GRAVO(IM),IM=1,MDUM)
            WRITE (50,'('' '',4A4,F11.4)') ((NAME(IM,I),I=1,4),GRAVO(IM),
           £                                IM=1,MDUM)

              IF (PARTS-1) 9,11,8

      C        OPTIONAL READ FOR PARTS>1

          8   READ(4,5003) (TSTART(IPART),IPART=1,PARTS)
       5003   FORMAT (F12.5)
              GO TO 11
          9   PARTS=-PARTS
              TDIFF=0.0D0

      C        OPTIONAL READS FOR PARTS<-1

              READ (4,5003) TGAP
               DO 10 IPART=1,PARTS
               READ (4,5003) TIME1,TIME2
               TSTART(IPART)=TIME1-TDIFF-TGAP*(IPART-1)
         10    TDIFF=TDIFF+TIME2-TIME1

      C        OPTIONAL READ FOR IFNODE=1

```

```
     11   NPLUS1=N+1
        IF (IFNODE.NE.1) GO TO 12
        READ (4,5003) (TNODE(IN),IN=1,NPLUS1)
        TSCALE=TNODE(NPLUS1)-TNODE(1)

C          READ TIME, GRAVITY AND SITE NUMBER

     12 DO 650 IJ = 1,J
            READ (4,5004) (TIME(IJ),GRAV(IJ),SET(IJ,2),SET(IJ,3))
 5004       FORMAT (2F12.5,2I3)
            WRITE (7,'(2I3)') SET (IJ,2),SET (IJ,3)

C                SET(IJ,2) = NUMBER OF GRAVITY STATION SITE
C                SET(IJ,3) = NUMBER OF PART OF DATA SET

 650        CONTINUE

        DO 13 IJ=1,J
     13 GRAV(IJ)=GRAV(IJ)+GRAV0(SET(IJ,2))
        CALL DMXMIN(J,GRAV,GMAX,IJMAX,GMIN,IJMIN)
        GSCALE=GMAX-GMIN
        IF (PARTS.EQ.1) GO TO 20
        DO 14 IFRED=1,J
     14 TIME(IFRED)=TIME(IFRED)-TSTART(SET(IFRED,3))

C       DEFINE NODAL TIMES AND PARAMETERS

     20 IF (IFNODE.EQ.1) GO TO 21
        CALL DMXMIN(J,TIME,TNODE(NPLUS1),ITMAX,TNODE(1),ITMIN)
        TSCALE=TNODE(NPLUS1)-TNODE(1)
        IF (IFNODE.LT.11) GO TO 21
        NFIRST=IFNODE-10
        NLAST = N
        GO TO 49
     21 NFIRST = 1
        NLAST = 1


 49       DO 20000 N=NFIRST,NLAST
          N1=N-1
          MN3=M+N+3
          NPLUS1=N+1
          NPLUS2=N+2
          NPLUS3=N+3
          NPLUS4=N+4
          IF (PARTS.GT.1) MN3=MN3+PARTS
          IF (IFNODE.EQ.1) GO TO 23
          TINT=TSCALE/N
            DO 22 IN=1,N
     22     TNODE(IN+1)=TNODE(1)+TINT*IN

     23   IF (PDRIFT.EQ.1)   WRITE(6,'('' NODAL TIMES'',//,F12.5)')
       £                               (TNODE(IN),IN=1,NPLUS1)

          WRITE(6,'(///I4,A15,''NODES WITH A NODAL INTERVAL OF '',F12.5,
       £        '' DAYS STARTING AT '',F12.5)') NPLUS1,CONS(1),TINT,TNODE(1)
          WRITE(9,'(I4,A15,''NODES WITH A NODAL INTERVAL OF '',F12.5,
       £      '' DAYS STARTING AT '',F12.5)') NPLUS1,CONS(1),TINT,TNODE(1)

C                        NORMALISE TIME AND GRAVITY MEASUREMENTS AND
```

```
C                          SET OBSERV EQUAL TO ZERO

                DO 100 IJ=1,J
                GRAV(IJ)=(GRAV(IJ)-GMIN)/GSCALE
                DRIFT(IJ)=0.0

C                ASSIGN SET(IJ,1) = NUMBER OF THE PRECEEDING NODE

                SET(IJ,1)=N
                   IF (N.EQ.1) GO TO 55
                  DO 50 IN=2,N
                     IF (TIME(IJ).GE.TNODE(NPLUS2-IN)) GO TO 55
                  SET(IJ,1)=NPLUS1-IN
   50             CONTINUE
   55           CONTINUE
                TIME(IJ)=(TIME(IJ)-TNODE(SET(IJ,1)))/TSCALE
                  DO 100 I=1,MN3
  100             OBSERV(IJ,I)=0.0

C                          NORMALISE NODE TIMES AND SET MATRICES
C                          A & B EQUAL TO ZERO

              TNODE(1)=TNODE(1)/TSCALE
                DO 200 IN=1,N
                INADD1=IN+1
                TNODE(INADD1)=TNODE(INADD1)/TSCALE
                H(IN)=TNODE(INADD1)-TNODE(IN)
                  DO 200 I=1,NPLUS2
                  A(IN,I)=0.0
  200             B(IN,I)=0.0


C                        SPLINE FITTING

C                    BETWEEN TNODE(N) AND TNODE(N+1),
C                    DRIFT = A(N) + B(N)*T + C(N)*T*T + D(N)*T*T*T
C                    WHERE  T = TIME - TNODE(N)

C                      THE UNKNOWNS X(I) (I=1,M+N+PARTS+3) ARE:
C                         X(1) = A(1)
C                         X(2) = B(1)
C                         X(3) = C(1)
C                            .....
C                         X(N+3) = C(N+1)
C                         X(N+4) = G(1)
C                            .....
C                         X(N+M+3) = G(M)
C                         X(N+M+4) = LEVEL(1)
C                            .....
C                         X(N+M+PARTS+3) = LEVEL(PARTS)

C                    AFTER THE SOLUTION OF THE NORMALS EQUATIONS
C                       ALPHA * X = BETA
C                    THE UNKNOWNS X ARE RETURNED IN BETA

C                        EVALUATE MATRICES A(N) AND B(N)

              DO 400 IN=1,N
              IN1=IN-1
              A(IN,1)=1.0
```

```
          B(IN,2)=1.0
          IF (IN.EQ.1) GO TO 400
          A(IN,2)=TNODE(IN)-TNODE(1)
          A(IN,3)=2.0*H(1)*H(1)/3.0
          A(IN,IN+2)=H(IN1)*H(IN1)/3.0
          B(IN,3)=H(1)
          B(IN,IN+2)=H(IN1)
          IF(IN.EQ.2) GO TO 400
          A(IN,3)=A(IN,3)+H(1)*(TNODE(IN)-TNODE(2))
          A(IN,IN+1)=(H(IN1)+H(IN-2))*(2.0*H(IN1)+H(IN-2))/3.0
            DO 300 I=2,IN1
            B(IN,I+2)=B(IN,I+2)+H(I)+H(I-1)
            IF (IN.EQ.3) GO TO 300
            IF (I.EQ.IN1) GO TO 300
            A(IN,I+2)=A(IN,I+2)+(H(I)+H(I-1))*((2.0*H(I)+H(I-1))/3.0
     £         +TNODE(IN)-TNODE(I+1))
  300       CONTINUE
  400     CONTINUE

C                    SET UP OBSERVATIONAL EQUATIONS

          DO 600 IJ=1,J
C             COEFFICIENT OF G(M)
          OBSERV(IJ,SET(IJ,2)+NPLUS3)=1.0
          IF (PARTS.LE.1) GO TO 450
C              COEFFICIENT OF LEVEL OF PART DATA SET
          OBSERV(IJ,SET(IJ,3)+NPLUS3+M)=1.0
C             COEFFICIENT OF C(N) FROM C(N) AND D(N)
  450     TIME2=TIME(IJ)*TIME(IJ)
          TIME3=TIME2*TIME(IJ)/(3.0*H(SET(IJ,1)))
          OBSERV(IJ,SET(IJ,1)+2)=TIME2-TIME3
C             COEFFICIENT OF C(N+1) FROM D(N)
          OBSERV(IJ,SET(IJ,1)+3)=OBSERV(IJ,SET(IJ,1)+3)+TIME3
C             COEFFICIENTS FORM A(N) AND B(N)
          DO 600 I=1,NPLUS2
  600     OBSERV(IJ,I)=OBSERV(IJ,I)+A(SET(IJ,1),I)+B(SET(IJ,1),I)*TIME(IJ)

C                     SET UP THE NORMAL EQUATIONS

          DO 800 NORMAL=1,MN3
          BETA(NORMAL)=0.0
          DO 700 II=1,MN3
  700     ALPHA(NORMAL,II)=0.0
          DO 800 IJ=1,J
          BETA(NORMAL)=BETA(NORMAL)+GRAV(IJ)*OBSERV(IJ,NORMAL)
          DO 800 I=1,MN3
          ALPHA(NORMAL,I)=ALPHA(NORMAL,I)+OBSERV(IJ,NORMAL)*OBSERV(IJ,I)
  800     CONTINUE
          DO 801 I=1,MN3
          ALPHA(NPLUS4+M,I)=0.0
          ALPHA(NPLUS3+MZERO,I)=0.0
  801     CONTINUE
          ALPHA(NPLUS4+M,NPLUS4+M)=1.0
          BETA(NPLUS4+M)=0.0
          ALPHA(NPLUS3+MZERO,NPLUS3+MZERO)=1.0
          BETA(NPLUS3+MZERO)=0.0

C             SETTING THE SECOND DERIVATIVE EQUAL TO ZERO AT THE ENDS

          IF (.NOT.L1) GO TO 816
```

```
      DO 802 I=1,MN3
      ALPHA(3,I)=0.0
      ALPHA(NPLUS3,I)=0.0
  802 CONTINUE
      ALPHA(3,3)=1.0
      ALPHA(NPLUS3,NPLUS3)=1.0
      BETA(3)=0.0
      BETA(NPLUS3)=0.0

  816  IF(INAME.EQ.0) GO TO 815
       DO 810 IM = 1,M
       DO 805 I= 1,MN3
  805  ALPHA(NPLUS3+IM,I)=0.0
       ALPHA( NPLUS3 + IM, NPLUS3 + IM ) = 1.0
  810 BETA (NPLUS3+IM) = 0.0
  815 CONTINUE

C           SOLVE THE NORMAL EQUATIONS

      CALL NAGSOLVE (AUSED,ALPHA,BETA,MN3,130,WSPCE)

      IF (PDRIFT.NE.2) GO TO 880


C          EVALUATION OF DRIFT AT EQUAL INTERVALS FOR PLOTTING

      HSUM=TNODE(1)
      DO 870 IN=1,N
      AN(IN)=0.0
      BN(IN)=0.0
      IN2=IN+2
      IN10=(IN-1)*10.0
      DO 850 I=2,IN2
      AN(IN)=AN(IN)+A(IN,I)*BETA(I)
  850 BN(IN)=BN(IN)+B(IN,I)*BETA(I)
      DO 860 INT=1,10
      TINTF=H(IN)*(INT-1)/10.0
      DRIFTF(IN10+INT)=GSCALE*(AN(IN)+TINTF*(BN(IN)+TINTF*(BETA(IN2)+
     £    TINTF*(BETA(IN2+1)-BETA(IN2))/(3.0*H(IN)))))
  860 TIMEF(IN10+INT)=TSCALE*(HSUM+TINTF)
  870 HSUM=HSUM+H(IN)
      K=N*10+1
      IN = IN -1
      DRIFTF(K)=GSCALE*(AN(IN)+H(IN)*(BN(IN)+
     £    H(IN)*(2.0*BETA(IN2)+BETA(IN2+1))/3.0))
      TIMEF(K)=HSUM*TSCALE
C
C
C           EVALUATE THE RESIDUALS
C
C
  880 RMS=0.0
      YSUM = 0.0
      YSSUM = 0.0
      TSSQD = 0.0
      TSSUM = 0.0
C
      DO 900 IM=1,M
      NUMBM(IM)=0
```

```
  900   RMSM(IM)=0.0
        DO 950 IPART=1,PARTS
        RMSLL(IPART) = 0.0
        RMSL(IPART) = 0.0
        NUMBLL = 0
        NUMBL(IPART) = 0
        IF (PARTS.GT.1) TS(IPART) = TSTART(IPART) - TSTART(1)
        LEVEL(IPART)= BETA(NPLUS3+M+IPART)*GSCALE
  950   LLEVEL(IPART) = LEVEL(IPART)
C
        DO 1050 IJ=1,J
        TIME(IJ)=(TIME(IJ)+TNODE(SET(IJ,1)))*TSCALE
        DO 1000 I=2,NPLUS3
 1000   DRIFT(IJ)=DRIFT(IJ)+OBSERV(IJ,I)*BETA(I)*GSCALE
        GRAV(IJ)=(GRAV(IJ)-BETA(1)-BETA(SET(IJ,2)+NPLUS3))*GSCALE
        IF (PARTS.GT.1)    GRAV(IJ)=GRAV(IJ)-LEVEL(SET(IJ,3))
        ERROR=DRIFT(IJ)-GRAV(IJ)
        ERROR2=ERROR*ERROR
        RMS=RMS+ERROR2
        RMSM(SET(IJ,2))=RMSM(SET(IJ,2))+ERROR2
        RMSL(SET(IJ,3))=RMSL(SET(IJ,3))+ ERROR2
        NUMBM(SET(IJ,2))=NUMBM(SET(IJ,2))+1
        NUMBL(SET(IJ,3)) = NUMBL(SET(IJ,3)) + 1
 1050   CONTINUE
        RMS=SQRT(RMS/J)
        DO 1100 IM=1,M
        BETA(IM+NPLUS3)=BETA(IM+NPLUS3)*GSCALE
        RMSM(IM)=SQRT(RMSM(IM)/NUMBM(IM))
        IF (IM.EQ.1) GO TO 1100
        GDIFF(IM)=BETA(IM+NPLUS3)-BETA(IM+NPLUS2)
        RMSMM(IM)=SQRT(RMSM(IM)*RMSM(IM)+RMSM(IM-1)*RMSM(IM-1))
 1100   CONTINUE
        TNODE(1)=TNODE(1)*TSCALE

C             DATA OUTPUT ON CHANNAL 6

        WRITE (6,6002) (HEAD),RMS
 6002   FORMAT (' ',A16//' LEAST SQUARES FIT OF THE METER DRIFT CURVE '
     £    ,' CUBIC SPLINE FUNCTIONS'/' ROOT MEAN SQUARE DEVIATION  = ',
     £     F7.4//' SITE NAME & NUMBER',7X,'GRAVITY  RMS DEVIATION  NUMB'
     £    ,'BER OF OBSERVATIONS'//)
        DO 1125 IM=1,M
        IF (IM.EQ.1) GO TO 1120
        WRITE (6,6012) GDIFF(IM),RMSMM(IM)
 6012   FORMAT (' ',20X,F14.4,F10.4)
 1120   WRITE (6,6013) (NAME(IM,I),I=1,4),IM,BETA(IM+NPLUS3),RMSM(IM)
     £      ,NUMBM(IM)
 6013   FORMAT (' ',4A4,I3,F14.4,F10.4,I17)
 1125   CONTINUE



