Monitoring Changes in Regional Ground Level, Using High Precision GPS

Technical Report
W210

Natural
Environment
Research
Council

Monitoring Changes in Regional Ground Level, Using High Precision GPS

R&D Technical Report W210

R M Bingley, V Ashkenazi, N T Penna, S J Booth (IESSG), R A Ellison and A N Morigi (BGS)

Research Contractor:
Institute of Engineering Surveying and Space Geodesy (IESSG)
University of Nottingham and British Geological Survey (BGS)

Further copies of this report are available from:
Environment Agency R&D Dissemination Centre, c/o
WRc, Frankland Road, Swindon, Wilts SN5 8YF

tel: 01793-865000 fax: 01793-514562 e-mail: publications@wrcplc.co.uk

Publishing Organisation:
Environment Agency
Rio House
Waterside Drive
Aztec West
Almondsbury
Bristol BS32 4UD

Tel: 01454 624400 Fax: 01454 624409

ISBN: 1 85705 121 1

Dissemination status

Internal: Released to Regions
External: Public Domain

Statement of use

This report is intended as a source of information to Environment Agency and external organisations working in the fields of Flood Defence, Coastal and Estuarine Management, Natural and Man-made Structure Monitoring and Geological Interpretation.

Research contractor

This document was produced under R&D Project W5-i698 by:

IESSG
University of Nottingham
University Park
Nottingham
NG7 2RD

Tel: 0115 951 3880 Fax: 01115 951 3881

Environment Agency Project Leader

The Environment Agency's Project Leader for R&D Project W5-i698 was:
Mr Keith Nursey, Survey Group, Thames Region

CONTENTS

Executive Summary **1**

1 **Introduction** **2**

2 **Geological Background of the Thames Region** **4**
2.1 Tectonic Processes 4
2.2 Isostatic Processes 6
2.3 Evidence of Ground Movement from Holocene Sediments in the Thames Estuary 6
2.4 Evidence for Holocene Ground Movement along the Essex Coast 7
2.5 Hydrogeological Effects 8
2.6 Geotechnical Considerations 8
2.7 Summary 10

3 **High Precision GPS** **11**
3.1 The Global Positioning System 11
3.2 The International Terrestrial Reference System 13
3.3 The International GPS Service 14
3.4 Systematic Errors 14
3.5 Summary 17

4 **Development of the Monitoring Strategy** **19**
4.1 Monitoring Network 19
4.2 Geodetic Observation Strategy 22
4.3 Geodetic Processing Strategy 24
4.4 Software Developments 27

5 **Development of the Geological Database** **33**
5.1 Database Inputs 33
5.2 Database Outputs 33
5.3 Compaction Studies 37

6 **Geodetic Results** **38**
6.1 Observations 38
6.2 Processing 40
6.3 Height Time Series 41

7 **Geodetic/Geological Interpretation** **45**
7.1 Reference Stations 45
7.2 Links to Sea Level 47
7.3 London Basin Tectonic Activity 49
7.4 Greenwich Fault 50
7.5 Aquifer Recharge 51
7.6 Alluvial Compaction 52
7.7 London Clay Swell-Shrink 54

8 **Conclusions and Recommendations** **57**

References **58**

APPENDICES

A Geological Time Scale 62

B Precision Measures Used 64

C Reference Station Height Time Series 66

D Monitoring Station Height Time Series 69

LIST OF FIGURES

1 Contours on the base of the Pliocene deposits (c 1.8 Ma) in the London Basin 5

2 Holme post, Cambridgeshire, showing former ground levels resulting from peat shrinkage and compaction 9

3 Schematic diagram of the monitoring network 20

4 Generalised thickness of Holocene deposits in the Thames valley 34

5 Generalised Peat thickness in the Thames valley 34

6 3-D view of the base of the Holocene deposits in the Thames valley, viewed from the south-east 35

7 3-D view of the base of Quaternary sediments below the Holocene deposits in the Thames valley, viewed from the south-east 36

8 3-D view of the base of the Holocene sediments in the Thames valley, draped with the digital terrain model, viewed from the south-east 36

9 Height time series for the three reference stations 45

10 Height difference time series for Barking Barrier minus Sunbury Yard 46

11 Height difference time series for Sheerness TG minus Sunbury Yard 46

12 Height time series for the 'western tide gauge monitoring stations' 48

13 Height time series for the 'eastern tide gauge monitoring stations' 48

14 Height time series for the 'northern regional monitoring stations' 49

15 Height time series for the 'southern regional monitoring stations' 50

16 Height and height difference time series for the Greenwich fault monitoring stations 51

17 Height and height difference time series for the aquifer recharge monitoring stations 52

18 Height and height difference time series for Tilbury TG and Gravesend Grammar School 53

19 Height and height difference time series for Southend Pier TG and Grain 53

20 Height time series for the London clay swell-shrink monitoring stations 55

21 Height time series for Dunton Hills based on GPS and precise levelling 55

LIST OF TABLES

1 Summary of potential rates of changes in ground level in the Thames region 10

2 Summary of geological considerations for stations in the monitoring network 21

3 Comparison of 'Mark 1' and 'Mark 2' automated procedures for the reference stations 30

4 Comparison of 'Mark 2' and 'Mark 3' automated procedures for the reference stations 32

5 Summary of settlement analyses results for three sites 37

6 Efficiency of the geodetic observation strategy for the reference stations 39

7 Efficiency of the geodetic processing strategy for the reference stations 40

8 Height standard deviations and precisions for the reference stations 42

9 Height standard deviations and precisions for the monitoring stations 43

EXECUTIVE SUMMARY

This R&D Technical Report is presented to the Environment Agency by the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham and the British Geological Survey (BGS). It forms the standard output from the R&D project titled "Monitoring Changes in Regional Ground Level, Using High Precision GPS". The project started in April 1996 and was completed in September 1999. The project was funded through the Natural Environment Research Council's CONNECT B Scheme, with the Agency and the NERC each paying 50% of the costs involved. The IESSG were the main contractor to the Agency, and the BGS acted as sub-contractors to the IESSG.

The aim of the project was to develop a generic strategy for monitoring small changes in ground level within regions of up to 100 x 100 km in extent, and providing an interpretation of such changes in terms of local and regional geology.

The monitoring strategy developed is based around a monitoring network, a geodetic observation strategy, a geodetic processing strategy and a geological database. The monitoring network consists of a small number of reference stations and a dense network of monitoring stations, with station locations based on geological and geodetic criteria. Through the geodetic observation strategy, GPS data is observed over a period of time, using a combination of continuously operating GPS receivers at the reference stations and episodic GPS measurements at the monitoring stations. The geodetic processing strategy then enables the archiving, processing and analysis of the GPS data in order to obtain estimates of changes in height at the reference and monitoring stations. From these, the geological database enables the assessment of past, current and future changes in ground level.

The monitoring strategy was tested in a pilot study related to flood defence, carried out in a region in and around the London basin, which will be referred to as the 'Thames region' in this report. In this region, historical evidence suggests an apparent rise in the water level of the Thames estuary relative to the land. Over the last century, this may be due partly to a rise in global sea level, as a consequence of climate change, and partly to changes in ground level.

The results from the pilot study show that with the monitoring strategy that has been developed it is possible to obtain time-averaged mean heights with a precision of 0.4 mm for the reference stations and 1.3 to 3.3 mm for the monitoring stations, after a period of 2.25 years. Over this monitoring period, these results suggest that the changes in regional ground level in and around the London basin do not exceed a few millimetres per year, unless there is seasonal swell-shrink where London Clay is at the surface.

Using this monitoring strategy over a longer monitoring period, it should be possible for vertical station velocities of 1 mm/yr to be estimated after 6 to 12 years. The exact length depends on the use of continuous or episodic GPS data and on the height standard deviation obtained for a particular station.

As a result of this project, the IESSG and the BGS have put in place a monitoring network that can be used by the Agency for the continued monitoring of long term changes in ground level in the Thames region. Furthermore, the monitoring strategy that has been developed is not specific to the Thames region and could be used by the Agency in any other regions where changes in ground level are of concern.

1 INTRODUCTION

Small ground movements can have major strategic or economic significance in certain regions of the world, for example in low lying river estuaries and coastal regions susceptible to flooding.

In 1996, the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham and the British Geological Survey (BGS) started work on a research project funded by the Environment Agency and the Natural Environment Research Council (NERC). The aim of the project was to develop a generic strategy for monitoring small changes in ground level within regions of up to 100 x 100 km in extent, and providing an interpretation of such changes in terms of local and regional geology. More specifically, the aims of the project, as outlined in the original proposal, were

(i) To develop a strategy for monitoring changes in regional ground level to millimetric accuracies using GPS.
(ii) To refine the strategy developed, by testing it on a pilot study related to flood defence in the 'Thames region'.
(iii) To investigate and quantify specific geological processes as they affect ground level over a range of time scales.

The Thames region was adopted for the pilot study based on historical evidence that suggests an apparent rise in the water level of the Thames estuary relative to the land. This evidence is provided by sediments deposited in the last 8000 years, at archaeological sites and from tide gauge information. However, quantification of this evidence is complex and is influenced by numerous natural and man-induced factors.

Archaeological evidence indicates that the River Thames was not tidal in Roman times and occupation levels in London were at least 2 m below current high water level (Muir Wood 1990). Today the River Thames is tidal, as far upstream as Teddington, and over the last two centuries there has been an increased tidal range caused by a decrease in tidal friction in the Thames estuary. The removal of the Old London Bridge in 1830, which had always acted as a partial barrage, and the extensive dredging of the River Thames, carried out in conjunction with the expansion of the London docks in the late 19th century, led to an increase in the tidal range from 4.6 to 6.3 m by 1877.

In 1978, the Thames tidal defences, including the Thames Barrier, were constructed to upgrade the protection of London and low-lying areas of Essex and Kent from flooding. Part of the justification for the construction of the barrier was an apparent 800 mm rise in the water level of the Thames estuary over the last century (an average of 8 mm/yr) indicated by the heights of storm tide surges and records from a tide gauge in Greater London (Muir Wood, 1990).

On a national scale, high quality tide gauge records have been used to produce mean sea level trends at coastal tide gauges which form part of the National Tide Gauge Network (Woodworth and Jarvis 1991; Woodworth et al 1999). However, the only high quality tide gauge records available for the Thames estuary are those for Tilbury, located to the East of London, and the coastal sites of Southend and Sheerness. In the most recent study, Woodworth et al (1999) published estimates for the mean sea level trends for these sites which showed rises in relative mean sea level at all three sites. The trends and their standard errors were +1.58 ± 0.91 mm/yr for Tilbury for the period from 1961-1983, +1.22 ± 0.24 mm/yr for Southend for the period 1933-1983 and +2.14 ± 0.15 mm/yr for Sheerness for the period 1901-1996 (Woodworth et al, 1999). Superimposed on these trends is a rise in global sea level. In 1990 and 1995, the Intergovernmental Panel on Climate Change (IPCC) reviewed the published evidence on the influence of global warming on sea levels (IPCC 1990; IPCC 1995). They found that global sea level had risen by between 10 and 20 cm over the past century. This is equivalent to a linear rise of the order of 1.0 to 2.0 mm/yr.

Contrasting the average 8 mm/yr rise in the level of the Thames estuary indicated by the heights of storm tide surges and records from a tide gauge in Greater London (Muir Wood, 1990) with the modern tide gauge records and the estimates of global sea level rise, the difference is of the order of 6 to 7 mm/yr. Muir Wood (1990) estimated that 40-75 % of the observed 8 mm/yr rise (ie 3 to 6 mm/yr) could be due to the increase in tidal range. However, this still leaves up to 4 mm/yr rise in water level possibly due to changes in ground level in Greater London.