          IF (PARTS.GT.1) THEN
          RMSL(1) = SQRT(RMSL(1)/NUMBL(1))
          LLEVEL (1) = GRAVO (1) - GRAV (1)
          WRITE(6,6003) TSTART(1),LLEVEL(1),RMSL(1),NUMBL(1)
 6003     FORMAT (/' DATUM LEVEL FOR DIFFERENT PARTS OF THE DATA SET'/
     £     /'PART NO     TSTART            DATUM (GU)          RMS(GU.)'
     £    ,'  NO OF OBS.'/'        1     ',(F12.5,F16.3,F18.3,I12))
       WRITE (9,'(''       0'',F16.5,F16.3,F18.3,I12)') TSTART(1),
```

```
     £    LLEVEL(1),RMSL(1),NUMBL(1)
          YSUM = LLEVEL(1) - AINT(GRAVO(1))
          YSSUM = TS(1) * YSUM
C
          DO 6014 IP = 2, PARTS
          NUMBLL = NUMBLL + NUMBL (IP-1)
          RMSL(IP) = SQRT(RMSL(IP) /NUMBL(IP))
          RMSLL(IP)  = SQRT(RMSL(IP)*RMSL(IP) + RMSL(IP-1)
     £        * RMSL(IP-1))
          LLEVEL (IP) = GRAVO (IP) - GRAV (1+NUMBLL )
          LDIFF(IP) = LLEVEL(IP) - LLEVEL(IP-1)
          WRITE (6,6005) LDIFF(IP),RMSLL(IP),IP,TSTART(IP),LLEVEL(IP),
     £      RMSL(IP),NUMBL(IP)
 6005     FORMAT (' ',/18X,F19.3,F21.3,//I8,F16.5,F16.3,F18.3,I12)
      IIP = NINT(REAL(IP/3))
      WRITE (9,'(I8,F16.5,F16.3,F18.3,I12)') IIP,TSTART(IP),
     £    LLEVEL(IP),RMSL(IP),NUMBL(IP)

          IF (PARTS.EQ.4) THEN
          IF(IP.EQ.2.OR.IP.EQ.4) THEN
          SLOPE(IP) = LDIFF(IP)/(TSTART(IP)-TSTART(IP-1))/2.4D1
          WRITE (6,6008) SLOPE(IP)
 6008     FORMAT (/,'SLOPE BETWEEN THE ABOVE TWO =',F8.3,'  G.U./HR,/')
          END IF
          IF (IP.EQ.4) THEN
          SLOPE(IP) = LLEVEL(IP-1) +  (TSTART(2)-TSTART(3))* 2.4D1
     £                                                 *SLOPE(IP)
          SLOPE(IP-2) = LLEVEL(IP-3) +  (TSTART(3)-TSTART(1))*2.4D1
     £                                                 *SLOPE(IP-2)
          WRITE (6,6009) TSTART(2),SLOPE(IP),TSTART(3),SLOPE(IP-2)
 6009     FORMAT (/,'EXTRAPOLATED VALUE AT TIME ',F12.5,'   IS',F12.3,)
          SLOPE(IP) = SLOPE(IP) - LLEVEL(2)
          SLOPE(IP-2) = LLEVEL(3) - SLOPE(IP-2)
          SLOPE(1) = (SLOPE(IP)+SLOPE(IP-2))/2.D0
          WRITE (6,6010)  SLOPE(IP),SLOPE(IP-2), SLOPE(1)
 6010     FORMAT('  POSSIBLE VALUE FOR GRAVITY DIFFERENCE ! ',F9.3,' +'
     £                ,F9.3,'  /2 =  ',F9.3)
           END IF
          END IF
          TSSUM = TSSUM + TS (IP)
          YSUM = YSUM + LLEVEL(IP) - AINT (GRAVO(1))
          YSSUM = YSSUM + (TS(IP) * (LLEVEL(IP)-AINT(GRAVO(1))))
          TSSQD = TSSQD + (TS(IP) * TS(IP))
 6014     CONTINUE
C          CALL DIAG
C
C              ASSIGN AL & BL VALUES
C
          AL(1,1) = PARTS
          AL(1,2) = TSSUM
          AL(2,1) = TSSUM
          AL(2,2) = TSSQD
          BL(1) = YSUM
          BL(2) = YSSUM
C          DETA = (AL(1,1)*AL(2,2) - AL(2,1)*AL(1,2))
C          BL(1) =  (BL(1) * AL(2,2) - BL(2) * AL(2,2)) /DETA
C          BL(2) = (BL(2) * AL(1,1) - BL(1) * AL(2,1)) /DETA
C
          CALL F04ARF (AL,2,BL,2,BL,WSPCE,IFAIL)
          IF (IFAIL.EQ.1) GO TO 999
```

```
C
C               USE RMSL AND TSSUM AGAIN  TO CALC RMS OF OBS TO S. L. FIT

                 TSSUM = 0.0
                   DO 6007 IP = 1, PARTS
                   RMSL(IP) = (LLEVEL(IP) - AINT(GRAV0(1)))
      £                  - (BL(1) + BL(2)*TS(IP))
                   RMSL(IP) = RMSL(IP) * RMSL(IP)
                   TSSUM = TSSUM + RMSL(IP)
 6007              CONTINUE
                 TSSUM = SQRT (TSSUM)

                 WRITE (6,6006)  BL(1),BL(2),TSSUM
  6006           FORMAT (/'    STRAIGHT LINE FIT Y = A + B.X'
      £           /'         A =  ',F12.4,'  B =  ',F12.4,'     RMS = ',F12.4/)
                 END IF


               IF (PDRIFT.NE.1) GO TO 1150
               WRITE (6,6004) (TIME(IJ),DRIFT(IJ),GRAV(IJ),(NAME(SET(IJ,2),I),
      £          I=1,4),SET(IJ,1),IJ=1,J)
  6004         FORMAT ('1',' DRIFT CHARACTERISTICS'//'       TIME       DRIFT
      £          OBSERVATION',6X,'SITE NAME  SPLINE INTERVAL'//(F12.5,F11.3
      £           ,F13.3,6X,4A4,I6))
C
  1150         IF (PDRIFT.NE.2) GO TO 1200
               WRITE (3,3000) K,RMS,(TIMEF(IK),DRIFTF(IK),IK=1,K)
  3000         FORMAT (I3,F7.4/(2F15.5))
               WRITE (3,3001) J,(TIME(IJ),DRIFT(IJ),GRAV(IJ),SET(IJ,3),IJ=1,J)
  3001         FORMAT (I3/(3F15.5,I3))
               WRITE (3,'(4I4,L5)') J,PM,MZERO,PPARTS,L1

  1200         DO 1300 IJ=1,J
  1300         GRAV(IJ)=GRAV(IJ)+BETA(SET(IJ,2)+NPLUS3)+LEVEL(SET(IJ,3))+GMIN
 20000         CONTINUE

             GO TO 1


 10000 WRITE (2,'('' CREATE PLOT FILE T70 ? (T/F) '')')
             READ (1,'(L1)') L2
               IF (L2)   CALL EMASFC ('RUN',3,'GPLOTOBJ',8)
                WRITE (2,'('' LIST TO GP15 ? (T/F) '')')
                READ (1,'(L1)') L3
               IF (L3)  CALL EMASFC ('GPLIST',6,'T70,.GP15',9)
                WRITE (2,'('' LIST TO .GP23 ? (T/F) '')')
                READ (1,'(L1)') L3
               IF (L3)  CALL EMASFC ('LIST',4,'T70,.GP23',9)


             STOP
   999 WRITE (6,'('' SOLUTION IMPOSSIBLE; SINGULAR MATRIX'')')
             STOP
             END



             SUBROUTINE NAGSOLVE (AUSED,ALPHA,BETA,MN3,N,WSPCE)
```

```
            REAL*8 ALPHA(N,N),BETA(N),AUSED(MN3,MN3),WSPCE(N)
C           £     ,C(100),WSPC1(100),WSPC2(100),AA(100,100)

            INTEGER MN3,N
            DO 1 IB = 1,MN3
            DO 1 IA = 1,MN3
1           AUSED (IA,IB) = ALPHA (IA,IB)
            IFAIL = 0
            CALL  F04ARF (AUSED,MN3,BETA,MN3,BETA,WSPCE,IFAIL)
C            CALL F04ATF (AUSED,MN3,BETA,MN3,C,AA,MN3,WSPC1,WKSPC2,IFAIL)
            IF (IFAIL.EQ..1) STOP 'F04ARF ; IFAIL = 1'
            RETURN
            END
```

```
CODE    21264 BYTES       PLT + DATA  1217104 BYTES
STACK    3128 BYTES       DIAG TABLES    1252 BYTES       TOTAL   1242748 BYTES
COMPILATION SUCCESSFUL
```

## APPENDIX 2

Computer Program: WFIT

Source: EGPH19.WFIT          Compiled: 18/06/84   22.59.00
Object: WOBJ

Parms set: FIXED

Edinburgh Fortran77 Compiler Release 3.5

```
      REAL*8 ALPHA(3,3),BETA(3),GSUM,TSUM,GNSUM,WSUM,TNSUM,TGSUM,T2SUM
     £  ,T0,G0,TIME(4),GRAV(4),WEIGHT(4),GRAVADJ(4),ERROR(4),VAR
     £  ,NSUM
      INTEGER N(4),IREF(4)
      DATA N/0,0,1,1/
   10 READ (9,3000,END=999) HEAD,(IREF(I),TIME(I),GRAV(I),WEIGHT(I),I=1
     £  ,4)
 3000 FORMAT (A4/(I8,F16.5,F16.3,F18.3))
      G0=GRAV(1)
      T0=TIME(1)
      GSUM=0.0D0
      TSUM=0.0D0
      NSUM=0.0D0
      GNSUM=0.0D0
      TNSUM=0.0D0
      TGSUM=0.0D0
      T2SUM=0.0D0
      WSUM=0.0D0
      VAR=0.0D0
      DO 100 I=1,4
      WEIGHT(I)=1.0D0/(WEIGHT(I)*WEIGHT(I))
      GRAV(I)=GRAV(I)-G0
      GSUM=GSUM+GRAV(I)*WEIGHT(I)
      TIME(I)=TIME(I)-T0
      TSUM=TSUM+TIME(I)*WEIGHT(I)
      WSUM=WSUM+WEIGHT(I)
      NSUM=NSUM+N(I)*WEIGHT(I)
      GNSUM=GNSUM+N(I)*GRAV(I)*WEIGHT(I)
      TNSUM=TNSUM+TIME(I)*N(I)*WEIGHT(I)
      TGSUM=TGSUM+TIME(I)*GRAV(I)*WEIGHT(I)
      T2SUM=T2SUM+TIME(I)*TIME(I)*WEIGHT(I)
  100 CONTINUE
      BETA(1)=GSUM
      BETA(2)=GNSUM
      BETA(3)=TGSUM
      ALPHA(1,1)=WSUM
      ALPHA(1,2)=NSUM
      ALPHA(1,3)=TSUM
      ALPHA(2,1)=ALPHA(1,2)
      ALPHA(2,2)=ALPHA(1,2)
      ALPHA(2,3)=TNSUM
      ALPHA(3,1)=ALPHA(1,3)
      ALPHA(3,2)=ALPHA(2,3)
      ALPHA(3,3)=T2SUM
      ISING=1
      CALL GAUSS (ALPHA,BETA,3,9,ISING)
      DO 200 I=1,4
      GRAVADJ(I)=BETA(1)+N(I)*BETA(2)+TIME(I)*BETA(3)
      ERROR(I)=GRAV(I)-GRAVADJ(I)
      VAR=VAR+ERROR(I)*ERROR(I)*WEIGHT(I)
  200 CONTINUE
      SIGMA=DSQRT(VAR/WSUM)
```

```
          SIGMA=SIGMA*100.0D0
          BETA(2)=BETA(2)*100.0D0
          WRITE (7,7000) HEAD,BETA(2),SIGMA
     7000 FORMAT(' ',A4,' NODES'/' GRAVITY DIFFERENCE = ',F15.3,' MICROGALS'
        1  /' ROOT MEAN SQUARE ERROR = ',F15.3,' MICROGALS')
          GO TO 10
      999 STOP
          END
```

```
CODE     4384 BYTES      PLT + DATA      824 BYTES
STACK     888 BYTES      DIAG TABLES     604 BYTES      TOTAL   6700 BYTES
COMPILATION SUCCESSFUL
```

# APPENDIX 3

Computer Program: MULTILINEAR

Source: EGPH19.TEMP        Compiled: 20/06/84   22.15.26
Object: MOBJ

Parms set: FIXED

Edinburgh Fortran77 Compiler Release 3.5

```
C**************************************************************************
C***
C***   This program adjusts base station values by fitting an independent qu
C***   drift curve to each gravity traverse.
C***
C***
C***   The input data consist of :-
C***  Line 1:      the total number of observations,  N;
C***               the number of base stations, M;
C***               the number of the base station, MZERO, chosen as datum,
C***           and the number of traverses, K.
C***
C***     Line 2:     the value to be assigned to the datum base station, G0.
C***
C***   Subsequent lines list base station names (up to 8 charecters, 1 per l
C***
C***   Gravity observations are then listed, one per line, with the format:-
C***
C***               TIME(I) in any decimal units;
C***               GRAV(I), observed gravity;
C***               NBASE(I), the base station number.
C***           and NTRAV(I), the traverse number.
C***
C***
C***   The dimensions of the normal equation arrays  A  and  B  must be set
C***          A(M+2*K,M+2*K)  and  B(M+2*K)  before compilation.
C***
C**************************************************************************
      PARAMETER (KX=114,KY=400)
      DOUBLE PRECISION A(KX,KX),B(KX),GRAV(KY),TIME(KY),G0,CF
     £  ,GRAV0,TIME0,ERROR(KY),SIGMA,DUMPA,Y,D

      DIMENSION RMSG(KX),NBASE(KY),VARG(KX),IHEAD(2,KX),NTRAV(KY)
     1  ,NUMBER(KX),FREQ(20)