To add to the uncertainty in the records of water level, there are very few historical geodetic observations of changes in ground level in Greater London. In the Second National Geodetic Levelling of Great Britain carried out by the Ordnance Survey (OS) between 1912 and 1921, the whole Thames region was omitted, but was surveyed between 1946 and 1951. The Third National Geodetic Levelling of Great Britain was carried out between 1952 and 1959. Not surprisingly, considering the precision of geodetic levelling at this time, Kelsey (1972) reported no significant change in the heights of OS benchmarks in Greater London between the Second and Third National Geodetic Levellings. Later, the inclusion of the results from a North - South levelling across London carried out by the OS in the 1960s, indicated a consistent sinking of Central London of approximately 2 mm/yr with respect to 'stable' points to the North and South. However, the high cost of such geodetic levelling exercises have meant that no further re-levellings have been carried out since.

Based on the historical evidence presented above, the general methodology and approach for this project, as outlined in the original proposal, were

(i) Design of a monitoring network, with station locations based on geological and geodetic criteria.
(ii) Development of an observation and processing strategy for a regional deformation monitoring GPS technique.
(iii) Geological modelling and interpretation of changes in ground level in the Thames region.

The way in which this methodology and approach were applied in order to meet the aims of the project is described in detail in the remainder of this R&D Technical Report. In particular, Chapters 2 and 3 provide the background information relating to the geological setting of the Thames region and the use of high precision GPS respectively. Chapters 4 and 5 detail the specific developments carried out by the IESSG and the BGS. Chapters 6 and 7 present the results from the pilot study, both in terms of geodetic quality and with some geodetic/geological analysis. Finally, Chapter 8 presents the conclusions and recommendations of this research project.

2 GEOLOGICAL BACKGROUND OF THE THAMES REGION

A broad understanding of geological processes operating in and around the London area formed the basis for the GPS network design and the interpretation of results. This chapter reviews these processes and their implications for current ground level change. Some of them involve displacement of the Earth's crust, others involve bulk volume changes with a largely vertical expression, yet others directly change the ground level by accretion or erosion. The processes operate within different time frames and over different geographical areas. Those leading to the displacement of the Earth's crust can be divided into tectonic and isostatic which in some instances are related. The bulk volume changes that may lead to ground level changes are of two contrasting types: hydrogeological, resulting from changes in the water table under Greater London, and geotechnical, concerning the behaviour of various deposits in response to natural and man-induced changes in soil geotechnical properties.

2.1 Tectonic Processes

London and its environs lie within a geological structure known as the London basin, which is an offshoot of the North Sea basin. The London basin has undergone spasmodic tectonic activity in the past several hundred million years, with episodes of relatively rapid structural change interspersed with periods of quiescence. The basin lies above the northern edge of the Variscan Front, a major crustal dislocation that has affected the ancient rocks that lie at least 250 m below the surface. Studies have shown that structures associated with the Variscan Front are arcuate in shape, trending WSW-ENE underneath London and ESE-WNW underneath north Kent. The most notable of these structures lies beneath the Thames estuary and passes beneath Tilbury. It appears to have influenced the deposition of chalk and Tertiary sediments 100 to 50 million years ago. It is also coincident with a zone of small folds and the Greenwich Fault in south London, formed during stresses associated with the Alpine mountain building period, between 20 and 8 million years ago. The most evident result of this Alpine event was the development of the broad synclinal fold that forms the London basin. At this time also the principal extensional fractures of the Chalk were developed roughly perpendicular to the crest of the North Downs. These have controlled the subsequent development of the dry valleys. Following the main Alpine folding there was a period of relative stability when subaerial planation surfaces developed on the folded sediments. Dissection of these surfaces began in the Pliocene (about 5 million years ago) when uplift-driven valley incision commenced (Maddy 1997).

An assessment of tectonic activity in Pliocene and more recent times is hampered because there are few reference deposits. It has been suggested, however, that about 2 million years ago, minor NE-SW trending faults controlled sedimentation of the Red Crag in a shallow sea in southern East Anglia, on the margins of the North Sea basin (Bristow 1983). In regional terms, the base of these deposits now increases in height from about sea level in the east to more than 120 m above sea level in the Chiltern Hills (Figure 1), an indication that tilting has occurred since their deposition. Other deposits, on the crest of the North Downs and in the Chiltern Hills, at elevations up to 180 m above sea level may also be degraded marine deposits of Pliocene age, although evidence is tenuous (see for example, Worssam (1963) for a review). Nevertheless, the data as a whole indicate a maximum uplift in the east of the London basin equivalent to 0.9 mm/yr over the past 2 million years. The hinge line for this uplift is thought to trend slightly west of north off the coast of East Anglia.

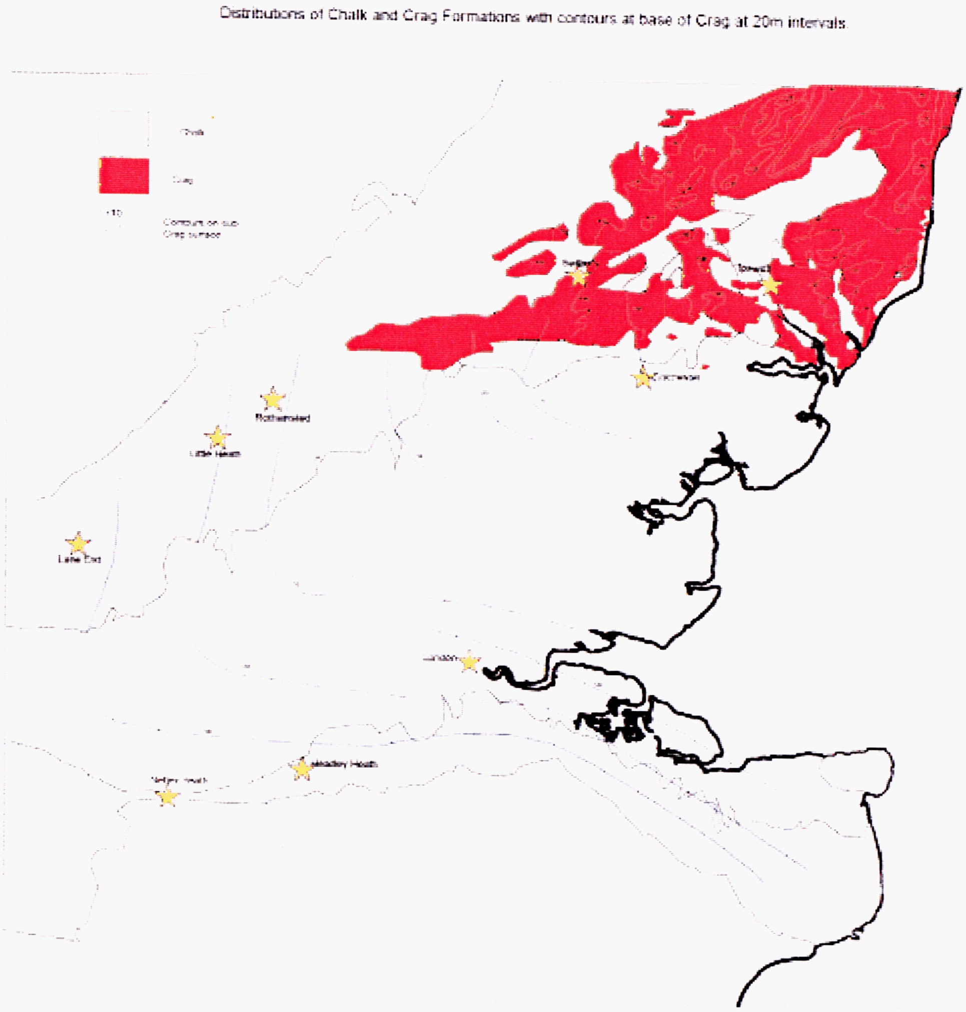

Distributions of Chalk and Crag Formations with contours at base of Crag at 20m intervals

Figure 1 Contours on the base of the Pliocene deposits (c 1.8 Ma) in the London basin

A further pointer to land level change concerns the terrace gravels of the River Thames. Following the penultimate glaciation about 500 000 years ago the River Thames was diverted from a course across southern East Anglia to its present valley through London. The gravel deposits laid down by this river form a staircase in the present day Thames valley, the oldest being at the greatest topographic elevation. The subsequent development of terrace gravels at progressively lower levels in the river valley is now thought to be due to land uplift equivalent to 0.7 mm/yr over the last 250 000 years (Maddy 1997).

The Thames gravels continue offshore as a series of submerged terraces. This pattern is consistent with the idea that the central and eastern part of the southern North Sea is an area of progressive downwarp, mainly as a response to the weight of sediment accumulating, whereas the west side of the southern North sea has been an area of net uplift during the past 500 000 years (Bridgland and D'Olier, 1995).

2.2 Isostatic Processes

Isostatic processes are adjustments of the earth's crust resulting from the loading or unloading of materials. Such loading changes may be due to changes in sea level, to tectonic stretching and thinning of the crust, to sedimentation or erosion, or to the building and wasting of ice cover during glaciation. This latter glacio-isostasy is considered to be the most important of these contributors in the Thames region. The last major glaciation to affect Britain reached its maximum between 20 000 and 15 000 years ago, with a maximum loading of ice centred over the Scottish Highlands. A consequence of this loading and crustal depression of northern Britain was the development of a largely concentric forebulge, or zone of crustal elevation, that included the southern North Sea and southern England, with Greater London and the Thames estuary within the forebulge. Deglaciation has led to the upward rebound of northern Britain as a consequence of forebulge collapse, a process that is thought to be continuing.

Current effects of glacio-isostatic forebulge are not suspected in the London basin. However it is likely that the area was previously affected several times by forebulge passage, not only by those related to the Scotland-centred ice sheets, but also those related to the much larger Scandinavian ice sheets. Evidence of changes of ground level associated with them has not been documented in the Thames region.

2.3 Evidence of Ground Movement from Holocene Sediments in the Thames Estuary

The Holocene alluvial sediments of the Thames estuary have been deposited in the last 8000 years. They consist largely of silts and clays, locally with peat (Marsland, 1986), generally 6 to 18 m thick and locally up to 23 m. The Holocene sediments rest on gravels of late Devensian age, the level of the base descending eastwards from about Ordnance Datum (OD) at Richmond to about 18 to 20 m below OD at Gravesend and 35m below OD north of the Isle of Grain (see Figure 2 in Section 2.4).

The estuary widens east of Tilbury and Gravesend, as the bedrock changes from relatively resistant chalk to the more easily eroded Palaeogene sediments. To the east of this point the alluvial sequence gradually changes from dominantly mud with peat layers to fine-grained sands.

Approximately from Woolwich eastwards to about mid-way between Tilbury and the Isle of Grain, evidence from boreholes show that the Thames alluvial sediments contain up to five peat beds (Spurrell 1889; Devoy 1979; 1982). The cross sections depicted by these authors show the oldest peat at a depth of 28 m below Ordnance Datum at the Isle of Grain, and the youngest at about Ordnance Datum. However, estuary-wide correlation of these peats is not established and thus the distribution of individual beds is not known in detail. This means that the significance of individual peats for an interpretation of estuary evolution cannot be firmly established.

Radiocarbon dates obtained from peat layers, and locally from fossil shell banks, have been used to construct sea level curves for the Thames estuary. This approach relies on a principle that the peat and the shell banks formed at or closely above the upper limit of marine influence, usually above the mean high water of spring tides. Devoy (1979) obtained 17 radiocarbon dates from peat layers in the Thames estuary. The occurrence of several peat beds in the succession indicates that there has been an overall rise in sea level as the Holocene sediments accumulated. There is an assumption that the accumulation was not steady but interrupted by marine transgressions following the accumulation of peat. However, the limited number of data points, the inability to accurately determine depth of deposition of the intervening marine sediments, and the difficulty of accounting for compaction of the peats, meant that it was not possible to present a precise sea level curve.

Devoy (1979) concluded that from about 8000 years BP there has been an overall rise in sea level, with minor fluctuations. He also identified that between 7000 years and 2500 BP there was an apparent 1.5 to 3 m difference in height of the mean high water spring tides between Tilbury and a site upstream. Possible explanations (see also Long, 1995) for this difference are:

- Variation in the amount of compaction and consolidation of the sequence.
- Greater upstream tidal amplitude and freshwater volume discharge, causing upstream deposition at relatively higher altitude. This is illustrated by the present day 0.6 m difference in mean high water spring tides between Tilbury and Woolwich.
- Downwarping or land sinking between Crossness and Tilbury; assuming that the maximum tidal height difference between the two localities has been constant at 0.6 m and that the rate of sinking has been constant, it can be deduced that a fall in land level of 0.9 to 2.4 m in 7000 years, or 0.13 to 0.34 mm/yr has occurred. Furthermore, since Devoy (1979) suggested that peat levels in the north and south sides of the estuary are roughly the same, it can be assumed that if land sinking has occurred it has occurred in a west to east direction.

These data for the Thames estuary were analysed further by Shennan (1989). He concluded that there was apparent uplift from 8500 to 6000 BP, no crustal movement from 6000 to 4000 BP and subsidence at a rate of -1.90 ± 0.32 mm/yr from 4000 BP to the present.

A wider view was taken by Long and Tooley (1994) who compared sea level index points in south-east England as a whole. They concluded that in the last 6000 years the net sea level rise in the Thames estuary has been 2 to 3 metres greater than on the Hampshire coast. This could be related to changes in ground level across the roughly east-west trending Variscan front, the deep seated geological structure referred to in section 2.1 of this report.

2.4 Evidence for Holocene Ground Movement along the Essex Coast

In the Blackwater estuary, along the northern shores of the outer Thames estuary the Holocene deposits are in generally a few metres thick. In contrast, beneath Maplin Sands, the deposits average 18 m thickness and reach 36 m in buried channels (Greensmith and Tucker 1980). This southward thickening may be caused by relatively rapid subsidence in the Thames estuary.

Greensmith and Tucker (1980) studied peats and shell beds, both assumed to have formed close to mean high water mark, dated as 3850 to 4959 years BP. They identified a height difference of 4.3 m between the Blackwater estuary and the Foulness/Maplin Sands, equivalent to a relative sea level change between the two localities of 3.9 mm/yr. Greensmith and Tucker (1980) suggested that differential downwarping in the outer Thames estuary may account for 1.5 m of this difference, equivalent to an average fall of 1.35 mm/yr. The axis of movement in this case is interpreted to trend north-east to south-west, parallel to inferred structures in the Tertiary strata in Essex.

2.5 Hydrogeological Effects

Groundwater in the aquifer sedimentary rocks under London served as an important supply to the city through the 19th and the early part of the 20th centuries. The aquifers into which wells and boreholes were sunk were the Chalk and the lower Tertiary sands; these formations being covered by the largely impermeable London Clay. Overpumping of the groundwater led to continued drawdown of the water table in the aquifers from a previously artesian condition. Abstraction largely ceased in the 1950s, and since then the water table has risen.

The drawdown of the aquifers was thought to have resulted in subsidence of up to 200 mm (Wilson and Grace 1942). This was due to draining of the Tertiary sands, consequent loss of pore space and sediment compaction. The rising groundwater is now replenishing the Tertiary sands aquifer, but it is not known whether this will result in an increase in volume and concomitant ground rise. Theory suggests that ground movement is unlikely as the loss of pore space due to dewatering in periods of low groundwater will not be recovered. Nevertheless this possibility is being investigated for the current project in the Enfield-Haringey area, north London, where the aquifer is being artificially recharged (O'Shea et al 1995).

2.6 Geotechnical Considerations

Ground movement occurs on account of the low strength and high compressibility of alluvial sediments, particularly peat (Marsland 1986). This natural compaction is particularly evident in the Fens and the Netherlands where peat layers locally have been eroded away by creeks, which have subsequently been filled with silt and mud. Compaction of the remaining peat has resulted in the former creek deposits being 2 m higher in elevation than the surrounding land. This represents roughly 4000 years of compaction, or an average rate of 0.5 mm/year. An illustration of the lowering of ground level in the Fens is illustrated by the Holme Post (Figure 2), a monument with plaques recording the successive fall in level, the greatest rate being between 1848 and 1870 when the water table was artificially lowered and the peat started to de-water.

The loading, due to construction, of strata containing peat leads to particularly acute problems of compaction and lowering of ground level. An example of this was the subsidence of nearly 0.4 m during the initial loading of a storage tank sited on the alluvial deposits of the Isle of Grain. Embankments may gradually sink into the alluvial deposits due to compaction, as at Dartford where settlement of 0.8 m in 5 years has been recorded (Marsland 1986).

Swelling is the term used to describe a number of processes that manifest themselves as an increase in volume of a soil (Hobbs et al 1982). As a consequence of swelling, the voids ratio (the ratio of pore spaces to solid material) of the soil will increase. As in situ natural soils are confined laterally and from below, swelling manifests itself as an upward displacement or heave of the ground surface, although the swelling pressures act in all directions. Shrinkage is the reverse process whereby the soil is subject to a reduction in volume. Shrinkage will not necessarily return a soil to its pre-swelling volume as there may be alterations in the soil mineralogy and changes to the soil structure caused by the swelling process.

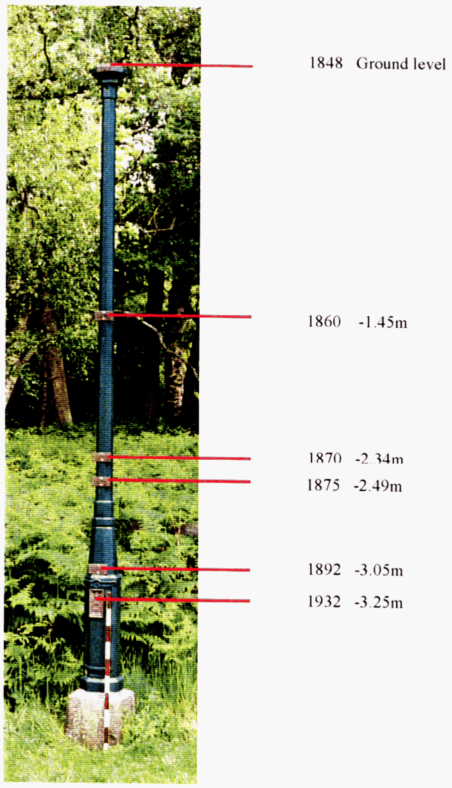


Figure 2 Holme post, Cambridgeshire, showing former ground levels resulting from peat shrinkage and compaction (Photo: Peter Balson)

London Clay is particularly susceptible to seasonal swelling and shrinkage on account of a high proportion of clay mineral that absorbs or releases water, depending on the ground conditions. Its impact upon structures can be severe, resulting in cracked walls and disturbed foundations. Studies in southern and south eastern England have shown that vegetation plays a dominant role in the seasonal swell/shrink of clays (Brackley 1975; Driscoll 1983). Long dry summers result in trees extracting large quantities of water from the soil causing shrinkage as the recharge rate is low, whilst in winter time, the surplus of water and low vegetation activity induces heave so perpetuating the cycle each year.

The combined effects of these seasonal swell/shrink phenomena result in a net heave of the surface due to changes in the soil structure. Driscoll (1983, 1984) reported 12 mm of heave in the London Clay over a three-year period, and 25 to 50 mm has been recorded elsewhere. The actual annual movement is greater still, and the Building Research Establishment has published figures showing that the total heave before summer shrinkage can be of the order of 50 to 100 mm (BRE 1980a, 1980b). Similar amounts of heave have been noted by Wimpey Laboratories Limited in the London Clay, following the removal of trees. In these cases more than 80 mm of vertical heave were recorded over a three-year period due to the increased amount of water available in the soil extending to a depth of around 5 metres (McEntee 1984).

2.7 Summary

Based on the background information presented in Sections 2.1 to 2.6 inclusive, the potential rates of change of the various components of ground level change in the Thames region are given in Table 1.

Table 1 Summary of potential rates of changes in ground level in the Thames region

Cause	Effect	Potential Rate of Change
Tectonic Processes	Relatively uniform uplift with regional tilt and/or flexure	0.7 to 0.9 mm/yr
Isostatic Processes	Subsidence due to collapse of forebulge	Negligible ?
Hydrogeological Effects	Ground uplift due to rising groundwater	Negligible ?
Geotechnical Considerations	Natural compaction: lowering of areas underlain by alluvial clays and peats	0.2 to 0.5 mm/yr ?
	Man-made compaction due to loading	300 mm in one year 800 mm over 5 years
	Movement of ground where London Clay is at or close to the surface	up to 50 mm/yr

The prime objective for the consideration of geology in the initial stages of the project was to ensure that the monitoring network was designed in a way that would test the models for these various components of ground level change (see Section 4.1).

3 High Precision GPS

The Global Positioning System (GPS) was designed by the US Department of Defence (DoD) in the late 1970s. The system was designed for satellite navigation, primarily for military purposes with civilians having limited access. However, since its introduction, the use of GPS has advanced far beyond its original conception, particularly as a tool for satellite positioning in surveying and geodesy (Ashkenazi and Ffoulkes-Jones, 1990; Ashkenazi et al 1993; Ashkenazi and Roberts 1997; Ashkenazi et al 1998).

On a global scale, the advancements in GPS have contributed to the development of the International Terrestrial Reference System (ITRS) and led to the introduction of an International GPS Service (IGS). The GPS, the ITRS and the IGS form a framework that enables high precision GPS to be used for detailed studies of geodynamics, on regional scales and within relatively short time frames, that were previously impossible.

3.1 The Global Positioning System

The fundamental concepts of GPS are best explained with reference to its three distinct segments: Space, Control and User. The Space Segment consists of a constellation of artificial satellites which receive information from the Control Segment whilst transmitting information to the User Segment. At the time of writing (July 1999) there are 27 GPS satellites in operation; eight Block II, 18 Block IIA and one Block IIR. The satellites are arranged in six orbital planes, have a 12 hour period and orbit at an altitude of approximately 20 000 km. These 'vital statistics' ensure that a minimum of four satellites are visible, in most parts of the world, for 24 hours a day. The Control Segment is responsible for the operation and maintenance of the system. It consists of five ground based control stations equipped to monitor the satellites and update the information transmitted by the satellites. The User Segment comprises an unlimited number of users equipped with GPS receivers capable of tracking the signals transmitted by the satellites.

The GPS signal consists of two carrier waves (L1 and L2) which are modulated by two timing codes, the Coarse Acquisition (C/A) code and the Precise (P) code. The L1 carrier has both the P code and the C/A code modulated onto it, while the L2 carrier has only the P code. Superimposed on these codes is a navigation message which contains the 'broadcast ephemeris', ie the positions of the satellites used for satellite navigation.