      READ (4,3000) N,M,MZERO,K,G0,((IHEAD(I,J),I=1,2),J=1,M)
 3000 FORMAT (4I4/F25.0/(2A4))
      READ (4,3001) (TIME(I),GRAV(I),NBASE(I),NTRAV(I),I=1,N)
 3001 FORMAT (2F12.5,2I3)
      M2K=M+2*K
      DO 90 I=1,M2K
      B(I)=0.0D0
      DO 90 J=1,M2K
      A(J,I)=0.0D0
   90 CONTINUE
      TIME0=TIME(1)
      GRAV0=GRAV(1)
      DO 100 I=1,N
      MK=M+NTRAV(I)
      MKK=MK+K
      TIME(I)=TIME(I)-TIME0
      GRAV(I)=GRAV(I)-GRAV0
```

```
      A(NBASE(I),NBASE(I))=A(NBASE(I),NBASE(I))+1.0D0
      A(MK,MK)=A(MK,MK)+1.0D0
      A(NBASE(I),MKK)=A(NBASE(I),MKK)+TIME(I)
      A(MKK,MKK)=A(MKK,MKK)+TIME(I)*TIME(I)
      A(MKK,MK)=A(MKK,MK)+TIME(I)
      B(NBASE(I))=B(NBASE(I))+GRAV(I)
      B(MK)=B(MK)+GRAV(I)
      B(MKK)=B(MKK)+GRAV(I)*TIME(I)
  100 CONTINUE
      AM0M0=A(MZERO,MZERO)
      DO 110 IM=1,M
      NUMBER(IM)=A(IM,IM)
      VARG(IM)=0.0
      A(IM,MZERO)=0.0D0
      A(MZERO,IM)=0.0D0
      DO 110 IK=1,K
      MK=M+IK
      MKK=MK+K
      A(MK,IM)=A(IM,MK)
      A(MKK,IM)=A(IM,MKK)
  110 CONTINUE
      DO 120 IK=1,K
      MK=M+IK
      MKK=MK+K
      A(MK,MKK)=A(MKK,MK)
      A(MZERO,MK)=0.0D0
      A(MZERO,MKK)=0.0D0
      A(MK,MZERO)=0.0D0
      A(MKK,MZERO)=0.0D0
  120 CONTINUE
      A(MZERO,MZERO)=1.0D0
      B(MZERO)=0.0D0
      IFAIL=0
      CALL SIMQ(A,B,M2K,IFAIL)
      VAR=0.0
      DO 200 I=1,N
      ERROR(I)=GRAV(I)-B(NBASE(I))-B(M+NTRAV(I))-B(M+K+NTRAV(I))*TIME(I)
      ERROR2=ERROR(I)*ERROR(I)
      VAR=VAR+ERROR2
      VARG(NBASE(I))=VARG(NBASE(I))+ERROR2
  200 CONTINUE
      RMS=SQRT(VAR/N)
      A(MZERO,MZERO)=AM0M0
      DO 130 IM=1,M
      RMSG(IM)=SQRT(VARG(IM)/NUMBER(IM))
  130 CONTINUE
      CF = SQRT(REAL(N)/REAL(N-M2K))
      SIGMA = CF * RMS
      WRITE (6,7000) RMS,SIGMA,((IHEAD(I,IM),I=1,2),IM,B(IM),RMSG(IM),
     £      NUMBER(IM),IM=1,M)
 7000 FORMAT (' NETWORK ADJUSTMENT USING MULTILINEAR DRIFT'///
     £  ' ROOT MEAN SQUARE ERROR =',F12.3/
     £  ' ESTIMATED STANDARD DEVIATION =',F12.3//
     £  /'    BASE              GRAVITY                STANDARD DEVIATION'
     £  ,'   NUMBER OF OBSERVATIONS'
     £  /(2A4,8X,I4,F14.4,F10.4,I17))

      WRITE (7,7001) (GRAV(I),ERROR(I),NBASE(I),NTRAV(I),I=1,N)
 7001 FORMAT (///'     GRAVITY    ERROR     STATION     TRAVERSE'
     £  //(2F12.3,2I10))
```

```
          WRITE (8,'(2F12.5)') (ERROR(I),GRAV(I)-ERROR(I),I=1,N)

           WRITE (9,'(2F12.5)') (ERROR(I),TIME(I),I=1,N)

C                     HISTOGRAM
          WRITE(6,'('' Each class interval is half the estimated standard'',
         £        '' deviation of'',F7.4)') SIGMA


          CALL DAGOST (ERROR,N,CF,D,Y)
          WRITE (6,'(''Result of Dagostinos test : D ='',F 9.5,
         £        ''Y = '',F9.5)') D,Y

          DO 71 J=1,20
   71     FREQ(J) = 0.
          IC = 0


          DO 26 I=1,N
          IF (ABS(ERROR(I)).GT.(SIGMA*5)) THEN
               IC = IC + 1
               GO TO 26
               END IF
          DUMPA = ERROR(I)/(SIGMA/2)
          IF (DUMPA.GT.0.0) THEN
              J = 11 + AINT (DUMPA)
              ELSE
              J = 10 + AINT (DUMPA)
              END IF
          FREQ(J)=FREQ(J)+1.
     26   CONTINUE
          WRITE (6,'('' The number of residuals greater than 5 std. dev.is''
         £       ,I2)')  IC
          CALL HIST(1,FREQ,20)
          STOP
          END
```

```
CODE     5968 BYTES      PLT + DATA  121520 BYTES
STACK    1080 BYTES      DIAG TABLES     412 BYTES      TOTAL  128980 BYTES
COMPILATION SUCCESSFUL
```

## APPENDIX 4

Computer Program: PBAS

Source: EGPH19.PBAS         Compiled: 11/06/84   09.49.37
Object: POBJ

Parms set: FIXED

Edinburgh Fortran77 Compiler Release 3.4

```
C***********************************************************************
C***
C***   THE PROGRAM SUPABASL REDUCES GRAVITY OBSERVATIONS MADE WITH THE
C***   LACOSTE & ROMBERG GRAVITY METER G-275 OR ANY OTHER METER
C***   WHOSE SCALE FACTOR IS GIVEN, OUTPUTTING THE DRIFT
C***   SINCE THE FIRST READING. IT CONVERTS DIAL TURNS TO GRAVITY UNITS
C***   USING THE MANUFACTURERS CALIBRATION TABLES.  (ONE GRAVITY UNIT =
C***   ONE MICROMETRE PER SECOND PER SECOND = ONE HUNDRED MICROGALS)
C***   TIDAL CORRECTIONS ARE MADE USING EVERY PARTIAL TIDE GIVEN IN
C***   CARTWRIGHT AND TAYLER (1971),  AS CORRECTED IN CARTWRIGHT AND
C***   EDDEN (1973).   STANDARD ATMOSPHERIC PRESSURE IS CALCULATED FOR
C***   EACH SITE USING THE I.C.A.O. STANDARD ATMOSPHERE AND THE GRAVITY
C***   VALUES ARE CORRECTED USING A COEFFICIENT OF 0.0037 GRAVITY UNITS
C***   PER MILLIBAR.
C***
C***********************************************************************
      REAL LONG,LAT,K(6),MBAR(200),MBARO
      REAL*8 TWOPI,DDAY(200),DCENT,TORAD,DLONG,DLAT,AGRAV,TIME(200),
     £ DDAY60,DCALIB,GRAV(200),GRAVO,VALUE(200),STND(200),PHI1,PHI2,
     £ TIMEO(20),TIMEF(20)

      INTEGER*2 IIE ,IIN,IE,IN,IW,IS,IIG,IG

      INTEGER SDAY(12),YEAR(200),DAY(200),HOUR(200),SET2(200)
      DIMENSION MONTH(200),MIN(200),F(7),TIDO(200),TID1(200),
     £  TID2(200),TIDE(200),IREF(200),CIVIL(200),DRIFT(200),TID3(200),
     £  CELCIUS(200),C(7,484)

      LOGICAL*1 LE(2),L1,L2, LN(2)


      CHARACTER*16 HEAD , STNAME(100)
      EQUIVALENCE (LE,IIE), (LN,IIN)
      COMMON NNBAS,ISKIP,N,INBAS,ICOUNT
      DATA IE/' E'/,IN/' N'/,IW/' W'/,IS/' S'/,IG/' G'/

      DATA LE/2*' '/, LN/2*' '/

      DATA SDAY/0,31,59,90,120,151,181,212,243,273,304,334/
      DATA SDAY/0,31,59,90,120,151,181,212,243,273,304,334/
      TWOPI=6.28318530700
      TORAD=TWOPI/360.D0
      INBAS = 0
      ICOUNT = 0
      NNBAS = 0
      ISKIP = 0
      INSTN = 0

C                           INTERACTIVE PROMPTS
```

```
      CALL EMASFC ('DEFINE',6,'FT02,.IN',8)
      CALL EMASFC ('DEFINE',6,'FT04,.OUT',9)
      WRITE (4,120)
120    FORMAT ( '    PRESSURE CORRECTION  (T/F)    ' )
       READ (2,118) L1
118   FORMAT (L1)
C***
C***   READ THE COEFFICIENTS OF THE TIDAL ARGUMENTS AND AMPLITUDES
C***   FROM THE FILE CARTRIDE ON CHANNAL 10
C***
      READ (10,171) ((C(I,J),I=1,7),J=1,484)
  171 FORMAT (6F2.0,F6.0)
C***
C***   READ SITE NAME
C***
  100 READ (5,60)  (HEAD)
   60 FORMAT (A16)
C***
C***   READ THE NUMBER OF OBSERVATIONS AT THE SITE, NN, TOGETHER WITH
C***   ITS LATITUDE, LONGITUDE AND HEIGHT. NT = 0 GIVES DEFAULT VALUES
C***   OF (1.159,0.000) FOR THE GRAVIMETRIC FACTOR AND PHASE LAG.
C***   THE ABSOLUTE VALUE OF GRAVITY MAY BE GIVEN IF KNOWN. NN=0 CAUSES
C***   THE PROGRAM TO TERMINATE.
C***
      READ (5,260) NN,NT,IIG,SCALE,LE,LOND,LONM,ALONS,LN,LATD,LATM,
     £  ALATS,HEIGHT,AGRAV,PHI1,PHI2
  260 FORMAT(2I3,A2,F8.4/2A1,I4,I3,F6.2,2X,2A1,2I3,F6.2,F8.3,F9.2,2F4.1)
      PHI1 = PHI1  * TORAD
      PHI2 = PHI2 * TORAD
  101 IF (NN.EQ.0) GO TO 606
      IGRAV0=0
      F(1)=1.159
      F(2)=1.159
      F(3)=1.159
      F(4)=1.069
      F(5)=1.069
      F(6)=1.069
      F(7)=1.069
      IF (NT.NE.1) GO TO 116
C***
C***   IF NT=1, READ NF0,NF1,NF2.
C***   IF ANY OF NF0,NF1,NF2 IS NON-ZERO, SPECIFIC GRAVIMETRIC FACTORS
C***   (F(1)), (F(2)), (F(3)) ARE READ.
C***
      READ (5,110) NF0,NF1,NF2
  110 FORMAT (3I3)
      IF (NF0.NE.0)   READ (5,113) F(1)
      IF (NF1.NE.0) READ (5,113) F(2)
      IF (NF2.NE.0) READ (5,113) F(3)
  113 FORMAT (F5.3)
  116 N=NN
      IF (NN.GE.100) N=100
      IGRAV0=IGRAV0 + 1
C***
C***   READ REFERENCE NUMBER, TIME, DATE, GRAVITY METER DIAL TURNS,
C***   PRESSURE AND TEMPERATURE.  CIVIL IS THE DIFFERENCE IN HOURS
C***   BETWEEN LOCAL TIME AND GREENWICH MEAN TIME (UNIVERSL TIME).
C***
      READ (5,360) (IREF(I),HOUR(I),MIN(I),DAY(I),MONTH(I),
     1  YEAR(I),CIVIL(I),GRAV(I),MBAR(I),CELCIUS(I),I=1,N)
```

```
  360 FORMAT (I5,I3,I3,I3,I3,I5,F4.1,F9.3,F8.2,F5.1)
C***
C***   CALCULATION OF STANDARD ATMOSPHERIC PRESSURE.
C***
      LONG=(((ALONS/60.0)+LONM)/60.0+LOND)*TORAD
      IF (IIE.EQ.IW) LONG=-LONG
      LAT=(((ALATS/60.0)+LATM)/60.0+LATD)*TORAD
      IF (IIN.EQ.IS) LAT=-LAT
 1300 DO 501 I=1,N
C***
C***  THE DAY NUMBER ROUTINE CONVERTS ANY TIME AND DATE OF THE GREGORIAN
C***   CALENDAR INTO THE NUMBER OF DAYS AND DECIMALS OF A DAY WHICH HAVE
C***    ELAPSED SINCE 24 00 (MIDNIGHT) GREENWICH MEAN TIME DECEMBER 31
C***   1899
C***
      DDAY(I)=(YEAR(I)-1)*365-6.93591 D 5-YEAR(I)/100+YEAR(I)/4+SDAY(MON
     1TH(I))+DAY(I)-1+(HOUR(I)-CIVIL(I))/24.+MIN(I)/1440.
      IF((YEAR(I)-((YEAR(I))/100)*100).EQ.0)  GO TO 301
      IF(((YEAR(I)-(YEAR(I)/4)*4)*365+SDAY(MONTH(I))+DAY(I)).GE.60) GO T
     1O 301
      DDAY(I)=DDAY(I)-1
  301 IF(DAY(I)*MONTH(I).EQ.58)DDAY(I) = DDAY(I) - 1
      CALL TIDAL(DDAY(I),LAT,LONG,STATIC,TID0(I),TID1(I),TID2(I),TIDE30,
     £  TIDE31,TIDE32,TIDE33,F,C,HEIGHT,PHI1,PHI2)
      TID3(I)=TIDE30+TIDE31+TIDE32+TIDE33
      TIDE(I)=TID0(I)+TID1(I)+TID2(I)+TID3(I)

      MBARO = 1013.2 * ((1.0-HEIGHT*2.2557D-5)**5.2613)

       IF  (MBAR(I).EQ.0..AND.L1) THEN
                   L1 = .FALSE.
                   WRITE (4,'(''   WARNING   CHECK PRESSURE OF '',I4)')I
                   END IF

      IF (SCALE.GT.1.0E-4) THEN
        IF (L1) THEN
             GRAV(I)=GRAV(I)*SCALE+TIDE(I)+(MBAR(I)-MBARO)*0.0037
             ELSE
             GRAV(I) = GRAV(I) * SCALE + TIDE (I)
             END IF
      END IF
      IF (SCALE .EQ. 0.000) THEN
        IF (.NOT.L1) THEN
        GRAV(I)=DCALIB(GRAV(I))+TIDE(I)
        ELSE
        GRAV(I)=DCALIB(GRAV(I))+TIDE(I)+(MBAR(I)-MBARO)*0.0037
        END IF
      END IF
501   CONTINUE

      GRAVO = GRAV(1)