In general terms, a GPS receiver uses the timing codes to form a pseudo-range observable and uses the carrier waves to form a carrier phase observable. The pseudo-range observable enables satellite navigation using a single receiver, whereas the carrier phase enables post-processed relative positioning between two or more geodetic receivers.

Considering a satellite (P) and a receiver located at a survey station (A), the carrier phase observation equation can be expressed as follows

$$\varphi_A^P = \frac{f}{c}\rho_A^P - f\left[\delta\tau_A - \delta t^P\right] + N_A^P \qquad \text{Equation 1}$$

where

φ_A^P	is the *carrier phase* observed by the receiver at station A from satellite P
f	is the *frequency* of the carrier wave
c	is the *speed of light* in vacuo
ρ_A^P	is the *geometric range* between station A and satellite P
$\delta\tau_A$	is the *receiver clock offset* from GPS time at the instant of signal reception
δt^P	is the *satellite clock offset* from GPS time at the instant of signal transmission
N_A^P	is the *integer ambiguity* at lock-on

The unknown coordinates of the receiver located at station A are implied in the geometric range as

$$\rho_A^P = \sqrt{[(X^P - X_A)^2 + (Y^P - Y_A)^2 + (Z^P - Z_A)^2]} \qquad \text{Equation 2}$$

where (X^P, Y^P, Z^P) are the coordinates of satellite P and (X_A, Y_A, Z_A) are the coordinates of the receiver at station A.

In post-processing the carrier phase observations made from two receivers, located at survey stations (A and B), to two satellites (P and Q) are combined to form a double difference carrier phase observation equations as follows.

$$\varphi_{AB}^{PQ} = \frac{f}{c}\rho_{AB}^{PQ} + N_{AB}^{PQ} \qquad \text{Equation 3}$$

where

φ_{AB}^{PQ}	is the double difference *carrier phase*
ρ_{AB}^{PQ}	is the double difference *geometric range*
N_{AB}^{PQ}	is the double difference *integer ambiguity*

This has the effect of eliminating the satellite clock and receiver clock offsets, and is used for relative positioning where the coordinates of the first station are considered known. In this case, only the coordinates of the second station and the double difference integer ambiguity remain as unknowns. The unknown coordinates of the second station are implied in the double difference geometric range and are solved for using least squares.

Here it is important to note, that a least squares solution can only be obtained if the integer ambiguity remains constant throughout an observation period, so that the carrier phase data observed at both stations is 'smooth'. In practice, if a receiver loses lock on the signal from a satellite, a 'jump' is introduced into the carrier phase data and an additional integer ambiguity is created. Such a loss of lock is known as a cycle slip. For high precision GPS, all cycle slips must be detected and corrected (often referred to as 'cleaned') during the pre-processing of GPS data (see Chapter 4).

3.2 The International Terrestrial Reference System

Considering Equation 2, it is logical that satellite and station coordinates must be expressed in a common geodetic reference system if a meaningful geometric range is to be computed. A geodetic reference system consists of definitions of scale, orientation, origin and directional axes, a reference ellipsoid, a geoid and a gravity model. For practical purposes, the geodetic reference system must be realised as a geodetic reference frame. This is typically carried out through the adoption of a set of station coordinates, enabling the coordinates of points on the Earth to be measured in the same geodetic reference frame.

The two geodetic reference systems used with GPS are the WGS84 and the ITRS. In general, the WGS84 is used for satellite navigation, as the coordinates of the satellites in the broadcast ephemeris are defined in the WGS84, whereas the ITRS is used for high precision GPS.

The ITRS is geodetic reference system defined by a combination of high precision space geodetic techniques, including Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), GPS and DORIS (Boucher and Altamimi 1996). The International Terrestrial Reference Frame (ITRF) is the realisation of the ITRS. As it is based on a combination of high precision space geodetic techniques, the ITRF is not only very precise but it is also takes into account the fact that due to geophysical processes, such as continental drift, the stations which define a geodetic reference frame are moving. Hence, the ITRF is realised as a set of station coordinates computed at a specific epoch, with a set of assumed or estimated station velocities.

The first ITRS realisation was published for 1988 (ITRF88) and subsequent realisations have been published on a more or less annual basis. The ITRF88 was based on the adoption of the coordinates of a network of 64 stations derived from VLBI and SLR and computed at epoch 1988.0. Subsequent realisations were then published as the ITRF89 and the ITRF90, based on new global VLBI and SLR solutions. Following on from these, the ITRF91 and ITRF92 were the first realisations to include global GPS solutions, the latter including station coordinates from the 'IGS 1992 Test Campaign' (see Section 3.3).

The quality of the station coordinates improved in the successive realisations of the ITRS, through improvements in the global VLBI and SLR solutions and the introduction of global GPS solutions. However, up to and including ITRF92, the geodetic reference frame was realised as a set of station coordinates computed at epoch 1988.0, with associated station velocities being based on a geophysical plate motion model, used to compute horizontal motion dependent on the location of a station on a continental plate.

Since the ITRF93, through to ITRF94, ITRF96 and the latest ITRF97, the geodetic reference frame has been realised as two sets of station coordinates computed at epochs 1988.0 and 1993.0, with station velocities computed to be consistent between the two sets of coordinates. The reliable computation of station velocities has been made possible through improvements in the global GPS solutions and the increase in the time span of data available from all of the high precision space geodetic techniques.

In summary, for high precision GPS the satellite and station coordinates must be expressed in a common geodetic reference frame at a common time-tag, if a meaningful geometric range is to be computed. In practice, this is facilitated by the links between the International Earth

Rotation Service (IERS) who are responsible for maintaining the ITRS, and the International GPS Service.

3.3 The International GPS Service

The International GPS Service (IGS) operates a global GPS network for supporting geodetic and geophysical research activities using high precision GPS. The IGS began life in 1989 when the need for a set of common GPS user standards and precise ephemerides was recognised. The development of the IGS continued over the following years resulting in the three month 'IGS 1992 Test Campaign', focusing on the routine determination of high accuracy orbits and Earth rotation parameters to serve as the proof of concept for the future IGS. This was followed by the 'IGS Pilot Service' which aimed to bridge the gap between the 'IGS 1992 Test Campaign' and the start of the official IGS on 1 January 1994 (Beutler 1995).

At the time of writing the IGS maintains a global GPS network, consisting of about 200 continuously operating GPS receivers. The data from these receivers are retrieved by operational data centres where the data is validated, formatted, and forwarded to the regional or global data centres where the data are archived (Neilan 1995). These IGS data is then made available free of charge to the geodetic and geophysical community on a next day basis.

The analysis centres retrieve the data from the global data centres in order to produce IGS products, which include precise ephemerides, Earth rotation parameters, GPS satellite clock information and ionospheric and tropospheric information. The products from each analysis centre are sent to the analysis centre coordinator who combines them into a single set of IGS products. These IGS products are then made available free of charge to the geodetic and geophysical community, with the final IGS precise ephemerides being available with a delay of about 10 days.

The synergy between the ITRS and the IGS enables high precision GPS to be used for monitoring movements on a regional scale. Since the realisation of the ITRF92, the IGS has contributed to the densification and improvement of successive ITRF realisations through the submission of global GPS solutions for IGS stations. In turn, the latest published ITRF station coordinates and velocities are used by the IGS analysis centres to define the coordinates of IGS stations at the epoch of observation, in order to compute the coordinates of satellites given in the precise ephemerides at the same epoch.

3.4 Systematic Errors

In order to achieve the best results from high precision GPS on a regional scale it is essential that all sources of systematic error are mitigated during the post-processing of carrier phase observations. The systematic errors that must be considered include satellite orbit errors, atmospheric refraction, antenna phase centre variations, Earth body tides and ocean tide loading.

(i) Satellite Orbit Errors

Satellite orbit errors arise when the coordinates of a satellite given in an ephemeris do not correspond to the true coordinates of the satellite. If not accounted for, satellite orbit errors propagate directly to errors in the station coordinates obtained using GPS. In relative positioning, it can be assumed that much of the satellite orbit error is eliminated through double differencing. In this case, the effect of a satellite orbit error on baseline length is given by the following rule of thumb (Bruyninx et al, 1997)

$$dL = 0.25 dS \frac{L}{S} \qquad \text{Equation 4}$$

where

dL is the baseline length error.
dS is the satellite orbit error.
L is the baseline length.
S is the satellite altitude.

Following the 'IGS 1992 Test Campaign', the expansion of the IGS network and improvements in computation procedures enabled a satellite orbit precision of 5 cm to be achieved by the end of 1996 (Kouba and Mireault 1997). This is still the current level of precision for the final IGS precise ephemerides.

Considering Equation 4, a satellite orbit error of 5 cm leads to a baseline length error of 0.6 ppb, which is equivalent to a baseline length error of 0.6 mm over a 1000 km baseline. Hence, in high precision GPS, satellite orbit errors are mitigated by using the final IGS precise ephemerides, which are sufficient for monitoring movements on a regional scale.

(ii) Atmospheric Refraction

Due to atmospheric refraction GPS signals do not follow a perfect straight geometric path from satellite to receiver, as they would if travelling through a vacuum. If ignored, this signal path length error will manifest itself as an error in the station coordinates, particularly in the height component. In the mitigation of atmospheric refraction in high precision GPS, the atmosphere is normally considered as two distinct segments, namely the ionosphere and the troposphere (Dodson 1986).

The ionosphere, spanning from approximately 50 to 1000 km above the Earth's surface, contains a high concentration of free electrons formed as a result of ionising radiation entering the atmosphere from space, and is a dispersive medium at GPS frequencies. The troposphere, spanning from approximately 0 to 50 km above the Earth's surface, is electrically neutral and is a non-dispersive medium at GPS frequencies. The effect of the troposphere is dependent on surface temperature and pressure, and on the distribution of liquid water and water vapour in the atmosphere (Dodson et al 1996).

In relative positioning, it can be assumed that much of the atmospheric refraction is eliminated through double differencing. However, as with satellite orbit errors, this assumption becomes less valid as baseline length increases.

In high precision GPS the effects of the ionosphere are mitigated by using the so-called 'ionospherically free' combination of L1 and L2 carrier phase observations, to account for about 98 % of ionospheric delay errors.

The effects of the troposphere are mitigated by appropriate modelling, with corrections to the model being solved for by including the tropospheric delay as an additional unknown in the double difference carrier phase observation equation. In this respect, Equation 3 can be re-written as

$$\varphi_{AB}^{PQ} = \frac{f}{c}\rho_{AB}^{PQ} + N_{AB}^{PQ} + dtrop_{AB}^{PQ} \qquad \text{Equation 5}$$

The double difference tropospheric delay ($dtrop_{AB}^{PQ}$) is then estimated, based on the carrier phase observations, as part of the least squares solution. This has the effect of reducing the errors in station heights from centimetres to millimetres, and is essential when using high precision GPS for monitoring movements on a regional scale.

(iii) Antenna Phase Centre Variations

The effect of antenna phase centre variations were first reported by Schupler and Clark (1991), who showed that variations of the electrical phase centre of a GPS antenna are a function of the elevation and azimuth angle between a station and a satellite. These variations are particularly evident in the vertical direction, and differ in amplitude and phase for different types of GPS antenna.