      DO 502 I=1,N
      INEW1 = I + INSTN
      TIME (INEW1) = DDAY (I)
      DRIFT (I) = GRAV(I) - GRAVO
  502 VALUE (INEW1)= DRIFT(I)
      INSTN = INSTN + N

      CALL SBAS (HEAD,STNAME,STND,GRAVO,SET2)
```

```

      TIMEO (INBAS) = DDAY (1)
      TIMEF (INBAS) = DDAY (N)

  600 IF (IGRAVO.NE.1) GO TO 607
C***
C***   DATA OUTPUT
C***
      WRITE (6,160) (HEAD)
  160 FORMAT (' ',A16)
      WRITE (6,460) LOND,LONM,ALONS,LE(2),LATD,LATM,ALATS,LN(2),
     1  HOUR(1),MIN(1),DAY(1),MONTH(1),YEAR(1),DDAY(1),AGRAV,GRAV(1),
     2  HEIGHT,MBARO
  460 FORMAT ('0',29X,'LONGITUDE',I8,I3,F6.2,1X,A1,14X,'LATITUDE',
     2  I9,I3,F6.2,1X,A1/30X,'EPOCH',I11,'H',I3,'M',I5,I3,I5,5X,
     3  'DAY NUMBER',F16.5/30X,'GRAVITY',F17.2,' GU',12X,'METER READING'
     4  ,F11.3,' GU'/30X,'STATION HEIGHT',F8.3,' METRES '/30X,'STANDARD
     5  ATMOSPHERIC PRESSURE ',F8.2,' MILLIBARS')
      WRITE (6,470) STATIC,F(1),F(2),F(3),F(4)
  470 FORMAT('0',4X,'THE HONKASALO TERM OF ',F6.3,' GU HAS BEEN ADDED
     1  IN ORDER TO MAKE THE TIDAL CORRECTIONS EQUIVALENT TO THOSE OF
     2  LONGMAN'//4X,'THE GRAVIMETRIC FACTOR IS '//10X,F5.3,
     3 ' FOR LONG-PERIOD TIDES'//10X,F5.3,' FOR DIURNAL TIDES'//
     4  10X,F5.3,' FOR SEMI-DIURNAL TIDES'//10X,F5.3,' FOR THIRD DEGREE
     5  TIDES')
      IF (.NOT.L1.OR.MBAR(I-1).EQ.0) WRITE (6,'(''         ***'',
     £                          ''   NO PRESSURE  CORRECTION    ***'',/)')
C       IF (NN.EQ.1)  GO TO  100
  607 IF (N-50)  601,601,602
  601 N1=1
      N2=N
      GO TO 603
  602 N1=1
      N2=50
  603 WRITE (6,480) (IREF(I),DDAY(I),HOUR(I),MIN(I),DAY(I),MONTH(I),YEAR
     1(I),DRIFT(I),TIDE(I),TID0(I),TID1(I),TID2(I),TID3(I),IREF(I),I=N1,
     2N2)
  480 FORMAT(' ',4X,'REFERENCE',5X,'DAY  NUMBER',5X,'TIME',7X,'DATE',8X,
     1'DRIFT',6X,'TIDE',4X,'SPECIES 0',2X,'SPECIES 1',2X,'SPECIES 2',2X,
     2'DEGREE 3',2X,'REFERENCE'/(5X,I7,F18.5,I5,'H',I3,'M',I5,I3,I5,F9.3
     3,' GU',F8.3,' GU',F8.3,' GU',F8.3,' GU',F8.3,' GU',F8.3,' GU',I9))
        WRITE (7,111)  (DDAY(I),DRIFT(I),I=N1,N2)
  111   FORMAT (F12.5,3X,F7.3)
      IF  ((N-N2).EQ.0)  GO TO 604
      N1=51
      N2=N
      GO TO 603
  604 CONTINUE
      NN=NN-N
      IF (NN.EQ.0)  GOTO 605
      GO TO 116
  605 CONTINUE
      GO TO 100
  606 WRITE (6,550)
  550 FORMAT ('1     END OF DATA')

C           OUTPUT TO CHANNEL 08 SUITABLE FOR PROGRAM SPLINEX


      WRITE (8,'(2I4,''    4    4   -1   11    2'')') INSTN,0-INBAS
```

```
      WRITE (8,'('' '',A16,I5,I3,I5,'' G-275'')')
     £   STNAME(1),DAY(1),MONTH(1),YEAR(1)
      WRITE (8,'(A16,F11.3)') (STNAME(J),STND(J),J=1,INBAS)
      WRITE (8,'('' '',F12.5)') (TIMEO(J),J=1,INBAS)
      WRITE(8,'(F12.5,F12.3,''  1'',I3)') (TIME(J),VALUE(J)
     £      ,SET2(J), J = 1 , INSTN)
      WRITE (8,'(////)')

      CLOSE (55)
      STOP
      END



C***********************************************************************
C***
C***   CONVERSION FROM DIAL TURNS TO GRAVITY UNITS FOR THE LACOSTE
C***    & ROMBERG GRAVITY METER G-275 USING THE MANUFACTURES CALIBRATION
C***   TABLES.
C***
      DOUBLE PRECISION FUNCTION DCALIB(SGRAV)
      REAL*8 TG(71), CG(70), SGRAV

      DATA TG/0.,105.12,210.22,315.33,420.43,525.52,630.62,725.71,840.8,
     1945.89,1050.98,1156.07,1261.17,1366.27,1471.38,1576.49,1681.62,178
     26.75,1891.89,1997.04,2102.20,2207.37,2312.55,2417.74,2522.93,2628.
     314,2733.36,2838.58,2943.82,3049.07,3154.33,3259.60,3364.88,3470.18
     4,3575.48,3680.80,3786.12,3891.46,3996.81,4102.16,4207.53,4312.90,4
     5418.28,4523.67,4629.06,4734.46,4839.86,4945.27,5050.69,5156.11,526
     61.52,5366.94,5472.35,5577.76,5683.16,5788.55,5893.94,5999.32,6104.
     769,6210.06,6315.41,6420.76,6526.09,6631.40,6736.70,6841.97,6947.23
     8,7052.45,7157.65,7262.82,7367.93/
      DATA CG/1.05115,1.05108,1.05104,1.05100,1.05095,1.05093,1.05090,1.
     105090,1.05090,1.05090,1.05094,1.05097,1.05103,1.05107,1.05115,1.05
     2124,1.05133,1.05140,1.05150,1.05160,1.05170,1.05180,1.05187,1.0519
     38,1.05207,1.05216,1.05226,1.05237,1.05248,1.05260,1.05270,1.05283,
     41.05295,1.05305,1.05316,1.05326,1.05337,1.05347,1.05356,1.05365,1.
     505374,1.05380,1.05385,1.05392,1.05399,1.05405,1.05411,1.05415,1.05
     6417,1.05416,1.05415,1.05412,1.05407,1.05402,1.05395,1.05388,1.0538
     70,1.05372,1.05364,1.05355,1.05344,1.05330,1.05315,1.05297,1.05275,
     81.05253,1.05227,1.05200,1.05163,1.05115/
      IG=SGRAV/100+1
      DCALIB=TG(IG)+(SGRAV+100-IG*100)*CG(IG)
      DCALIB=DCALIB*10.0
      RETURN
      END


C***********************************************************************
C***
C***        THE SUBROUTINE TIDAL COMPUTES THE VERTICAL COMPONENT OF
C***        GRAVITATIONAL ATTRACTION DUE TO THE SUN AND MOON FOLLOWING
C***        THE EXPANSION OF CARTWIGHT & TAYLOR AND CARTWRIGHT & EDDEN
C***
C***********************************************************************
      SUBROUTINE TIDAL(DDAY,LAT,LONG,STATIC,TIDE20,TIDE21,TIDE22,TIDE30,
     £  TIDE31,TIDE32,TIDE33,F,C,HEIGHT,PHI1,PHI2)
```

```
      REAL LONG, LAT, LATC
      REAL*8 TWOPI,DDAY,DDAY60,DCENT,K(6),PHI1,PHI2

      DIMENSION C(7,484), F(7)
      TWOPI = 6.2831853070D0
      DDAY60=(DDAY-22056.5)*TWOPI
      TIDE20=0.0
      TIDE21=0.0
      TIDE22=0.0
      TIDE22=0.0
      TIDE30=0.0
      TIDE31=0.0
      TIDE32=0.0
      TIDE33=0.0
C***
C***   EVALUATION OF THE FUNDEMENTAL ARGUMENTS
C***
      K(2)=DMOD((DDAY60*0.0366011013D0+0.3878297800),TWOPI)
      K(3)=DMOD((DDAY60*0.0027379092D0+1.0492785000),TWOPI)
      K(4)=DMOD((DDAY60*0.0003094548D0+4.7397039000),TWOPI)
      K(5)=DMOD((DDAY60*0.0001470940D0+3.2955390700),TWOPI)
      K(6)=DMOD((DDAY60*0.0000001308D0+4.9263522000),TWOPI)
      K(1)=DMOD((DDAY60-K(2)+K(3)+TWOPI/2.0+LONG),TWOPI)
C***
C***   SECOND DEGREE TIDES - LONG PERIOD COMPONENTS
C***
      DO 201 I=1,104
  201 TIDE20=TIDE20+COS(C(1,I)*K(1)+C(2,I)*K(2)+C(3,I)*K(3)
     1  +C(4,I)*K(4)+C(5,I)*K(5)+C(6,I)*K(6))*C(7,I)
C***
C***   SECOND DEGREE TIDES - DIURNAL COMPONENTS
C***
      DO 202 I=105,266
  202 TIDE21=TIDE21+SIN(C(1,I)*K(1)+C(2,I)*K(2)+C(3,I)*K(3)
     1  +C(4,I)*K(4)+C(5,I)*K(5)+C(6,I)*K(6)+PHI1)*C(7,I)
C***
C***   SECOND DEGREE TIDES - SEMI-DIURNAL COMPONENTS
C***
      DO 203 I=267,385
  203 TIDE22=TIDE22+COS(C(1,I)*K(1)+C(2,I)*K(2)+C(3,I)*K(3)
     1  +C(4,I)*K(4)+C(5,I)*K(5)+C(6,I)*K(6)+PHI2)*C(7,I)
C***
C***   THRID DEGREE TIDES - LONG PERIOD COMPONENTS
C***
      DO 204 I=386,402
  204 TIDE30=TIDE30+SIN(C(1,I)*K(1)+C(2,I)*K(2)+C(3,I)*K(3)
     1  +C(4,I)*K(4)+C(5,I)*K(5)+C(6,I)*K(6))*C(7,I)
C***
C***   THRID DEGREE TIDES - DIURNAL COMPONENTS
C***
      DO 205 I=403,437
  205 TIDE31=TIDE31+COS(C(1,I)*K(1)+C(2,I)*K(2)+C(3,I)*K(3)
     1  +C(4,I)*K(4)+C(5,I)*K(5)+C(6,I)*K(6))*C(7,I)
C***
C***   THIRD DEGREE TIDES - SEMI-DIURNAL COMPONENTS
C***
      DO 206 I=438,468
  206 TIDE32=TIDE32+SIN(C(1,I)*K(1)+C(2,I)*K(2)+C(3,I)*K(3)
     1  +C(4,I)*K(4)+C(5,I)*K(5)+C(6,I)*K(6))*C(7,I)
C***
```

```
C***   THRID DEGREE TIDES - TER-DIURNAL COMPONENTS
C***
      DO 207 I=469,484
  207 TIDE33=TIDE33+COS(C(1,I)*K(1)+C(2,I)*K(2)+C(3,I)*K(3)
     1  +C(4,I)*K(4)+C(5,I)*K(5)+C(6,I)*K(6))*C(7,I)
C***
C***   CORRECTIONS FOR THE ELLIPTICTY OF THE EARTH.
C***   GEODETIC LATITUDE IS CONVERTED TO GEOCENTRIC LATITUDE AND THE
C***   RADIUS IS REDUCED TO THAT OF THE INTERNATIONAL SPHEROID OF 1967.
C***
      ECCEN2 = 6.694605 E -3
      LATC = ATAN((1.0-ECCEN2)*TAN(LAT))
      SINLAT = SIN(LATC)
      COSLAT = COS(LATC)
      RADIUS = 1.0/SQRT(1.0+ECCEN2*SINLAT*SINLAT/(1.0-ECCEN2)
     £  +HEIGHT/6378160.0D0)
      RAD2 = RADIUS*RADIUS
C***
C***   CALCULATION OF THE LATITUDE FUNCTIONS
C***
      TOGRAV = 3.0725E-5*RAD2
      TEMP20=(1.5*SINLAT*SINLAT-0.5)*0.6307831*TOGRAV*F(1)
      TEMP21= -3.0*SINLAT*COSLAT*0.2575161*TOGRAV*F(2)
      TEMP22=3.0*COSLAT*COSLAT*0.1287580*TOGRAV*F(3)
      TOGRAV=TOGRAV*RADIUS*1.5
      TEMP30=SINLAT*(2.5*SINLAT*SINLAT-1.5)*0.7463527*TOGRAV*F(4)
      TEMP31=-1.5*COSLAT*(5*SINLAT*SINLAT-1)*0.2154534*TOGRAV*F(5)
      TEMP32=15.0*COSLAT*COSLAT*SINLAT*0.06813236*TOGRAV*F(6)
      TEMP33=-15.0*COSLAT*COSLAT*COSLAT*0.02781492*TOGRAV*F(7)
C***
C***   EVALUATION OF THE STATIC TIDE
C***
      STATIC=C(7,1)*TEMP20
C***
C***   WEIGHTING TIDAL FAMILIES WITH THEIR LATITUDE FUNCTION
C***
      TIDE20=TIDE20*TEMP20
      TIDE21=TIDE21*TEMP21
      TIDE22=TIDE22*TEMP22
      TIDE30=TIDE30*TEMP30
      TIDE31=TIDE31*TEMP31
      TIDE32=TIDE32*TEMP32
      TIDE33=TIDE33*TEMP33
      RETURN
      END



      SUBROUTINE SBAS (HEAD,STNAME,STND,GRAVO,SET2)
      CHARACTER*16 HEAD,STNAME(*)
      INTEGER SET2(*),INBAS
      REAL*8 STND(*),GRAVO

      COMMON NNBAS,ISKIP,N,INBAS,ICOUNT
      INBAS = INBAS + 1
      ICOUNT = ICOUNT + 1

      IF (INBAS.EQ.1) THEN
                     STND(1) = GRAVO
                     STNAME (1) = HEAD
```

```
                            DO 1  J = 1,N
      1                     SET2 (J) = 1
                            NNBAS = NNBAS + N
                            RETURN
                            END IF

      C       DO 3 I = 1,INBAS-1
      C       IF (STNAME(I).EQ.HEAD.AND.ICOUNT.GT.ISKIP) THEN
      C                             DO 2 J = NNBAS+1 , NNBAS+N
      C                             SET2(J) = I
      C2                            CONTINUE
      C                             NNBAS = NNBAS + N
      C                             ISKIP = ICOUNT
      C                             END IF
      C3       CONTINUE

              STND(INBAS) = GRAVO
              STNAME(INBAS) = HEAD
              DO 4 I = NNBAS+1 , NNBAS+N
      4       SET2(I) = INBAS
              NNBAS = NNBAS+N
              RETURN

              END
```

```
CODE    13664 BYTES      PLT + DATA   41408 BYTES
STACK    2016 BYTES      DIAG TABLES   1604 BYTES      TOTAL  58692 BYTES
COMPILATION SUCCESSFUL
```

## APPENDIX 5

Computer Program: LSQTILT

```
      C        Simple multivariate  polynomial regression for data
      C        obtained due tilting experiments .
      C        David , Geophysics, Edinburgh University


               PARAMETER (IUNK=20,NOBS=200)
               REAL*8 A(IUNK,IUNK),B(IUNK),AINV(IUNK,IUNK),TEMP(IUNK),W(IUN
              £NOBS),N(NOBS),X,Y,RESULT(NOBS,3),ERROR(NOBS),WEIGHT,ERROR2
              £,YHAT(NOBS),YMEAN,YHATM,SSDR,SSAM,RSQD,R,CCORRN,LAMBDA,CTHEO

NING 242      Specification of item length in bytes is not standard FORTRAN

NING 201      Identifier CTHEORY contains >6 characters - not standard FORT

               INTEGER EXP,ICOUNT,REXP(NOBS)
               LOGICAL LWEIGH,LLONG,LEXPT
               DATA LAMBDA/632.8D-9/,GRAV/9.8158D0/
               ICOUNT=0

               WRITE(6,'('' DO YOU WISH TO WEIGHT? (T/F)'')')
               READ (5,*) LWEIGH
               READ (3,*) NEXP
               N2EXP = 2 * NEXP
               N2EXP1 = N2EXP + 1
               DO 3 I=1,N2EXP1
               B(I) = 0.D0
               DO 3 J=1,N2EXP1
             3 A(J,I) = 0.D0
               SSDR = 0.D0
               SSAM = 0.D0
               YHATM  = 0.D0
               YMEAN = 0.D0
               WEIGHT=1.D0

          1    READ (3,*,END=2) X,Y,EXP
               ICOUNT = ICOUNT+1
               RESULT(ICOUNT,1) = X
               RESULT(ICOUNT,2) = Y
               RESULT(ICOUNT,3) = EXP
               REXP(ICOUNT) = EXP
               YMEAN = Y + YMEAN
               IF (LWEIGH) WEIGHT =1.D0/(RESULT(ICOUNT,1)*RESULT(ICOUNT,1))

               A(EXP,EXP) = A(EXP,EXP) + 1*WEIGHT
               A(NEXP+EXP,NEXP+EXP) = A(NEXP+EXP,NEXP+EXP) + X*X*WEIGHT
               A(NEXP+EXP,EXP) = A(NEXP+EXP,EXP) + X*WEIGHT
               A(N2EXP+1,EXP) = A(N2EXP+1,EXP) +  X*X*WEIGHT
               A(N2EXP+1,NEXP+EXP) = A(N2EXP+1,NEXP+EXP) + X*X*X*WEIGHT
               A(N2EXP+1,N2EXP+1) = A(N2EXP+1,N2EXP+1) + X*X*X*X*WEIGHT
               B(EXP) = B(EXP) + Y*WEIGHT
               B(NEXP+EXP) = B(NEXP+EXP) + X*Y*WEIGHT
               B(N2EXP+1) =  B(N2EXP+1) + X*X*Y*WEIGHT
               GO TO 1
          2     CONTINUE

               DO 4 EXP=1,NEXP
               A(EXP,NEXP+EXP) = A(NEXP+EXP,EXP)
               A(EXP,N2EXP+1) = A(N2EXP+1,EXP)
               A(NEXP+EXP,N2EXP+1) = A (N2EXP+1,NEXP+EXP)
          4    CONTINUE


      C         CALL SIMQ (A,B,9,IFAIL)

               IFAIL = 1
               CALL FO1AAF(A,IUNK,N2EXP1,AINV,IUNK,TEMP,IFAIL)
```

```
      4   CONTINUE


C         CALL SIMQ (A,B,9,IFAIL)

          IFAIL = 1
          CALL FO1AAF(A,IUNK,N2EXP1,AINV,IUNK,TEMP,IFAIL)
          IF (IFAIL.NE.O) STOP 'IFAIL .NE. O'

          DO 5 I=1,N2EXP1
    5     TEMP(I) = O.DO

          DO 6 I=1,N2EXP1
          DO 6 J=1,N2EXP1
    6     TEMP (I) = AINV(J,I) * B(J) + TEMP(I)

          ERROR2 = O.DO
          YMEAN = YMEAN/ICOUNT

          DO 8 I=1,ICOUNT
          YHAT(I) = TEMP(REXP(I)) + TEMP(NEXP+REXP(I)) * RESULT(I,1) + TEMP
     £    (N2EXP1)  * RESULT(I,1) * RESULT(I,1)
          YHATM = YHATM + YHAT(I)
          ERROR(I) = YHAT(I) - RESULT(I,2)
          ERROR2 = ERROR(I) * ERROR(I) +ERROR2
          SSDR = (YHAT(I) - YMEAN) * (YHAT(I) - YMEAN) + SSDR
          SSAM = (RESULT(I,2) - YMEAN) * (RESULT(I,2) - YMEAN) + SSAM

C         Output to ft08 for plotting routines

          WRITE (8,*) RESULT(I,1),RESULT(I,2)

      8   CONTINUE
          WRITE (8,'(''PLOT'',/,''OVERLAY'',/,''LINE CURVE'',/,''DATA'')')
          WRITE (8,'(2E12.5)')( RESULT(I,1),YHAT(I),I=1,ICOUNT)

          RSQD = SSDR/SSAM
          SIGMA = ERROR2/(ICOUNT-N2EXP1)
          WRITE (7,'(8X,''Results of analysis of tilting experiment'',//)')
          WRITE (7,'('' The number of observations is'',I4,'' with '',I4
     £ ,'' constraints'')') ICOUNT,N2EXP1
          WRITE (7,'('' The estimated standard deviation of the fit is'',F1
     £2.4)') SQRT(SIGMA)
          WRITE (7,'('' R squared for fit:'',F12.5)') RSQD
          WRITE (7,'('' The Regression Coefficents with their variances'',
     £'' (std. err. squared) are:'')')
          WRITE (7,'(I6,2E15.5)') ( (I,TEMP(I),AINV(I,I)*SIGMA),I=1,N2EXP1)

          WRITE (6,'('' Is this a laser experiment? (T/F)'')')
          READ (5,*) LEXPT
          WRITE (6,'('' Is this the long level? (T/F)'')')
          READ(5,*) LLONG
          IF (LEXPT) THEN
          R = 3.5747D-1
          IF (.NOT.LLONG) R = 3.4334D-1
          CTHEORY = (GRAV*LAMBDA*LAMBDA)/(8.DO*R*R)
          CCORRN = O.DO - CTHEORY/TEMP(N2EXP+1) * 1.0D6
          WRITE (7,'('' CCORRN is :'',F12.9)') CCORRN
          ELSE
          R = 0.365DO
          IF (.NOT.LLONG) R = 0.3275DO
          CTHEORY = GRAV*2.54D-2*2.54D-2 / (4.92D3 * 4.92D3 * R * R * 4.DO)
          CCORRN = O.DO - CTHEORY /  TEMP(N2EXP1) * 1.0D6
          WRITE (7,'('' CCORRN is :'',F12.9)') CCORRN
          END IF

          STOP
```

## APPENDIX 6

Computer Program: NEWSM9

Source: EGPH19.NEWSM9          Compiled: 12/06/84   21.50.13
Object: NEW9OBJ

Parms set: FIXED

Edinburgh Fortran77 Compiler Release 3.5

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C                          IDA TAPE READING PROGRAM
C                          INTERACTIVE CORRECTIONS
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

C          DECLARATIONS

      INTEGER*2 IA2(500),IFRED(20)
      LOGICAL LSHIFT,LSUBS,LVIEW,LJOIN,LTRY,LSKIP,LOK,LBAD
      INTEGER BUFF1(500),OARRAY(1000),BUFF2, SAVE (500)
     £      ,BUFF3(2500),DSHIFT
      REAL*8 X(2500),Y(2500),W(2500),WORK1(3,2500)
      REAL SMOOTH(50000),OPUT
      COMMON  BUFF2(50000)
      CHARACTER CHAR(3)*4,NUM(27)*4,FILE(2)*4

C          INTIAL VALUES AND DATA STATEMENTS

      DATA NUM /'1001','1003','1005','1007','1009'
     £         ,'1011','1013','1015','1017','1019'
     £      ,'0001','0003','0005','0007','0009'
     £         ,'0011','0013','0015','0017','0019','0021'
     £         ,'0023','0025','0027','0029','0031','0033'/
C     £         ,'0035','0037','0039','0041','0043','0045'
C     £         ,'0047','0049','0051','0053','0055','0057'/
      DATA CHAR(1)/'007,'/
      DATA CHAR(2)/'PART'/
      DATA FILE(1)/'PART'/
      LBAD = .FALSE.
      IBAD = 0
      ISMCT2 = 1
      I180 = 0
      I180TOT =0
      IPT = 0
      DSHIFT = 0
      IDIFF = 0
      IDIFF2 = 0
      J = 1
      IDATUM = 0
      ISMCT = 0
      IEND2 = 0

C         OPEN LOGICAL UNIT NO 7
C         PROGRAM REQUIRES SOME ALTERATIONS HERE IF
C         RUN AT INSTALLATIONS OTHER THAN EMAS

C1000  OPEN (7,FILE=FILE(J),ACCESS='SEQUENTIAL',FORM='UNFORMATTED')

 1000 CHAR(3) = NUM(J)
      CLOSE (7)
```

```
      CALL EMASFC ('DEFINE',6,CHAR,12)
      CALL EMASFC ('DEFINE',6,'FT05,.IN',8)
      CALL EMASFC ('DEFINE',6,'FT06,.OUT',9)

C         READ FIRST BLOCK WHICH CONTAINS HEADER INFORMATION

      READ (7,END=999) IA2

C          DECODE  BINARY DATA BY SPLITTING UP HEX
C          AND CALL EBCDIC TO TO OBTAIN INTEGER
C          VALUE OF HEADER VARIABLES

      DO 1002  I = 1,500
1002  BUFF1(I) = IA2(I)
CANCEL      PRINT*,  '  THE FIRST 100 INTEGERS ARE  '
CANCEL      WRITE (6,'('' '',20I6,/)') (IA2(I),I=1,100)

      CALL  DECODE (BUFF1,OARRAY,500,1000)
      CALL EBCDIC (OARRAY,1000,IYO,IDO,IHO,IMO,ISO,IY1,ID1
     £,IH1,IM1,IS1,ISCANS)
CANCEL      WRITE (6,'('' START TIME '',6I8)') IYO,IDO,IHO,IMO,ISO,ISCANS
      IF (J.EQ.1) THEN
         IYORIG = IYO
         IDORIG = IDO
         IHORIG = IHO + 1
         IMORIG = IMO
         ISORIG = ISO
      IFIRST = ITDIFF (IYO,IYO,IDO,IDO,IHO+1,IHO,0,IMO,0,ISO,ISCANS)+90
      IPIRST = IFIRST
      ELSE
      IPIRST = 0
      END IF
CANCEL      PRINT*, '  START TIME ',IYO,IDO,IHO,IMO,ISO,ISCANS
      PRINT*, 'IFIRST  IS',  IFIRST



      ICOUNT = 0
      IBLOCK = 1
      IF (J.NE.1) IDIFF = ITDIFF(IYO,IY2,IDO,ID2,IHO,IH2,IMO,IM2
     £              ,ISO,IS2,ISCANS2)


C         READ IN TWO'S COMPLIMENT INTEGER DATA A BLOCK AT A TIME


      WRITE (10,'('' IFIRST IS'',I10,''IPIRST IS'',I10)') IFIRST,IPIRST
CANCEL      WRITE (10,'(''    ICOUNT     IEND2     IDIFF        IX         IY
CANCEL     £ BUFF2(IX) '')')
1001  READ(7,END=999) IA2
      IFLAG = 0

C        INTERACTIVE TEST PROCEDURE
C        NOTE: PROMPTS PREFIXED 'L' REQUIRE A LOGICAL
C        RESPONSE ; E.G.   .TRUE. ,   F   ,T

 1015 DO 1003 I = 3 + IFIRST,502
      IF (IFLAG.GT.I) GO TO 1012
      IF (I.EQ.502) GO TO 1012