If the same antenna types are used on a relatively short baseline, the antenna phase centre variations will be cancelled out because both stations have practically the same elevation angle to a particular satellite. However, as baseline length increases, the elevation angles to a satellite from both ends of a baseline differ, and the antenna phase centre variations become more significant. Furthermore, if different antenna types are used, then the different antenna phase centre variations will certainly not be cancelled. For example, Schupler and Clark (1991) showed that the differences between a Rogue Dorne-Margolin B and Trimble Geodetic antenna can reach 35 mm at an elevation angle of 55 degrees.

Models for antenna phase centre variations, including mean phase centre offsets and associated variations for particular antenna types, were first estimated based on anechoic chamber tests, as outlined by Schupler and Clark (1991). In such chamber tests, it is attempted to determine 'absolute' phase centre characteristics for a single antenna. More recently, 'relative' antenna phase centre characteristics have been measured 'in-situ', using GPS data gathered over very short baselines (< 10m). These in-situ generated variations are usually with respect to the mean offsets and variations for a reference antenna obtained from a chamber test, as detailed in Rothacher et al (1995).

As a result of these tests, in 1996 the IGS published a standard set of antenna phase centre models for most common geodetic antenna types. These models are essential for high precision GPS as station heights can actually be worsened if tropospheric delay is estimated without proper antenna phase centre modelling (Beamson 1995).

(iv) Earth Body Tides

The surface of the Earth is displaced periodically due to the tidal gravitational attractive forces predominantly caused by the Sun and the Moon. This means that stations on the surface of the Earth do not have constant coordinates, but vary about a mean position. The extent of this (mainly vertical) displacement is dependent on both time and location, but at low latitudes the surface can move through a range of over 40 cm in little over six hours (Baker 1984). For high precision GPS, a correction must be applied, so that the final computed coordinates are those of the mean position that the station occupies.

Besides these periodic movements, there is also a permanent (long period) displacement of the Earth's surface due to tidal forces. When expressing a position that has been corrected for the effects of Earth body tides, it is important to state whether the final coordinates include the effect of the permanent Earth body tidal displacement, or whether it has been eliminated. For example, the ITRF station coordinates and the final IGS precise ephemerides are in fact referred to the 'non-tidal crust', ie the physically meaningless surface with all Earth body tide effects removed.

Due to the long wavelength nature of Earth body tides, the tidal displacements at stations at either end of a short baseline will be the same. Thus the effect may be considered to be eliminated in relative positioning. For longer baselines though, the displacements at the two stations cannot be assumed to be equal and must be corrected using an appropriate model. Such a model is provided as part of the IERS 1992 standards (McCarthy 1992) and should be applied when using ITRF station coordinates and IGS precise ephemerides for monitoring movements on a regional scale.

(v) Ocean Tide Loading

The oceans respond dynamically to tidal forces (predominantly from the Sun and the Moon), causing periodic rises and falls in sea level. This periodic change in water distribution causes additional loading on the surface of the Earth, causing further (mainly vertical) displacements in addition to the Earth body tide effects. In some areas this further displacement can be over 10 cm (Baker et al 1995). The extent of this displacement is dependent on both time and location, and is a combination of the effects of hundreds of tidal constituents, the most significant of which are generally termed M2, S2, N2, K2, K1, O1, P1, Q1, Mf, Mm and Ssa. The main constituent in Great Britain is M2, which has a loading amplitude of up to 4 cm and a period of about 12 hours.

In terms of high precision GPS, the effects of ocean tide loading differ depending on the baseline length, the length of the observation session and the location of the stations. For continuous GPS data, where the carrier phase observations are processed over 12 or 24 hours, the effects of ocean tide loading may be mainly considered to be 'averaged out', even over long baselines. However, for episodic GPS data, where the carrier phase observations are processed for periods of less than 12 hours, this will not be the case.

Hence, when using high precision GPS for geodynamics applications that mainly involve vertical movements, the modelling of ocean tide loading must be considered.

3.5 Summary

Based on the background information presented in Sections 3.1 to 3.4, it has been demonstrated that the GPS, the ITRS and the IGS form a framework that enable high precision GPS to be used for detailed studies of geodynamics on regional scales. Furthermore, it has been highlighted that the treatment of systematic errors is extremely important, particularly for precise height determination and the monitoring of vertical movements.

In addition to the precision and the scale of the measurements, another major advantage of using high precision GPS is that, unlike conventional surveying techniques, monitoring is carried out in a geodetic reference system. Firstly, this means that monitoring is not carried out relative to stations that are assumed to be 'stable', but may in fact be moving themselves. Instead, it is carried out relative to IGS stations whose station coordinates and velocities are computed and updated, based on a combination of precise space geodetic techniques. Secondly, this means that monitoring is not carried out relative to a physical reference surface, such as a datum related to mean sea level, which will vary over time. Instead, any cartesian (X, Y, Z) coordinates produced using high precision GPS are given in a specific ITRF realisation and time-tagged to a specific observation epoch. This ensures that these coordinates can be related to those obtained from any precise space geodetic techniques which may be developed and applied in the future.

4 DEVELOPMENT OF THE MONITORING STRATEGY

The aim of the project was to develop a generic strategy for monitoring changes in regional ground level and providing an interpretation of such changes in terms of local and regional geology. This has been achieved through the design of a monitoring network, with station locations based on geological and geodetic criteria, the establishment of a geodetic observation strategy based on high precision GPS and the development of a geodetic processing strategy, that has been refined through a series of software developments.

4.1 Monitoring Network

In the design of the monitoring network, both geodetic and geological criteria were considered. In considering the geology, the objective was to ensure that the monitoring network was designed in a way that would test the models for the various components of ground level change that have been proposed. In addition the geological input aimed to ensure that the foundation conditions for all of the stations in the monitoring network were fully understood. The main geodetic criteria considered were the suitability of the station for GPS observations and the suitability of the station for long term geodetic monitoring. In addition, other criteria such as permission and access arrangements were also considered.

The stations that form the monitoring network fall into two categories, namely reference stations and monitoring stations.

The main role of the reference stations was to facilitate the connection of the monitoring network to the ITRS through the use of continuous GPS data. For this purpose it was preferable that the geological conditions at these stations would result in a linear vertical station velocity, from which epochal coordinates could be inferred. In addition, the reference stations were selected in order to provide a range of baseline lengths for the development and testing of the monitoring strategy. Finally, consideration was given to the fact that for long term monitoring, the reference stations should be located at Environment Agency sites.

The selection of the monitoring stations was based on two criteria. The first relates to the need to provide a link between current and future changes in sea level, as measured by a tide gauge, and changes in ground level at that tide gauge site. The second relates to the project objectives of determining the scale and trend of regional, sub-regional and local geological movements resulting from the processes described in Chapter 2 and listed in Table 1 of Section 2.5.

In the earliest, desk study, phase of the project a number of potential sites for the stations in the monitoring network were identified. Firstly, these included sites for the reference stations, located to cover the region from east to west, and sites for monitoring stations at tide gauges located about every 10 km along the Thames estuary. The role of these monitoring stations was to provide an estimation of the changes in sea level along the tidal extent of the Thames estuary, in order to form better future evidence than the limited historical evidence based on storm surges and a single tide gauge in Greater London.

In addition to the monitoring stations at tide gauges, it was proposed that a set of stations should be located to determine tectonic activity in the London basin. A number of potential sites for these stations were identified around the margins of the basin, located on geological formations such as the chalk, considered to be largely unaffected by local geological processes.

For the other monitoring stations, a set of stations situated within areas considered to be susceptible to ground movements on a sub-regional scale, including fault activity and aquifer recharge, were proposed. Finally, a further set of monitoring stations to measure movements due to local geological processes such as the compaction of unconsolidated alluvial deposits and the swell-shrink of clay were also proposed. For the sub-regional and local geological processes, potential sites were identified where pairs of monitoring stations could be used to enable relative movement to be measured over distances of a few kilometres.

During the period from April to August 1996, all of the proposed sites were visited in a series of field reconnaissances to confirm the site geology, check the condition and suitability of any existing monuments and check the suitability for GPS observations. Several of the proposed sites were discounted as a result of these visits. In addition, some compromises had to be made, particularly in the central and north-eastern part of the region where 'stable' bedrock is absent and the geology is predominantly London Clay. In these areas the monitoring stations intended to be 'stable' were sited, wherever possible, on gravel deposits overlying the London Clay to mask its tendency to swell-shrink behaviour.

Following the field reconnaissances, a monitoring network of 26 stations was designed comprising three reference stations, six 'tide gauge monitoring stations', eight 'regional monitoring stations' and nine 'local monitoring stations' (see Figure 3).

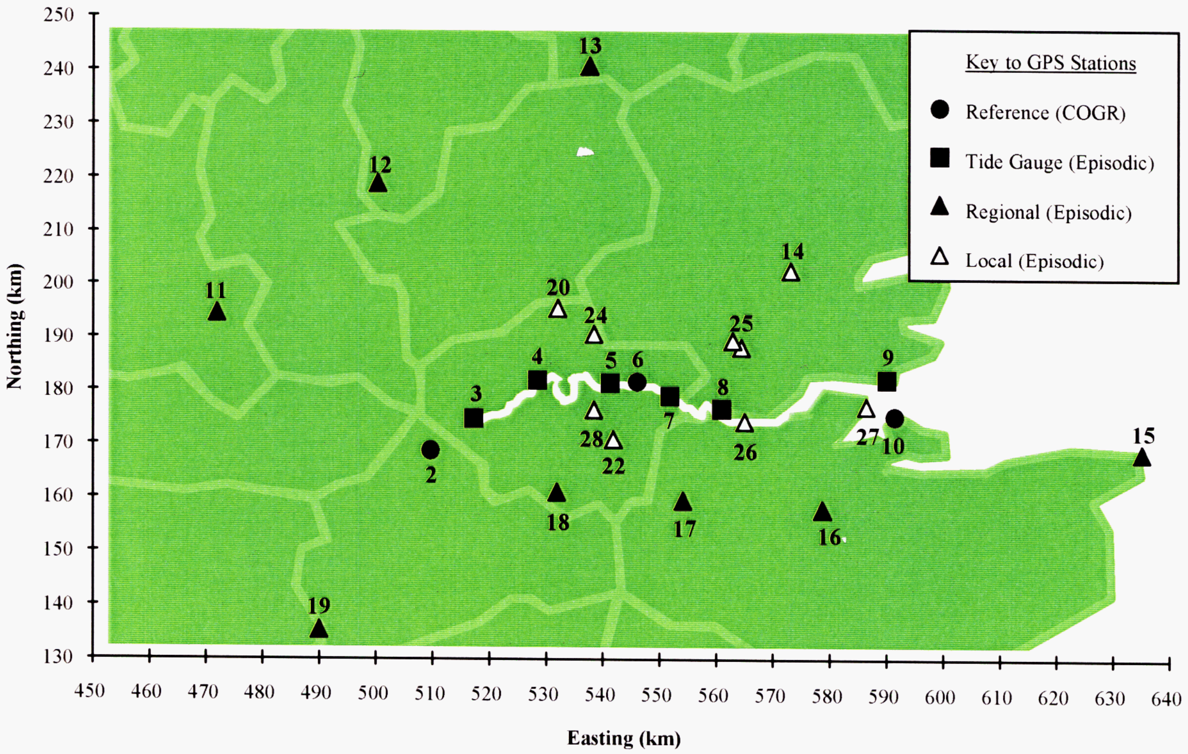


Figure 3 Schematic diagram of the monitoring network

The final locations and geological considerations for the stations are shown in Table 2.

In this table it is important to note that some of the stations have more than one role and are, therefore, listed twice

Table 2 Summary of geological considerations for stations in the monitoring network

Station Role	Station Name	Station No	Station Geology Formation	Lithology
Reference Station	Sunbury Yard	2	Alluvium	clay, silt, peat
	Barking Barrier	6	Upper Chalk	chalk
	Sheerness TG	10	Alluvium ?	clay, silt, peat
Links to Sea Level	Richmond TG	3	Alluvium ?	clay, silt, peat
	Tower Pier TG	4	Alluvium ?	clay, silt, peat
	Silvertown TG	5	Upper Chalk	chalk
	Erith TG	7	Upper Chalk	chalk
	Tilbury TG	8	Alluvium ?	clay, silt, peat
	Southend Pier TG	9	Alluvium ?	clay, silt, peat
	Sheerness TG	10	Alluvium ?	clay, silt, peat
London basin Tectonic Activity	Shirburn Hill	11	Upper Chalk	chalk
	Dunstable Downs	12	Upper Chalk	chalk
	Heath Farm	13	Upper Chalk	chalk
	Isle of Thanet	15	Upper Chalk	chalk
	Thurnham	16	Upper Chalk	chalk
	Rowdow Hill	17	Upper Chalk	chalk
	Riddlesdown Park	18	Upper Chalk	chalk
	Hindhead	19	Hythe Beds	mainly sand
Greenwich Fault	Sundridge Pk GC	22	Thanet Formation	sand
	Greenwich Park	28	Blackheath Beds	sand and gravel
Aquifer Recharge	Bush Hill Pk GC	20	River Terrace	sand and gravel
	Mill Plane	24	River Terrace	sand and gravel
Alluvial Compaction	Tilbury TG	8	Alluvium ?	clay, silt, peat
	Southend Pier TG	9	Alluvium ?	clay, silt, peat
	Sheerness TG	10	Alluvium ?	clay, silt, peat
	Gravesend Gr Sch	26	Upper Chalk	chalk
	Grain	27	River Terrace	sand and gravel
London Clay Swell-Shrink	Mascalls	14	Claygate Beds	clay, sand
	Dunton Hills	25	London Clay	clay
	Dunton Hills Aux	25a	London Clay	clay

Of the 26 stations in the monitoring network, ten were identified at sites with existing monumentation considered acceptable for this project. This included one Ordnance Survey Fundamental Bench Mark, seven Ordnance Survey triangulation pillars and two Ordnance Survey Surface Blocks. The other sixteen stations required new monumentation to be installed. This included customised brackets on existing buildings for the three reference stations, brass survey markers in existing concrete structures for the six monitoring stations at tide gauges and Berntsen Survey Markers for the other seven monitoring stations.

During the period from July 1996 to February 1997 the preparations for the observations were completed. For the reference stations this involved the installation of the customised brackets for the permanently mounted GPS antennas and the connection of new telephone lines for the continuously operating GPS receivers. For the monitoring stations, new monumentation was installed, where necessary, and permissions to access all of the stations was obtained.

4.2 Geodetic Observation Strategy

At the time of writing the case for support for the project, in 1995, most geodesists recognised the advantages of the increased temporal resolution offered by continuous GPS data when compared to episodic GPS data. This had been clearly demonstrated by the success of the IGS tracking network and also by the development of national networks of continuously operating GPS receivers (COGRs), for example in Fennoscandia for the study of vertical movements related to isostatic processes (BIFROST 1996). However, in most studies of geodynamics on a regional scale, the spatial resolution required means that the use of a network consisting purely of COGRs is not feasible. One of the aims of this project, therefore, was to develop a strategy for monitoring movements on a regional scale, which would combine the advantages of the temporal resolution of continuous GPS data with the increased spatial resolution available from episodic GPS data. A similar strategy was later proposed by Bevis et al (1997).

The framework for the monitoring strategy is provided by the monitoring network, which was designed as a network of stations at specific geological and non-geological sites, and resulted in a variant station density across the region (see Section 4.1). The geodetic observation strategy was designed so that the three reference stations were equipped with COGRs, 22 of the monitoring stations would be observed using episodic GPS measurements and one of the monitoring stations would be observed using precise levelling.

(i) Continuous GPS Data

The complete equipment set up at each reference station consists of a Trimble Dorne-Margolin T (choke ring) antenna, a Trimble 4000 SSI receiver and a US Robotics Sportster modem connected to a dedicated telephone line. The role of the reference station was to record continuous GPS data, ie 365 days per year, for 24 hours each day, at a 30 second epoch interval. In this context, the requirements of the project were for the scheduling, downloading, reformatting and archiving of the continuous GPS data to be automated, as far as possible. This automation was achieved through the development of a series of MS-DOS batch files, functioning around programs which form part of the IESSG GPS Analysis Software (GAS) and the Trimble RUTILS software. The development of the initial automated procedures was carried out in the period from December 1996 to March 1997, and was completed so that the COGRs at Sheerness TG, Sunbury Yard and Barking Barrier came on-line on 27 March 1997, 9 April 1997 and 25 April 1997 respectively. Through the automated procedures the observation session is scheduled on a previous day basis and the continuous GPS data are downloaded on a next day basis. The continuous GPS data are downloaded as a single, compressed, binary file for each 24 hour observation session, converted to RINEX format, archived on a PC and transferred to a UNIX workstation in preparation for data processing.

The data management for the reference stations was designed to be in sympathy with the data management at the IGS stations. For the project, further automated procedures were developed based on UNIX Shell scripts, in order to retrieve the continuous GPS data for a number of IGS stations and the final IGS precise ephemerides. These IGS data and products were transferred directly to the UNIX workstation via ftp, and archived along with the continuous GPS data from the reference stations in preparation for data processing. The specific IGS data that was transferred were from the IGS stations at Herstmonceux in Sussex and Kootwijk in the Netherlands.

(ii) Episodic GPS Data

The 22 monitoring stations at which episodic GPS measurements were planned, were observed by using one or two 'roving' GPS receivers. In this concept, the 'roving' GPS receiver visited the stations in turn, remaining at each station for a limited observation session. In order to detect, or mitigate, the effects of seasonal variations in ground level, the schedule for the observation sessions was arranged so that each station was observed for one day, four times per year, on a three monthly basis. The 'roving' GPS receiver concept placed some constraints on the measurements, and in order to allow sufficient time for travel between stations, the observation session length used was nine hours, from 0900 UT to 1800 UT (where UT is Universal Time).

For the episodic GPS measurements, a Trimble 4000 SSI receiver complete with Trimble Dorne-Margolin T (choke ring) antenna was used at 18 of the stations and an Ashtech Z-XII receiver complete with an Ashtech Dorne Margolin T (choke ring) antenna was used at four of the stations.

A schedule for carrying out the episodic GPS measurements was designed, in which the stations were sub-divided into two types. The first type were observed using one 'roving' GPS receiver at one station for one day. This included most of the monitoring stations at tide gauges (station numbers 3, 4, 5 and 7) and most of the other monitoring stations (station numbers 11, 12, 13, 14, 15, 16, 17, 18, 19 and 25). The second type comprised the pairs of monitoring stations that were only a few kilometres apart, namely station numbers 8 & 26, 9 & 27, 20 & 24, and 22 & 28. These were observed using two 'roving' GPS receivers, to simultaneously record data at both stations on the same day.

The observation schedule required a total of 18 days of episodic GPS measurements every three months. Following the completion of a monthly set of measurements, the episodic GPS data were downloaded as a single, binary file for each 9 hour observation session, converted to RINEX format and archived on a PC. These data were then transferred to the UNIX workstation and archived along with the continuous GPS data from the reference stations, the continuous GPS data from the IGS stations and the final IGS precise ephemerides in preparation for data processing.

(iii) Episodic Levelling Data

The remaining monitoring station was located very close to another monitoring station, and was observed using precise levelling to provide an independent control on the station height estimates obtained from the episodic GPS data.

This monitoring station (station number 25a) was installed as part of the study on the swell-shrink of London Clay. Station number 25a is a Berntsen Survey Monument installed deep into the London Clay, and is located about 2 m away from station number 25, which is an Ordnance Survey triangulation pillar that sits on top of the London Clay, which outcrops at this site. During the episodic GPS measurements at station number 25, a precise levelling connection was made between station numbers 25 and 25a. Assuming the Berntsen Survey Monument to be 'stable', this precise levelling link was designed to monitor the seasonal movements of station number 25, as an independent check on the movements detected using episodic GPS data at this site.

4.3 Geodetic Processing Strategy

As stated in Section 4.2, one of the aims of this project was to develop a strategy for monitoring movements on a regional scale, which would combine the advantages of the temporal resolution of continuous GPS data with the increased spatial resolution available from episodic GPS data. The framework for this monitoring strategy is provided by the monitoring network and facilitated by the geodetic observation strategy, which manages the flow of data on to a UNIX workstation in preparation for data processing (see Section 4.2).

The geodetic processing strategy was designed as a three stage process. The first stage involves the processing of the continuous GPS data from the reference stations in combination with continuous GPS data taken from the IGS global GPS network. The second stage involves the processing of the episodic GPS data from the monitoring stations in combination with simultaneous data observed at the reference stations. The third stage involves the combination of the results from the first and second stages in order to produce station coordinates, time series and velocities in the ITRS, and to make an assessment of any significant movements that may have taken place over the monitoring period.

(i) Continuous GPS Data

The geodetic processing strategy for the continuous GPS data was designed in order to compute daily estimates of station coordinates for the reference stations, in a specific ITRF realisation and time-tagged to the epoch of observation. This ensures that successive daily estimates of station coordinates can be represented as a homogeneous coordinate time series, from which meaningful station velocities can be inferred.

To produce daily estimates of station coordinates, the geodetic processing strategy requires the 24 hour RINEX observation data files for the reference stations to be processed along with the 24 hour RINEX observation data file from one IGS station and the final IGS precise ephemeris data file. In this regional GPS network solution, the satellite coordinates given in the final IGS precise ephemeris and the coordinates of the IGS station are held fixed, and the coordinates of the reference stations are solved for as unknowns. Hence, the coordinates of the reference stations are computed in the same ITRF realisation and time-tagged to the same observation epoch as the global GPS network solution.

In this strategy the treatment of reference frame and time tag is critical. Through the global GPS network, the final IGS precise ephemerides are computed in a specific ITRF realisation and time-tagged to the epoch of observation. For consistency, the coordinates of the IGS station should also be computed in the same ITRF realisation and time-tagged to the same observation epoch. In practice this is achieved by combining the published ITRF station coordinates and velocities for the IGS station. These values are given as coordinates at a reference epoch and velocities in millimetres per year, on the assumption that the movement of the station is linear. Hence, for any observation epoch the coordinates of the IGS station can be computed as

$$X_{obs} = X_{ref} + Vx(t_{obs} - t_{ref}) \qquad \text{Equation 6}$$

where

X_{obs}	Coordinate at the observation epoch
X_{ref}	Coordinate at the reference epoch
Vx	Station velocity
t_{obs}	Observation epoch, eg 1997.50
t_{ref}	Reference epoch, eg 1993.00

In order to use the Thames region as a 'typical' region for the pilot study it was important to process the continuous GPS data from the reference stations in combination with continuous GPS data from a 'typical' IGS station. In this context, it was considered that the IGS station should be neither too close nor too far away from the region. It was also considered that, although the 200 stations in the IGS tracking network are not of the same quality in all parts of the world, it was important to use an IGS station with reliable ITRF station coordinates and velocities. This was done in order to enable the most reliable results to be obtained for the reference stations, particularly in terms of vertical movements.