```

```
         QUERY = IA2(I-1) - IA2 (I-2)

            IF(ABS(QUERY).GT.25.000.OR.IBAD.GT.0)   THEN
            IF (IBAD.GT.0) GO TO 1013
            IQUERY = ABS(QUERY)

C                BAD  BITS

             IF((IA2(I-1).EQ.1286) .OR.
     £       IA2(I-1).EQ.1287 .OR.
     £       IA2(I-1).EQ.817)  THEN
 1024        CALL ROUTE1286 (IA2,I,IFLAG)
             GO TO 1012
             END IF

C            DESPIKING

               IF (ABS (ABS(IA2(I)-IA2(I-1))-IQUERY).LT.2) THEN
               IFLAG = I + 1
               IA2(I-1) = IA2 (I)
               GO TO 1012
               END IF

C            INTERACTIVE PROMPTS

            WRITE (6,'(''  DIFFERENCE .GT. 25.00 DETECTED AT'',I5)')
     £       ICOUNT + 2 + IPIRST
            WRITE (6,'(20I5)') (IA2(K),K=(I/20-1)*20+1,(I/20+2)*20)

               IF (IA2(I+1).EQ.0) THEN
               CALL FPRMPT ('LSKIP?:',7)
                READ (5,*,ERR=1013) LSKIP
                IF (LSKIP) GO TO 1012
               END IF

 1013       CALL FPRMPT ('VIEW BLOCK?:',12)
            READ(5,*,ERR=1013) LVIEW

              IF (LVIEW) THEN
              WRITE (6,'(20I5)') IA2
 1019           CALL FPRMPT ('BAD BLOCK?:',11)
              READ(5,*,ERR=1013) LBAD
                 IF (LBAD) THEN
                 IFLAG = 502
                 IBAD = IBAD + 1
                 GO TO 1012
                 END IF
              IF (IBAD.GT.0) GO TO 1020
              END IF
            CALL FPRMPT ('LSHIFT?:',8)
            READ(5,*,ERR=1013) LSHIFT

               IF (LSHIFT) THEN
               DSHIFT = 0
               CALL FPRMPT ('DSHIFT?:',8)
               READ(5,*,ERR=1013) DSHIFT
               PRINT*, DSHIFT,IDATUM
               CALL FPRMPT ('STARTING AT?:',13)
               READ(5,*,ERR=1013) IPT
               CALL FPRMPT ('IMAX?:',7)
```

```
                READ(5,*,ERR=1013) IMAX
                PRINT*, IPT,IMAX
                CALL FPRMPT ('LOK?:',5)
                READ(5,*,ERR=1013) LOK
                IF (.NOT.LOK) GO TO 1013
                DO 1010 IM = 1,IMAX
                   IF (IM.LT.IPT) THEN
                   BUFF1(IM) = IA2(IM)
                   ELSE
                   BUFF1(IM) = IA2(IM) - DSHIFT
                   END IF
       1010     CONTINUE
                CALL JOIN (BUFF1,IMAX+1,I-3,IPT-I+2,IMAX,X,Y,W,WORK1)
                WRITE (6,'(20I5)') (BUFF1(K),K= (I/20)*20+1,(I/20+4)*20)
                DO 1011 IM = I-2,IPT
       1011     IA2(IM) = BUFF1(IM) +DSHIFT
                IFLAG = IPT + 1
                CALL FPRMPT ('TRY AGAIN?:',11)
                READ(5,*,ERR=1013) LTRY
                IF (LTRY) GO TO 1013
                IDATUM = IDATUM + DSHIFT
                GO TO 1012
                END IF

             CALL FPRMPT ('LSUBS?:',7)
             READ(5,*,ERR=1013) LSUBS

                 IF (LSUBS) THEN
                 CALL FPRMPT ('HOW MANY?:',10)
                 READ(5,*,ERR=1013) IHM
                 CALL  FPRMPT ('STARTING AT?:',13)
                 READ(5,*,ERR=1013) ISTART
                 CALL FPRMPT ('LOK?:',5)
                 READ(5,*,ERR=1013) LOK
                 IF (.NOT.LOK) GO TO 1013
                 DO 1006 IK = ISTART,ISTART + IHM-1
                 PRINT*, IA2(IK)
                 CALL FPRMPT ('SUBSTITUTE?:',12)
                 READ(5,*,ERR=1013)  IX
                 PRINT *, IX
                 IA2 (IK) = IX
       1006      CONTINUE
                 IFLAG = ISTART + IHM
                 GO TO 1007

                 END IF
             CALL FPRMPT ('LJOIN?:',7)
             READ(5,*,ERR=1013) LJOIN

                IF (LJOIN) THEN
                CALL FPRMPT('START & END?:',13)
                READ(5,*,ERR=1013) IBOT,ITOP
                PRINT*, IBOT,ITOP
                CALL FPRMPT ('LOK?:',5)
                READ(5,*,ERR=1013) LOK
                IF (.NOT.LOK) GO TO 1013
                DO 1008 IL = 1,500
       1008     BUFF1(IL) = IA2 (IL)
                CALL JOIN (BUFF1,501,IBOT-2,ITOP-IBOT,500,X,Y,W,WORK1)
                DO 1009 IL = 1,500
```

```
 1009       IA2(IL) = BUFF1(IL)
            IFLAG = ITOP
            END IF

 1007    WRITE (6,'(20I5)') (IA2(K),K=(I/20-1)*20+1,(I/20+2)*20)
 1014    CALL FPRMPT ('TRY AGAIN?:',11)
         READ(5,*,ERR=1013) LTRY
         IF (LTRY) GO TO 1013
         END IF

 1012 ICOUNT = (IBLOCK-1)*500 + I - 2 - IPIRST
      IF (ICOUNT.LT.1) GO TO 1003
      BUFF2 (ICOUNT+IEND2+IDIFF) = IA2(I - 2) - IDATUM
      IF (ICOUNT.LT.I180TOT+700) THEN
      IX = ICOUNT + IEND2 + IDIFF
      IY = I - 2
CANCEL      WRITE (10,'(6I10)') ICOUNT,IEND2,IDIFF, IX,IY,BUFF2(IX)
      END IF
 1003 CONTINUE

 1020    IF ( IFLAG.EQ.IPT + 1)
     £   WRITE (6,'(20I5)') (BUFF2(K),K=(IBLOCK-1)*500+IEND2+IDIFF+1
     £   -IPIRST,IBLOCK*500+IEND2+IDIFF-IPIRST)


           IF (IBAD.GT.0) THEN
              IF (IBAD.EQ.1) THEN
              DO 1022 K = ICOUNT - 999 , ICOUNT-500
 1022         BUFF3 (K-ICOUNT+1000) =  BUFF2 (K)
              END IF
           IF (.NOT.LBAD) THEN
           DO 1017 K = (IBAD)*500 + 1 , IBAD*500 + 500
 1017      BUFF3( K ) = IA2 (K-(IBAD)*500) - IDATUM

           ELSE
           IF (IBAD.GT.3)   STOP  'BUFF3 TOO SMALL'
           DO 1023 K = (IBAD+1) * 500 + 1, (IBAD+1) * 500 + 500
 1023      BUFF3 (K) = IA2 (K-(IBAD+1)*500) - IDATUM
C           WRITE (6,'(20I6)')(BUFF3(K),K=1,(IBAD+2)*500)
C           DO 1021 K = 501 + IBAD*500, 1000 + IBAD*500
C 1021      BUFF3(K) = IA2 (K-500)
           IMAX = (IBAD+2) * 500
           CALL JOIN (BUFF3,IMAX+1,499,IBAD*500,
     £                   IMAX,X,Y,W,WORK1)
            DO 1018 K = 501,(IBAD*500) + 500
 1018       BUFF2(ICOUNT-(IBAD+1)*500+K) = BUFF3(K)
C        DO 1018 K = 501,501,IBAD*500+499
C 1018      BUFF2(IMEM+K) = BUFF3(K)
           IBAD = 0
            GO TO 1015
           END IF
           END IF

      IBLOCK = IBLOCK + 1
      IFIRST = 0
      GO TO 1001
999   CONTINUE


      I180 = ((ISCANS-IPIRST+IEND2+IDIFF)/180)*180
```

```
      IEND = ISCANS - I180 - IPIRST + IEND2 + IDIFF

         IF (J.NE.1) THEN
         CALL SAVER (BUFF2,SAVE,IDIFF,IEND2)
CANCEL         WRITE (10,'('' PARAMETERS ENTERING JOIN  IEND2,IDIFF,SAVE'',
CANCEL    £                 /,2I10,/,50(10I8/),/)')  IEND2,IDIFF,SAVE
         CALL JOIN (SAVE,IEND2,250,IDIFF,500,X,Y,W,WORK1)
         WRITE (10,'('' PARAMETERS LEAVING JOIN  IEND2,IDIFF,SAVE'',
     £                 /,2I10,/,50(10I8/),/)') IEND2,IDIFF,SAVE
         END IF

      DO 1005 I = ISCANS - 249   , ISCANS
      SAVE ( I-ISCANS+250 )  =  BUFF2 ( I - IPIRST )
1005   CONTINUE


      IY2 = IY1
      ID2 = ID1
      IH2 = IH1
      IM2 = IM1
      IS2 = IS1
      ISCANS2 = ISCANS
      IEND2 = IEND

      ISTART = 1
      ISTOP = 180

4000  DO 4001 I= ISTART,ISTOP
4001  BUFF1(I-ISTART+1) = BUFF2(I)

      ISMCT = ISMCT + 1
      IF (ISTOP.LT.400) THEN
      WRITE (10,'( ''   PARAMETERS ON ENTERING FIT  ISTART,ISTOP,ISMCT,
     £ISMCT2,BUFF1 ''/4I10,//,18(10I8/),/,18(10I8/))')ISTART,ISTOP,ISMC
     £T,ISMCT2,(BUFF1(K),K=1,180),(BUFF1(K)+IDATUM,K=1,180)
      END IF

      IF (ISTART.EQ.1) WRITE (10,'(''       I180     ISMCT    ISTART
     £  ISTOP      I180TOT           OPUT'',//)')
      CALL FIT (BUFF1,180,OPUT)
      WRITE (10,'(5I10,F10.3)') I180,ISMCT,ISTART,ISTOP,I180TOT,OPUT
      SMOOTH(ISMCT) = OPUT
CANCEL      ITIM = (IYORIG - 1900) * 100000
CANCEL      WRITE (10,'(4I10,4X,F10.3)')   I180,ISMCT,ISTART,ISTOP,OPUT
CANCEL    £         + (IDORIG + INT ((IHORIG+ISMCT - 1)/24)) * 100
CANCEL    £         +  IHORIG  + ISMCT  -INT ((ISMCT+IHORIG)/24) * 24
      BTIM = IDORIG + (IHORIG + ISMCT)/2.4D1
      WRITE (8, '('' '',F10.3,3X,F10.3)' ) BTIM,OPUT/2.
      ISTART = ISTART + 180
      ISTOP = ISTOP +180
      IF (ISTOP.LE.I180) GO TO 4000
C      DO 1025 K = ISMCT2,ISMCT
C      ITIM = ITIM + 1
C 1025 WRITE (8 , '('' '', I8,3X,F10.3)'  ) ITIM , SMOOTH (K)
      ISMCT2 = ISMCT


C          INSTALLATION SPECIFIC CALL TO
C             CLEAR VIRTUAL MEMORY OF READ FILES

```

```
      IF (J.GT.3) THEN
      FILE (2) = NUM (J-3)
      CALL EMASFC ('DISCONNECT',10,FILE,8)
      END IF

      I180TOT = I180TOT+ I180TOT
      J = J + 1
      IF (J.LT.28)      GO TO 1000

C225   FORMAT (' RUN EBM007.GRAPH'/'LINETYPE 5'/'FILE IDAPLOT01'/
C     £'IDENTIFICATION DAVID LYNESS GEOPHYSICS'/'SYMBOL 11'
C     £/'XSCALE DAYS'/'DATA'    )

CANCEL      DO 1004  I = 1,ISMCT
CANCEL      DY = IDORIG +(((ISORIG/60.D0)+IMORIG)/60.D0+IHORIG+(I-1))/24.D0
CANCEL      WRITE (9,226) (DY,SMOOTH(I))
CANCEL226   FORMAT (' ',F8.3,2X,F10.3)
CANCEL1004  CONTINUE

      STOP ' HOPEFULLY SUCCESSFUL '
9999  STOP ' ERROR IN OPEN '
      END



      SUBROUTINE DECODE (JARRAY,OARRAY,IRLTH,IRLTH2)
      INTEGER JARRAY(IRLTH),OARRAY(IRLTH2)
      DO 105 I=1,IRLTH
      IF (JARRAY(I)) 100,101,102
101   STOP 'ZERO VALUE PASSED TO DECODE'
100   JARRAY(I) = 256*256 + JARRAY(I)
102   ITEMP1 = JARRAY(I)/256
      ITEMP2 = JARRAY(I) -( ITEMP1 *256) -240
      OARRAY(I*2-1) = ITEMP1 - 240
      OARRAY(I*2) = ITEMP2
CANCEL      IF (I.LT.25) THEN
CANCEL      PRINT*, '  DECODE  - OARRAY(I*2-1) ', OARRAY(I*2-1)
CANCEL      PRINT*,  '  DECODE - OARRAY(I*2) ', OARRAY(I*2)
CANCEL      END IF
105   CONTINUE
      RETURN
      END



      SUBROUTINE EBCDIC (OARRAY,IRLTH2,IY0,ID0,IH0,IM0,IS0,
     £                                  IY1,ID1,IH1,IM1,IS1,ISCANS)
      INTEGER  OARRAY (IRLTH2)
      IY0 = I4(OARRAY,20,IRLTH2)
      ID0 = I4(OARRAY,24,IRLTH2)
      IH0 = I4(OARRAY,28,IRLTH2)
      IM0 = I4(OARRAY,32,IRLTH2)
      IS0 = I4(OARRAY,36,IRLTH2)
      IY1 = I4(OARRAY,42,IRLTH2)
      ID1 = I4(OARRAY,46,IRLTH2)
      IH1 = I4(OARRAY,50,IRLTH2)
      IM1 = I4(OARRAY,54,IRLTH2)
      IS1 = I4(OARRAY,58,IRLTH2)
      ISCANS = OARRAY(63)*10000 +  I4(OARRAY,64,IRLTH2)
      RETURN
```

```
      END


      INTEGER FUNCTION I4 (OARRAY,I,IRLTH2)
      INTEGER OARRAY (IRLTH2)
      I4 = 0
      DO 200 J = 0,3
      IF (OARRAY(I+J).LT.0.OR.OARRAY(I+J).GT.9) THEN
      OARRAY(I+J) = 0
      GO TO 200
      ELSE
      I4 = OARRAY(I+J) * (10**(3-J))+I4
      END IF
200   CONTINUE
      RETURN
CANCEL      PRINT*, ' I4',I4
      END



      INTEGER FUNCTION ITDIFF (IY2,IY1,ID2,ID1,IH2,
     £                 IH1,IM2,IM1,IS2,IS1,ISCAN2)
      IMINC = 0
      IF(IY2.NE.IY1 ) WRITE (6,'(''  ***** WARNING  -  IY2.NE.IY1 '')')
      IF (ID2.NE.ID1) WRITE (6,'(''  *****  WARNING  -  ID2.NE.ID1'')')
C      ID1 = ID1 + ISCAN2/3.D0/6.D1/2.4D1
C      HR1 = ISCAN2/3.D0/6.D1 - ID1 * 2.4D1
C     £      +  IH1 + (IS1/6.D1 + IM1)/6.D1
C      IH1 = INT (HR1)
C      IM1 = INT ((HR1-IH1)*6.D1)
C      IS1 = INT (((HR1-IH1)*6.D1 - IM1) * 6.D1)
      IF (IH2.LT.IH1) PRINT*,  ' FUNCTION ITDIFF HI2.LT.IH1'
      IF (IH2.GT.IH1) THEN
      IM1 = 60.0 - IM1 - 1
      IS1 = 60.0 - IS1
      ITDIFF = ((IM2+IM1)*60.0 + IS2 +IS1 )/20
      RETURN
      END IF
      ITDIFF = ((IM2-IM1)*60.0 + (IS2 - IS1))/20
CANCEL      WRITE (10, '('' END TIME '',3I10)')IH1,IM1,IS1
CANCEL      WRITE (10, '(''  START TIME '',3I10)') IH2,IM2,IS2
            PRINT*, ' ITDIFF ' ,ITDIFF
      RETURN
      END



      SUBROUTINE SAVER (BUFF2,SAVE,IDIFF,IEND)
       INTEGER SAVE (500)
      INTEGER BUFF2(50000)
      DO 400 I = 251,250 + IDIFF
      SAVE (I) = 9999
400   CONTINUE
      DO 401 I = 251 + IDIFF , 500
      SAVE (I) = BUFF2 (I - 250 + IEND )
401   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE JOIN (SAVE,IEND2,IBOT,IDIFF,IMAX,X,Y,W,WORK1)
      REAL *8   Y(IMAX), X(IMAX), W(IMAX), WORK1(3,IMAX)
     £         ,WORK2(2,3), A(3,3), S(3), AK(3), XM, MPUT
      INTEGER SAVE(IMAX),BUFF2,M,IFAIL,NROWS,K1,IMAX
      COMMON BUFF2(50000)
      M = IMAX - IDIFF
      NROWS = 3
      K1 = 2 + 1
      DO 501 I = 1, IBOT
      Y (I)  =  SAVE(I)
      X(I)  = I
  501 W(I)  = 1.0
      DO 502 I = IBOT + 1 , IMAX - IDIFF
      Y(I) = SAVE (I + IDIFF)
      W(I) = 1.00
  502 X(I) = I + IDIFF
      IFAIL = 0

C             TEMPORARY OUTPUT CHANNEL FOR EXAMINING INPUT TO E02ADF
CANCEL      WRITE (10,'(4I6)') IEND2,IBOT,IDIFF,IMAX
CANCEL      WRITE (10,'(12F8.2)') (X(K),K=1,M)
CANCEL      WRITE (10,'(12F8.2)') (Y(K),K=1,M)
CANCEL      WRITE (10,'(12F8.2)') (W(K),K=1,M)

       CALL E02ADF (M,K1,NROWS,X,Y,W,WORK1,WORK2,A,S,IFAIL)
      IF (IFAIL.NE.0) GO TO 598
      DO 504 I = 1,K1
  504 AK(I) = A(K1,I)
      K1 = 3
      DO 503 I =  IBOT + 1 , IBOT + IDIFF
      XM = ((I-1) - (IMAX-I)) / (IMAX - 1.0)
      IF (DABS(XM).GT.1) GO TO 599
      IFAIL = 0
      CALL E02AEF (K1,AK,XM,MPUT,IFAIL)
      SAVE(I) = NINT(MPUT)
   503 CONTINUE
      IF (IEND2.GT.IMAX) RETURN
      DO 500 I = 1 , IDIFF + IEND2
      BUFF2 (I) = SAVE (IBOT-IEND2+I)
 500  CONTINUE
      RETURN
  598  STOP  ' JOIN E02ADF - IFAIL '
   599 STOP ' JOIN  DABS (XM)   '
      END


      SUBROUTINE FIT (BUFF1,M,OPUT)
      INTEGER BUFF1 (M),M,IFAIL,NROWS,K1
      REAL*8 X(360),Y(360),W(360),A(3,3), MPUT,
     £WORK1(3,360),WORK2(2,3),S(4),AK(4)
      NROWS = 3
      K1 = 2 + 1
      DO 600 I = 1,M
      Y(I) = REAL (BUFF1(I))
      X(I) = I
  600 W(I) = 1.00
```

```
      IFAIL = 0
      CALL E02ADF (M,K1,NROWS,X,Y,W,WORK1,WORK2,A,S,IFAIL)
      IF(IFAIL.NE.0) GO TO 699
      DO 601 I = 1 , 3
  601 AK (I) = A (K1,I)
      CALL E02AEF (K1,AK,0,MPUT,IFAIL)
      IF (IFAIL.NE.0) GO TO 699
      OPUT = SNGL(MPUT)
      RETURN
  699  WRITE (6,'(''IFAIL.NE.0'')')
      END


      INTEGER FUNCTION  ISHIFT  (IA2,IP,ISIZE)
      INTEGER*2 IA2(ISIZE)
      INTEGER  IP, ISIZE
      IF ((IP+10).GT.500)  STOP  ' IP.GT.490   SHIFT '
      DO 700 I = IP, IP+20
      PRINT*, IA2(I),I
      IF (IA2(I)-IA2(I-1).EQ.0.AND.I.NE.IP)  GO TO 703
  700 CONTINUE
   703 IB = IA2(I)
      DO 701 I = IP, IP-20,-1
      PRINT*, IA2(I),I
      IF (IA2(I) - IA2(I+1).EQ.0.AND.I.NE.IP) GO TO 704
  701 CONTINUE
   704 IA = IA2(I)
      ISHIFT = IB - IA
      PRINT*, ISHIFT
      RETURN
      END


      SUBROUTINE ROUTE1286 (IA2,I,IFLAG)
      INTEGER*2 IA2(500)
      DO 801 K = I-1,I+1
  801 IA2(K) = IA2 (I-2)
      IFLAG = I + 4
      RETURN
      END


CODE    16080 BYTES       PLT + DATA  361888 BYTES
STACK    3592 BYTES       DIAG TABLES   2152 BYTES      TOTAL  383712 BYTES
COMPILATION SUCCESSFUL
```

probable annual magnitude of 5.3 (Makropoulos 1978, fig. 7.3). The earthquakes of 1894 were the last major events in this locality and the elapsed time, 88 yr exceeds the determined return period (82 yr) of a magnitude 6.5 event. After the 1981 February/March earthquakes in the Gulf of Corinth ($M_S$ = 6.7, 6.4, 6.4, USGS) seismic activity increased in the area north of Thibes consistent with the hypothesis of eastward migration (Båth 1979). In 1981 July the Seismological Laboratory of the University of Athens established a local network of six 'Sprengnether' instruments. These were withdrawn in 1982 July with the introduction of a telemetred network of Willmore MK III seismometers operated jointly with the Institute of Geological Sciences, UK. The positions of four of these seismic stations are shown in Fig. 1, five further stations are located approximately radially about station VSI (average distance, 70 km).

## Data collection

A network of 68 stations (with a total of 370 observations) was established during each survey period. The instruments used were La Coste and Romberg model G gravimeters with optical read out only (1981, G-496 and G-275; 1982, G-496 and G-478). La Coste and Romberg gravimeters have been shown to be capable of measuring single gravity differences with a standard error of 0.018 gu when rigorous measuring procedures are followed (Hipkin 1978). Many high precision surveys quote standard deviations in the range 0.10–0.20 gu (e.g. Kinviniemi 1974; Torge & Drewes 1977).

All measurements were made in a ladder sequence of the form ABCDEEDCBA which controls a wide spectrum of drift. The station locations are shown in Fig. 1. Base stations (o, Fig. 1) were measured on more than one sequence and were also tied independently to the master base in Athens in a separate ladder sequence. The Greek National Calibration Line, consisting of five monumented stations on Mount Parnis, near Athens, was measured before and after any field campaign. The calibration line overlaps only part of the gravity range of the network. It serves to demonstrate possible variations in the scale factor before and after a campaign and to relate different field campaigns.

Station locations were photographed and positions marked with a masonry pin and a circle of paint. Wherever possible, sites, particularly base stations, are located on bedrock. One foot of a hemispherical plate sits on the masonry pin and the meter, which has one foot fixed, is placed within a confined location on the plate. In this manner height variations upon return to a station are in the range 0–2 mm and never exceed 5 mm. Pressure and temperature are read simultaneously with gravity to 0.01 mbar and 0.1 K respectively. The resurvey of 1982 failed to locate only one station, S7.

The stations are located on both sides of the main fault with a predominance of stations on the downthrown side in the area of complex secondary faulting. A group of 10 stations is located a few kilometres north of Thibes where local activity increased ($M_L$ 4.0–4.4) immediately following the 1981 Gulf of Corinth earthquakes ($M_S$ 6.7, 6.4, 6.4, USGS). Some poorly built rough-hewn stone outhouses collapsed in this area during these major shocks.

## Data processing

The data were first corrected for earth tides using the harmonic expansion of Cartwright & Tayler (1971) as amended in Cartwright & Edden (1973). Tests on the program show it to be in good agreement with Broucke, Zurn & Schlichter (1972) and also Heikkanen (1978) with maximum differences at the hundredth of a gravity unit level. No pressure correction was applied (0.004 gu mb$^{-1}$, Brien *et al.* 1977) as the pressure was not measured sufficiently

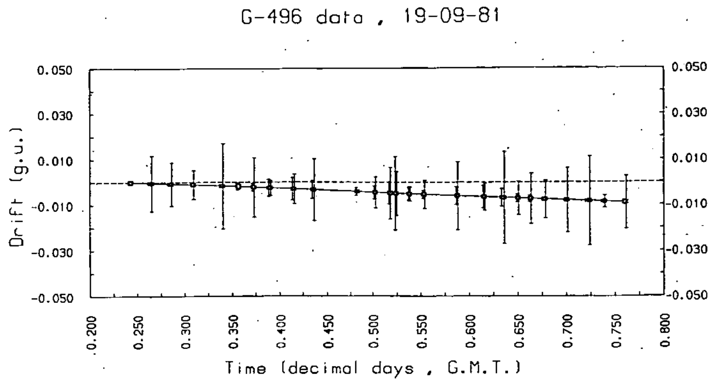


**Figure 2.** Typical daily linear fit.

accurately in 1982. It should be noted that pressure systems over Greece during the summer months are very stable and frequently the pressure difference upon return to a site during a ladder sequence was less than 1 mb, during the 1981 survey.

The advantage of using a harmonic expansion to evaluate the tidal potential rather than the computationally more rapid closed expression is that it enables one to apply different gravimetric factors at different frequencies. In the case of the eastern Mediterranean the ocean loading signal is not well determined but may be assumed to be small because of the limited tidal range of the Mediterranean and the distance from large oceans.

Daily drift curves were constructed for each instrument using a simple linear fit to isolate misreadings and abnormally high drift rates. Fig. 2 illustrates such a fit for the 1981 September 19 using G-275. These daily drift curves exhibit very low root mean square values and illustrate the consistency of the measured gravity differences during one day. No readings from instrument G-496 have been excluded from the final adjustment but it was necessary to exclude station S25 from the G-275 data set. Furthermore it was noted that G-275 exhibited a large scatter on the 1981 September 15 when a battery failure occurred. The results from instrument G-478 are not discussed here as this instrument possesses significantly higher root mean square errors than G-275 and G-496. This instrument had presented problems in the field, the beam sticking firmly in the mid-range.

A network adjustment computer program (a modified version of Lagios & Hipkin 1980) was now applied to the culled data set as corrected for earth tides. This program performs a least squares adjustment to all the data and also incorporates an independent first, or optionally second-order drift curve to each observation sequence; only linear solutions were used in the final analysis. More than half the total observations are repeat readings at a base station (i.e. stations occupied on more than one day) and every third day includes a remeasurement of base stations only. These repeat measurements in addition to the calibration line observations control the long-term drift and strengthen the network adjustment.

## Results of observations

Table 1 lists the gravity differences obtained in 1981 from a combined network adjustment of both instruments. (Values shown are relative to the Mount Parnis Summit Station, an arbitrary choice of the lowest valued station.) Fig. 3 is the histogram of the network residuals compared with the best fitting normal curve.

The standard deviation is 0.083 gravity units and $P(\chi^2_9 < 5.02)$ equals 0.84 implying a normal distribution of the sample with that standard deviation (class intervals with fewer

**Table 1.** Gravity values with respect to Mount Parnis, summit, 1981.

NETWORK ADJUSTMENT USING MULTILINEAR DRIFT

| BASE | | GRAVITY | STD. DEV. | NO. OF OBS. |
|---|---|---|---|---|
| B0 | 1 | 2217.705 | 0.095 | 9 |
| B1 | 2 | 2027.146 | 0.048 | 12 |
| B1A | 3 | 2025.812 | 0.098 | 5 |
| B2 | 4 | 2508.173 | 0.118 | 6 |
| B3 | 5 | 2462.735 | 0.074 | 6 |
| B4 | 6 | 2443.064 | 0.066 | 6 |
| B5 | 7 | 1884.791 | 0.099 | 12 |
| B6 | 8 | 2189.887 | 0.085 | 4 |
| B7 | 9 | 2030.269 | 0.142 | 14 |
| B8 | 10 | 2659.036 | 0.086 | 8 |
| B9 | 11 | 2592.061 | 0.096 | 12 |
| B10 | 12 | 2383.158 | 0.080 | 20 |
| B11 | 13 | 1405.987 | 0.096 | 8 |
| B12 | 14 | 2249.939 | 0.095 | 12 |
| B13 | 15 | 2057.332 | 0.039 | 8 |
| B14 | 16 | 2441.320 | 0.059 | 8 |
| B15 | 17 | 2158.449 | 0.268 | 8 |
| GNCL1 | 18 | 1819.474 | 0.140 | 6 |
| GNCL2 | 19 | 1249.472 | 0.153 | 6 |
| GNCL3 | 20 | 846.135 | 0.113 | 6 |
| GNCL4 | 21 | 379.121 | 0.119 | 6 |
| GNCL5 | 22 | 0.000 | 0.116 | 6 |
| S1 | 23 | 1536.709 | 0.115 | 2 |
| S2 | 24 | 2462.167 | 0.011 | 4 |
| S3 | 25 | 2532.478 | 0.027 | 4 |
| S4 | 26 | 2529.381 | 0.074 | 4 |
| S5 | 27 | 2542.742 | 0.036 | 4 |
| S6 | 28 | 2164.528 | 0.034 | 4 |
| S7 | 29 | 2482.211 | 0.074 | 4 |
| S8 | 30 | 2508.927 | 0.047 | 4 |
| S9 | 31 | 2129.428 | 0.111 | 4 |
| S10 | 32 | 2110.166 | 0.085 | 4 |
| S11 | 33 | 2428.242 | 0.060 | 4 |
| S12 | 34 | 2558.103 | 0.031 | 4 |
| S13 | 35 | 2546.457 | 0.067 | 4 |
| S14 | 36 | 2554.550 | 0.084 | 4 |
| S15 | 37 | 2530.514 | 0.088 | 4 |
| S16 | 38 | 2464.732 | 0.034 | 4 |
| S17 | 39 | 2450.075 | 0.060 | 4 |
| S18 | 40 | 2221.558 | 0.043 | 4 |
| S19 | 41 | 2044.108 | 0.051 | 4 |
| S20 | 42 | 1955.573 | 0.062 | 4 |
| S21 | 43 | 1901.396 | 0.105 | 4 |
| S22 | 44 | 1709.467 | 0.077 | 4 |
| S23 | 45 | 2285.937 | 0.088 | 4 |
| S24 | 46 | 2283.740 | 0.058 | 4 |
| S25 | 47 | 2386.083 | 0.060 | 2 |
| S26 | 48 | 2411.504 | 0.079 | 4 |
| S27 | 49 | 2448.345 | 0.061 | 4 |
| S28 | 50 | 2483.059 | 0.086 | 4 |
| S29 | 51 | 2503.796 | 0.033 | 4 |
| S30 | 52 | 2479.436 | 0.054 | 5 |
| S31 | 53 | 2258.368 | 0.094 | 4 |
| S32 | 54 | 2210.567 | 0.061 | 4 |
| S33 | 55 | 2228.518 | 0.006 | 4 |
| S34 | 56 | 2233.458 | 0.061 | 4 |
| S35 | 57 | 2032.695 | 0.079 | 4 |
| S36 | 58 | 1909.074 | 0.116 | 4 |
| S37 | 59 | 2638.612 | 0.135 | 4 |
| S38 | 60 | 2002.174 | 0.072 | 4 |
| S39 | 61 | 1998.661 | 0.027 | 4 |
| S40 | 62 | 2116.910 | 0.091 | 4 |
| S41 | 63 | 1934.386 | 0.050 | 4 |
| S42 | 64 | 2025.181 | 0.069 | 4 |
| S43 | 65 | 2143.646 | 0.019 | 4 |
| S44 | 66 | 2192.978 | 0.008 | 4 |
| S45 | 67 | 2220.827 | 0.038 | 4 |
| S46 | 68 | 2176.563 | 0.058 | 4 |

than five members are excluded). The individual single instrument adjustments yield standard deviations of 0.046, 0.066 and 0.077 gravity units for G496 (1981), G275 (1981) and G496 (1982) respectively.