Up to the end of 1997, Herstmonceux was adopted as the IGS station for this project. This station is not 'typical', as it is only about 60 to 80 km from the reference stations. However, the short baselines enabled preliminary results to be obtained for the reference stations in the early part of the project.

In 1998, a change in the geodetic processing strategy was implemented. In some ways this was a forced change, as Herstmonceux was off-line for about six months from January to July 1998 due to receiver problems. However, it led to the definition of the criteria given above, for a 'typical' IGS station. Based on these criteria, it was decided to use Kootwijk as the IGS station for this project. This is located approximately 400 km from the centre of the Thames Region. In addition to a COGR that has been operational since 1991, it also has a permanent SLR facility that has been operational since 1976, and it has been included in all of the realisations of the ITRS. The IGS station at Kootwijk is considered to be one of the best in the world, as it is one of the stations used to define the final IGS precise ephemerides. In the latest ITRF realisation (ITRF97), the formal errors for the station coordinates at Kootwik were 1 mm in X, Y and Z. The station velocities and their standard errors were –13.0 ± 0.5 mm/yr in X, +15.8 ± 0.3 mm/yr in Y and +9.2 ± 0.5 mm/yr in Z. These are equivalent to a linear horizontal movement of about 22 mm/yr in a north-east direction, which is mainly due to the motion of the Eurasian plate, and a linear vertical movement of about +0.3 mm/yr.

Underlining the statement made in Section 3.5 of Chapter 3, the monitoring of the reference stations is carried out relative to the IGS station at Kootwijk, which is not assumed to be 'stable', but has known horizontal and vertical movements that are assumed to be correct. Obviously, any errors in the station velocities for Kootwijk will propagate into the station velocities determined for the reference stations, but these errors are small when compared to the false assumption that otherwise might be made, that Kootwijk is 'stable'. Furthermore, in survey terms, the use of Kootwijk as a higher order station, to serve as 'control' for the reference stations, is justified when considering the respective quantities of data and lengths of monitoring periods for these stations.

(ii) Episodic GPS Data

The geodetic processing strategy for the episodic GPS data was designed in order to compute epochal estimates of station coordinates for the monitoring stations, in a specific ITRF realisation and time-tagged to the epoch of observation. As with the reference stations, this was done to ensure that a sequence of epochal estimates of station coordinates could be represented as a homogeneous coordinate time series, from which meaningful station movements could be inferred.

To produce epochal estimates of station coordinates, the geodetic processing strategy requires the 9 hour RINEX observation data file for one or two monitoring stations to be processed along with the 24 hour RINEX observation data files for the reference stations, the 24 hour RINEX observation data file for an IGS station and the final IGS precise ephemeris data file. In this regional GPS network solution, the satellite coordinates given in the final IGS precise ephemeris and the coordinates of the reference stations are held fixed, and the coordinates of the monitoring stations are solved for as unknowns. Hence, the coordinates of the monitoring stations are computed in the same ITRF realisation and time-tagged to the same observation epoch as the reference stations.

In this strategy the treatment of reference frame and time tag is critical. Through the global GPS network, the final IGS precise ephemerides are computed in a specific ITRF realisation and time-tagged to the epoch of observation. For consistency, the coordinates of the reference stations should also be computed in the same ITRF realisation and time-tagged to the same observation epoch. In practice this is achieved by analysing the coordinate time series produced for the reference stations in order to describe the movements of these stations as linear velocities, so that for any observation epoch the coordinates of the reference stations can be computed.

In summary, the monitoring stations are monitored relative to the reference stations, which are monitored relative to the IGS station at Kootwijk. However, neither the IGS station nor the reference stations are assumed to be 'stable'. Instead, they are attributed with 'known' horizontal and vertical movements that are assumed to be correct. Obviously, any errors in the station velocities for Kootwijk will propagate into the station velocities determined for the reference stations, and any errors in the station velocities for the reference stations will propagate into the station movements for the monitoring stations. However, in survey terms, the use of the reference stations as higher order stations, to serve as 'control' for the monitoring stations, is justified when considering the respective quantities of data for these stations.

4.4 Software Developments

Considering the relatively large quantities of continuous and episodic GPS data observed as part of this project it was essential that the processing and analysis of the data was automated, as far as possible. Not only was this considered necessary in terms of efficiency but it was also considered to be central to the aim of developing a generic monitoring strategy that could be effectively transferred and applied in other regions.

All of the geodetic results presented in Chapters 6 and 7 have been produced using the IESSG GPS Analysis Software (GAS), which has been developed over a number of years (Stewart et al 1997; Penna 1997). At the start of this project, GAS could only be used in a manual mode. This required user input, in the creation of program control files, the execution of programs and the reviewing of output files. It also required user intervention, particularly in making subjective decisions during cycle slip cleaning. Through this research project, a series of MS-DOS batch files, UNIX Shell scripts and C/FORTRAN 77 programs have been developed in order to automate these procedures. These developments can be separated into three distinct sets of increasingly more refined, automated procedures, which are termed 'Mark 1', 'Mark 2' and 'Mark 3' in this report.

(i) The IESSG GPS Analysis Software (GAS)

GAS consists of a series of programs, or processing modules, that enable the processing and analysis of GPS data. The main GAS processing module is PANIC, which is based on a least squares estimation using the double difference algorithm. For simplicity, the processing and analysis of GPS data can be considered in four stages; pre-processing; cycle slip cleaning; network solution; post-processing.

The first stage is a preparatory stage, often termed pre-processing. This involves the GAS processing module FILTER, which is used to convert the 'raw' observation data files from RINEX format to the GAS NOTT2 format (an ASCII format similar to RINEX) and to detect and correct large cycle slips (> 500 cycles).

The second stage is cycle slip cleaning, or more strictly cycle slip detection and correction. This involves the GAS processing modules PANIC and SLIPCOR. The 'raw' observation data files output from FILTER are used as input to PANIC in a series of defined baselines. In cycle slip detection mode, PANIC estimates cycle slips by considering the change in double difference carrier phase residuals from epoch to epoch on a single baseline. The cycle slip estimates output by PANIC are then used as input to the GAS processing module SLIPCOR in order to correct for the cycle slips and create 'clean' observation data files. This process is repeated for all of the independent baselines in a network.

The third stage is the production of a network solution, such as the regional GPS network solution or the sub-regional GPS network solution referred to in Section 4.3. At this stage, the 'clean' observation data files for all of the stations in a network are used as input to PANIC, which is run in network adjustment mode. In this mode, PANIC produces least squares estimates for the station coordinates and enables the mitigation of systematic errors. For this, PANIC includes the option to model antenna phase centre variations, Earth body tides and ocean tide loading, and the option to model and/or estimate tropospheric delay. The output from PANIC is a set of vectors with a corresponding covariance matrix for each independent baseline within the network, for a single observation session. This is termed a sessional solution.

The final stage is an analysis, or post-processing, of the sessional solutions. At this stage, the vectors from a number of observation sessions are combined in order to produce station coordinates and estimates of standard errors. This is carried out using the GAS processing module CARNET, which is network adjustment software that operates on GPS vectors and other survey observations.

For continuous GPS data it is common practice to combine a series of sessional solutions either as a single daily solution or as a single weekly solution. For episodic GPS data it is common practice to combine a series of sessional solutions as an epochal solution. The weighted mean coordinates output from CARNET (ie the daily, weekly or epochal solutions) can then be compared with the series of coordinates output from PANIC (ie the sessional solutions) in order to compute session-to-session coordinate repeatabilities. This is carried out using the GAS processing module REPDIF, which enables quality control through outlier detection, ie the identification of any poor sessional solutions.

Following these four stages, a series of quality controlled daily, weekly or epochal solutions can then be represented as coordinate time series.

(ii) 'Mark 1' Automated Procedures

The 'Mark 1' automated procedures were initially developed as a series of MS-DOS batch files. These were then re-written as a series of UNIX Shell scripts, to take advantage of commands and utilities such as *sed* and *grep* that are not routinely available in MS-DOS. The basic idea behind the 'Mark 1' automated procedures was to devise a series of MS-DOS batch files or UNIX Shell scripts, that represented the various tasks carried out when using GAS in a manual mode.

A key development in these procedures was the definition of templates for the control files used in GAS. These templates were designed to enable the automatic creation of control files through, for example 'stream editing' and the insertion of time parameters. Time parameters define the various ways in which a day can be uniquely identified, namely the year, day and month, or the GPS week and day-of-the-week, or the year and day-of-the-year (or julian day). These are central to the majority of data management and file naming conventions used in GPS processing. For example the final IGS precise ephemerides are referred to as igs*wwwwd*.sp3, where *wwww* is the GPS week and *d* is the day-of-the-week, and RINEX observation data files are referred to as *nameddd*s.*yy*o, where *name* is the four character station ID, *ddd* is the julian day and *yy* is the year.

The series of MS-DOS batch files and UNIX Shell scripts basically carry out the following functions:

- make a series of processing directories.
- get the ephemeris and observation data files from the archive.
- create control files for pre-processing.
- carry out pre-processing.

- create control files for cycle slip detection and correction.
- carry out cycle slip detection and correction.
- create control files for network solutions.
- carry out network solutions.
- create control files for post-processing.
- carry out post-processing.

The 'Mark 1' automated procedures were initially used for data processing and analysis from April 1997 to November 1997. During this time it became apparent that these procedures were not very efficient at cycle slip cleaning. This was due to the fact that although the user input required when using GAS in manual mode had been automated, the user intervention and subjective decision making had not. Consequently, during this period, the procedures used for the continuous GPS data were separated from those used for the episodic GPS data. For the continuous GPS data, the UNIX Shell scripts were retained as the 'Mark 1' automated procedures. In producing preliminary results for the reference stations the inefficiencies in cycle slip cleaning were accepted, as a trade off with the relatively large amount of data that was being processed. For the episodic GPS data, however, it was considered important to retain as much of the data from the 9 hour observation session as possible. Hence, the MS-DOS batch files were adapted to form the 'Mark 1' semi-automated procedures, which allowed for user intervention during cycle slip cleaning.

In the 'Mark 1' automated procedures, the continuous GPS data from the three reference stations were processed separately. Each reference station was processed relative to Kootwijk as a series of 12 hour observation sessions (ie 0000 – 1159 and 1200 – 2359 UT). The 14 sessional solutions from a single GPS week were then combined to produce a weekly solution for each station. Following outlier detection, the accepted sessional solutions were re-combined to produce a series of quality controlled weekly solutions, which could be represented as coordinate time series.

Through the use of one or two 'roving' GPS receivers, the episodic GPS data for the monitoring stations was also processed separately for each station, or pair of stations, observed on a single day. In the 'Mark 1' automated procedures, the episodic GPS data for one or two monitoring stations were processed relative to the nearest reference station, as a series of 3 hour observation sessions (ie 0900 – 1159, 1200 – 1459 and 1500 – 1759 UT). The three sessional solutions from a single day were then combined to produce an epochal solution for each station. Following outlier detection, the accepted sessional solutions were re-combined to produce a series of quality controlled epochal solutions, which could be represented as coordinate time series.

In terms of coordinate time series, it is important to note that for the 'Mark 1' automated procedures, the IGS station at Kootwijk was allowed to 'move', as described in Section 4.3 (i). Hence, the coordinate time series for the reference stations were represented truly, as the movement of the station in the ITRS. However, due to the relatively short time over which data had been processed for the reference stations in the early stages of the project, the monitoring stations were processed relative to the reference stations, which were assumed to be 'stable'. This mean that the coordinate time series for the monitoring stations were 'relative', ie they showed the motion of the monitoring station relative to the reference station and therefore, included a combination of the movements of the two stations.