Fig. 4 illustrates the difference between the readings before and after 10 days of field observations as measured on the calibration line during the 1981 survey. The gravity values used to obtain the differences were derived from independent daily straight line fits. The standard deviation of the differences is 0.09 gravity units, and the curve exhibits no discernible trend. The manufacturer's calibration tables were used throughout since it was not possible to observe on well-defined gravity differences in Greece.

TOTAL NUMBER OF OBS. = 368
STANDARD DEVIATION OF BEST FITTING NORMAL DISTRIBUTION IS 0.083 G.U.
EACH CLASS INTERVAL IS HALF THE STANDARD DEVIATION
NUMBER OF DEGREES OF FREEDOM = 9
CHI SQUARED IS 5.02

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NORMAL | 0 | 0 | 0 | 0 | 2 | 6 | 16 | 34 | 55 | 70 | 70 | 55 | 34 | 16 | 6 | 2 | 0 | 0 | 0 | 0 |
| FREQUENCY | 0 | 0 | 0 | 1 | 2 | 5 | 20 | 29 | 47 | 74 | 80 | 53 | 30 | 15 | 6 | 3 | 0 | 3 | 0 | 0 |

EACH * EQUALS 2 POINTS

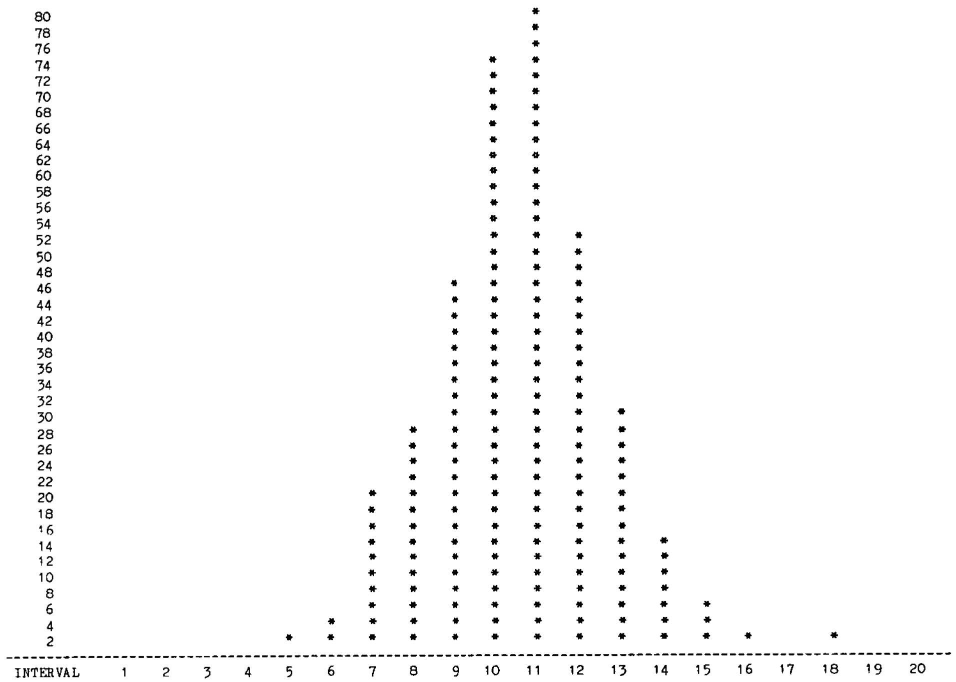


**Figure 3.** Histogram of residuals; least squares network adjustment, 1981.

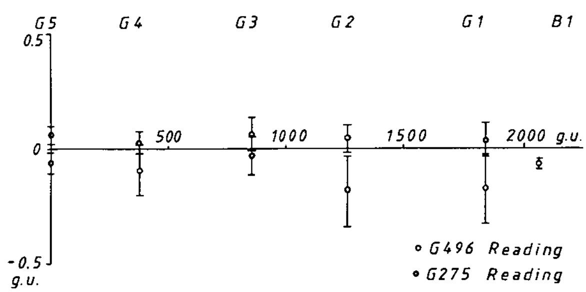


**Figure 4.** Differences between initial and final readings on Mount Parnis calibration line. Gravity values are relative to GNCL5, linear least squares adjustment.

Fig. 5 is a graph of the temporal variation of observed gravity between 1981 and 1982, adjusted such that there is zero change of the mean. The error bars shown are the combined root mean square errors of that individual station's adjustment. A histogram of the distribution (Fig. 6) indicates a high probability of normality ($P(\chi_4^2 < 0.21) = 0.97$). The difference distribution's standard deviation of 0.11 gu is in agreement with the combination of sigmas of the component data sets 0.077 and 0.083 gu ($(0.077^2 + 0.083^2)^{1/2} = 0.113$). Therefore the residual differences are consistent with the hypothesis of no gravity change at the 0.11 gu level.

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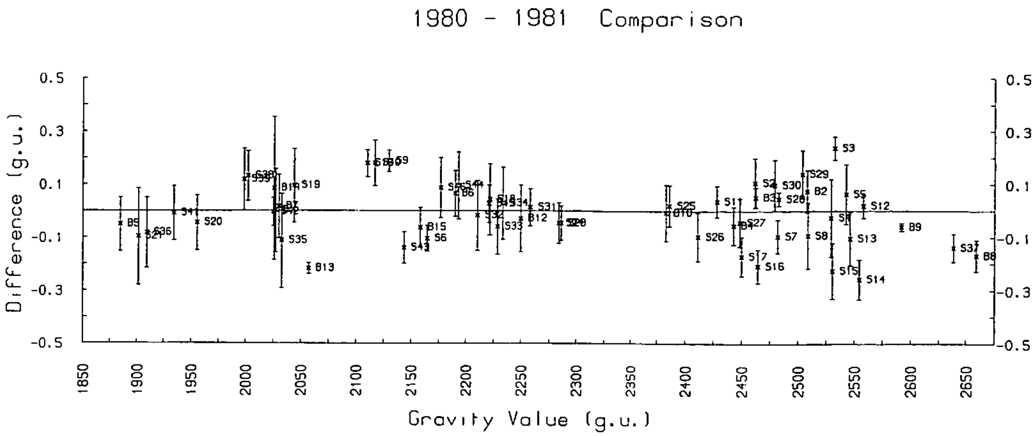


**Figure 5.** Gravity difference 1981–1982. Values are with respect to station GNCL5 (Mount Parnis summit). Six stations with values between 0 and 1850 gu are not shown.

```
TOTAL NUMBER OF OBS. = 64
DISTRIBUTION STANDARD DEVIATION OF  0.11 G.U.
EACH CLASS INTERVAL IS HALF THE STANDARD DEVIATION
NUMBER OF DEGREES OF FREEDOM = 4
CHI SQUARED IS  0.21

NORMAL       0   0   0   0   0   1   3   6  10  12  12  10   6   3   1   0   0   0   0   0
FREQUENCY    0   0   0   0   0   2   4   3  10  12  13  10   5   4   1   0   0   0   0   0
-------------------------------------------------------------------------------------------
   13                                            *
   12                                        *   *
   11                                        *   *
   10                                    *   *   *   *
    9                                    *   *   *   *
    8                                    *   *   *   *
    7                                    *   *   *   *
    6                                    *   *   *   *
    5                                    *   *   *   *   *
    4                            *       *   *   *   *   *   *
    3                            *   *   *   *   *   *   *   *
    2                        *   *   *   *   *   *   *   *   *
    1                        *   *   *   *   *   *   *   *   *   *
-------------------------------------------------------------------------------------------
INTERVAL     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
```

**Figure 6.** Histogram of gravity differences 1981–1982.

Future measurements, collected in an identical fashion, will be included in a common adjustment procedure to detect sites with a 'non-normal' behaviour possibly caused by tectonic activity.

## Conclusion

A high precision gravity network has been established in the Atalanti area involving a comparatively short measuring period (10 day). This network has obtained a normally distributed set of residual differences between the years 1981 and 1982 with a standard deviation of 0.11 gu. Should the difference distribution have been non-normally distributed or possessed a higher standard deviation (> 0.11 gu) there would be grounds for an immediate gravity remeasurement and possibly other geodetic observations. Hence it has been shown that no tectonic movements have occurred in the period 1981–1982, in the Atalanti region, within the limits of accuracy of the survey.

Anderson & Whitcomb (1975) present a relationship between earthquake magnitude and a precursory anomalous area of the form:

$$\log L\ (\mathrm{km}) = 0.26\,M + 0.46$$

$L$ = horizontal extent, $M$ = earthquake magnitude

for some events. Thus for a magnitude 6.5 event the horizontal extent of the anomalous area is 141 km. The duration of preseismic crustal deformation of a magnitude 6.5 event is five years when calculated using the formulation of Tsubokawa (1973). The network established by the authors in the Atalanti area of Eastern Greece is situated on an active fault zone with a station spacing of approximately 2 km traversing the anticipated anomalous area. Rundle (1978) has modelled the gravitational effect of a thrust fault at a depth of 10 km, and obtains a maximum gravity change of 0.5 gu, well within the precision limits of the network (see 'Results of observations').

## Background

The Atalanti region (Fig. 1), is one area of high seismic potential in the Hellenides (Makropoulos 1978). One large fault, trending WNW–ESE, extends from the town of Molos, passing through the southern outskirts of Atlanti, and terminates in Western Evia. The region to the east, on the downthrow side of the main fault, is dissected by minor faulting as shown in Fig. 1 (based on Mercier 1975; Philippson 1930). The most recent large magnitude events last occurred in 1894 April ($M > 6.7$, $M > 6.9$, Karnik 1970) and resulted in large surface ruptures (maximum 2 m, Karnik 1970) visible on *Landsat* images (Mackenzie 1977, fig. 17).

Statistical analysis using the Extreme Value Method (Gumbell 1966) of a reconstructed earthquake catalogue for the Hellenic Area shows a pronounced high in this area with a most

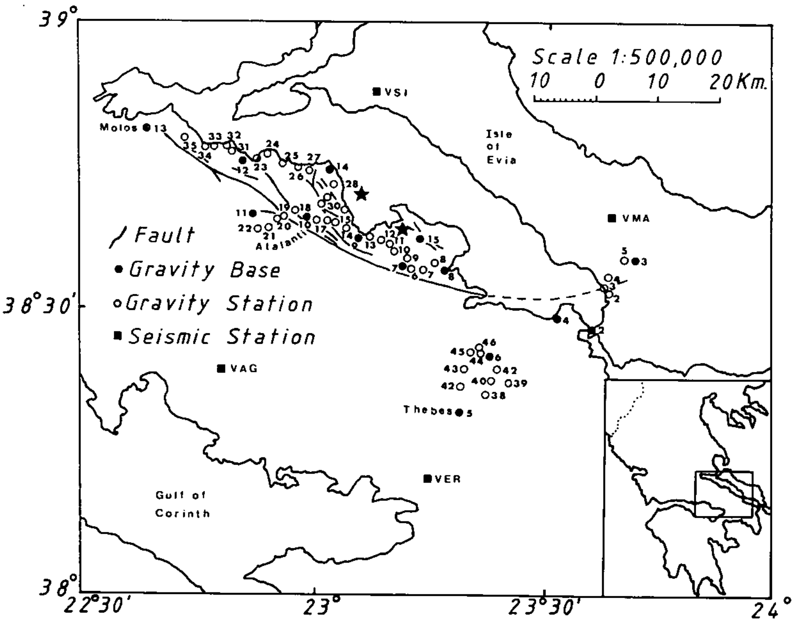


**Figure 1.** Map and station plan of the survey area (★ shows the epicentres of the seismic events of 1894 April).

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# A microgravimetric network in East Central Greece – an area of potential seismic hazard

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**Summary**. The eastern Mediterranean is a region of complex tectonic processes and associated horizontal and vertical displacements. A high precision gravity network has been established in the Atalanti area of central Greece to monitor temporal gravity changes on an annual or more frequent basis. A total of 68 sites have been measured in 1981 and 1982 with a maximum single instrument standard deviation of 0.08 gravity units after a least squares network adjustment. Analysis of the gravity differences between the two measuring epochs exhibits no change of gravity over the network with a precision of 0.11 gravity units. It is proposed that the gravity values given form a stable base for continued observations which will enable the authors to resurvey the region in the event of precursory foreshocks. Observation of the Atlantic network will continue on an annual basis preserving the same observation sequence for reasons of symmetry.

## Introduction

It has been shown that conventional gravity surveys can register gravity changes before and after earthquakes (e.g. Barnes 1966; Chen, Hao-Ding & Zao-Xun 1979; Oliver *et al.* 1975). Gravity surveying is inexpensive and extremely rapid when compared with geodetic levelling. Though not capable of detecting as small a deformation, gravity surveying has the advantage that errors are not significantly distance dependent (levelling precision is related to the square root of the distance traversed, typically 1.5 mm $\sqrt{}$km, Bomford 1980). High precision gravity surveying to assist in the assessment of earthquake deformation parameters is currently taking place in several seismic risk areas on the globe. Networks have been established in southern California (Whitcomb *et al.* 1980), Japan (National Report IUGG 1975) and also in Iceland (Torge & Drewes 1977).

Gravity data alone can provide important diagnostic information and perhaps precursory data but Whitcomb (1976) emphasizes the need for combined levelling and gravity measurements and presents analytic relationships between the measured quantities. It is proposed that should a large seismic event take place, new first-order levelling will be undertaken.