(iii) 'Mark 2' Automated Procedures

Between December 1997 and June 1998 a series of refinements were made to the 'Mark 1' automated procedures in order to improve the efficiency of cycle slip cleaning. These developments led to the 'Mark 2' automated procedures.

The 'Mark 2' automated procedures follow the same functions as the 'Mark 1' automated procedures. The main difference, however, was the introduction of a series of improved UNIX Shell scripts and new auxiliary programs for carrying out pre-processing and cycle slip cleaning. These attempted to automate the user intervention and subjective decisions associated with cycle slip cleaning when using GAS in a manual mode.

For the continuous GPS data, the 'Mark 2' automated procedures were used in parallel with the 'Mark 1' automated procedures during the period from July 1998 to May 1999. Through the 'Mark 2' automated procedures, the improved efficiency of cycle slip cleaning meant that the continuous GPS data from the three reference stations and Kootwijk could be processed together, as a proper regional GPS network solution. Furthermore, this processing was carried out as a series of 24 hour observation sessions (ie 0000 – 2359 UT). The seven sessional solutions from a single GPS week were then combined to produce a weekly solution for each station. Following outlier detection, the accepted sessional solutions were re-combined to produce a series of quality controlled weekly solutions, which could be represented as coordinate time series.

Table 3 summarises the results obtained for the three reference stations, based on the processing and analysis of 2.25 years of continuous GPS data using the 'Mark 1' and the 'Mark 2' automated procedures.

Table 3 Comparison of 'Mark 1' and 'Mark 2' automated procedures for the reference stations

Station Name	% Accepted Solutions		Weekly Height SD (mm)	
	'Mark 1'	'Mark 2'	'Mark 1'	'Mark 2'
Sunbury Yard	57	88	10.0	6.4
Barking Barrier	61	90	10.7	6.2
Sheerness TG	57	92	11.2	5.9

Considering the percentage of accepted sessional solutions, these results confirmed that the 'Mark 2' automated procedures were much more efficient at cycle slip cleaning. Furthermore, the "Mark 2" automated procedures produced almost a two-fold improvement in height precision, when considering the standard deviation of a weekly solution from the 2.25 year mean height. This improvement in precision is mostly due to the more efficient cleaning of cycle slips. However, it is also due to the fact that the individual sessional solutions are more accurate, due to the time-averaging of systematic errors over 24 hours as opposed to 12 hours, and that the weekly solutions are more accurate, as they are based on time-averaging over about 151 hours as opposed to 97 hours.

Based on the preliminary results for the reference stations, the 'Mark 2' automated procedures were adapted for use with episodic GPS data, during the period from January to May 1999.

The main objective was to take advantage of the improved efficiency of cycle slip cleaning and remove the user intervention necessary with the 'Mark 1' semi-automated procedures.

In adapting the 'Mark 2' automated procedures, the episodic GPS data were processed in the same way as for the 'Mark 1' automated procedures, ie relative to the nearest reference station and as a series of 3 hour observation sessions (ie 0900 – 1159, 1200 – 1459 and 1500 – 1759 UT). Furthermore, in terms of coordinate time series, the monitoring stations were still represented in a 'relative' sense, ie the motion of the monitoring station relative to the reference station.

Based on the processing and analysis of five epochs of episodic GPS data, the results obtained for the monitoring stations confirmed that the 'Mark 2' automated procedures could maintain the high level of acceptable solutions attained when using the 'Mark 1' semi-automated procedures. In terms of height precision, the 'Mark 1' semi-automated procedures led to coordinate time series with standard deviations (of a single epochal solution from a time-averaged mean) of about 5 to 10 mm in height at most monitoring stations. With the 'Mark 2' automated procedures, the standard deviations were at a similar level, with some stations being improved slightly and some being degraded slightly.

(iv) 'Mark 3' Automated Procedures

Between June and September 1999, a further series of refinements were made to the 'Mark 2' automated procedures in order to improve the flexibility of the UNIX Shell scripts and create a set of common procedures for use with both continuous GPS data and episodic GPS data. These final developments resulted in the 'Mark 3' automated procedures.

For the continuous GPS data, the 'Mark 3' automated procedures followed the same functions as the 'Mark 2' automated procedures, in that the data from the three reference stations and Kootwijk were processed together, as a series of 24 hour observation sessions (ie 0000 – 2359 UT). These sessional solutions were then adopted as daily solutions, in addition to the seven sessional solutions from a single GPS week being combined to produce a weekly solution for each station. Following outlier detection, the accepted sessional solutions were archived as a series of quality controlled daily solutions and were re-combined to produce a series of quality controlled weekly solutions, which could be represented as coordinate time series.

In order to test the 'Mark 3' automated procedures, they were used in parallel with the 'Mark 2' automated procedures during the period from June to September 1999. Table 4 summarises the results obtained for the three reference stations, based on the processing and analysis of 2.25 years of continuous GPS data using the 'Mark 2' and the 'Mark 3' automated procedures.

These results confirmed that the refinements made to the 'Mark 2' automated procedures had 'fine tuned' the 'Mark 3' automated procedures, resulting in a slight improvement in both the percentage of accepted solutions and the standard deviation of a weekly solution from the 2.25 year mean height.

Table 4 Comparison of 'Mark 2' and 'Mark 3' automated procedures for the reference stations

Station Name	% Accepted Solutions		Weekly Height SD (mm)	
	'Mark 2'	'Mark 3'	'Mark 1'	'Mark 3'
Sunbury Yard	88	93	6.4	5.3
Barking Barrier	90	92	6.2	5.1
Sheerness TG	92	92	5.9	5.9

For the episodic GPS data, the increased flexibility of the 'Mark 3' automated procedures meant that the episodic GPS data for one or two monitoring stations could be processed in a proper regional GPS network solution, ie relative to all three reference stations and Kootwijk. In addition, this processing was carried out both as a series of 3 hour sessions and as a series of 9 hour observation sessions (ie 0900 – 1759 UT) for each station, or pairs of stations.

At this final stage of the development, the coordinate time series for both the reference stations and the monitoring stations could be represented truly, as the movement of the stations in the ITRS. All of the geodetic results presented in Chapters 6 and 7 are based on these 'Mark 3' automated procedures.

5 DEVELOPMENT OF THE GEOLOGICAL DATABASE

In order to study the past and present effects of potential changes in ground level in the Thames estuary it is important to understand the geometry and composition of the deposits within the lower Thames valley and estuary. Therefore, as a basis for future studies, a database was established using the substantial body of surface and borehole information held by the BGS for this area.

The area covered by the database is from Tower Bridge to a line joining the eastern end of the Isle of Sheppey with the mouth of the River Crouch. The database, held in Oracle tables with an ACCESS front end, was populated following current BGS procedures for quality assurance and data management. The database design is compatible with the BGS corporate standards and therefore could be combined with other, national databases.

5.1 Database Inputs

For the database input, about 4500 boreholes and 55 km of seismic profiles were geologically classified. All data points are sited on the alluvial deposits of the Thames estuary, which have been laid down over the last 8,000 years. The strata consist of silt, clay and peat beds (the Holocene deposits) overlying sand and gravel, the base of which is also the base of the Quaternary.

All of the BGS onshore and offshore borehole data (3500 in total) were encoded. For each borehole the following information was entered into the database:

- National Grid reference: Ordnance Datum level; BGS unique registration number based on Ordnance Survey 1:10 000 scale sheets.
- Geological horizons: top and base of peats; top of (basal) gravel; rockhead.
- Principal lithology codes.

These data were supplemented by a further 1000 borehole records in the inner Thames estuary, that had already been encoded for the BGS LOCUS (LOndon Computerised Underground and Surface) geological project.

In addition, the level of the base of the Holocene deposits, taken from interpretations of 55 km of seismic profiles in three traverses in the Thames estuary were incorporated into the database.

5.2 Database Outputs

The data were contoured using Dynamic Graphics Earth Vision geo-spatial modelling software, manually adjusted to ensure geological integrity. The surface distribution of the Holocene deposits was taken from published BGS maps.

Examples of the isopachytes derived from the data are given in Figures 4 and 5. Figure 4 shows the thickness of Holocene deposits in the Thames valley and Figure 5 shows the total peat thickness in the Thames valley. In these figures, the isopachytes are highly generalised because of the irregular distribution of data points and poor quality of much of the borehole data, however they show interesting broad regional trends.

The Holocene deposits are particularly thick at Canvey Island and between the Isle of Sheppey and the River Medway. This is because these areas have been unaffected by erosion in river channels of the Thames and Medway respectively.

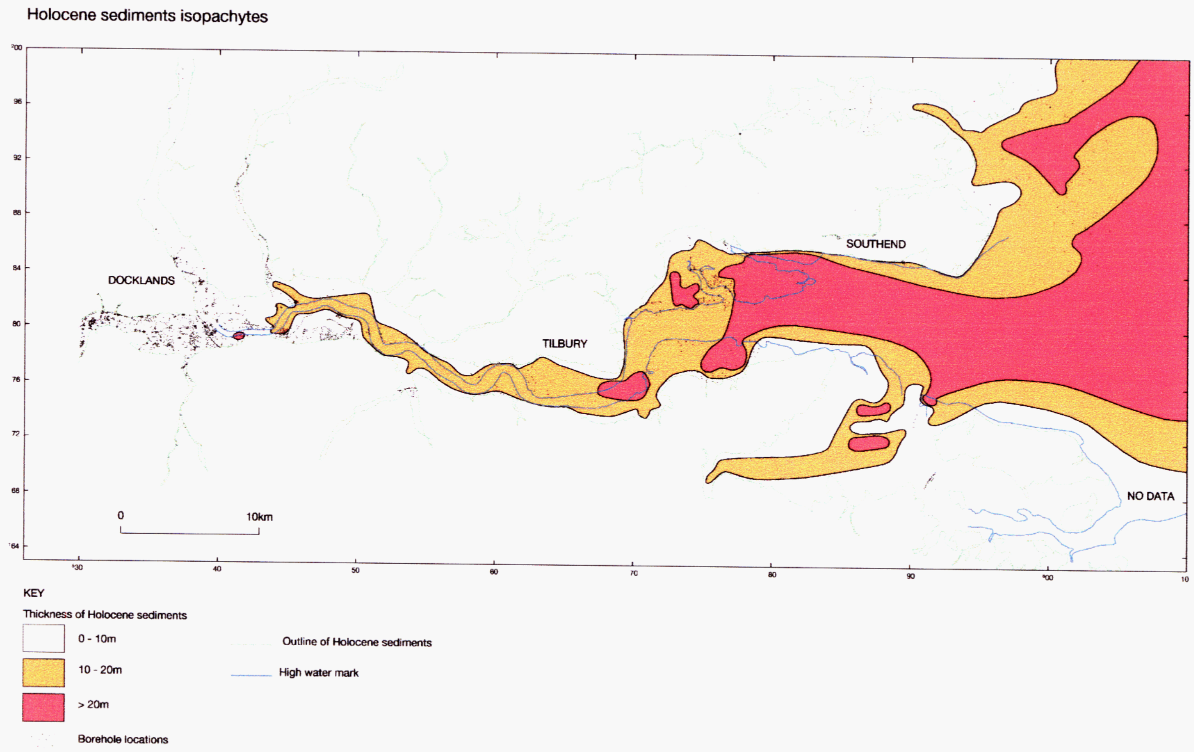


Figure 4 Generalised thickness of Holocene deposits in the Thames valley

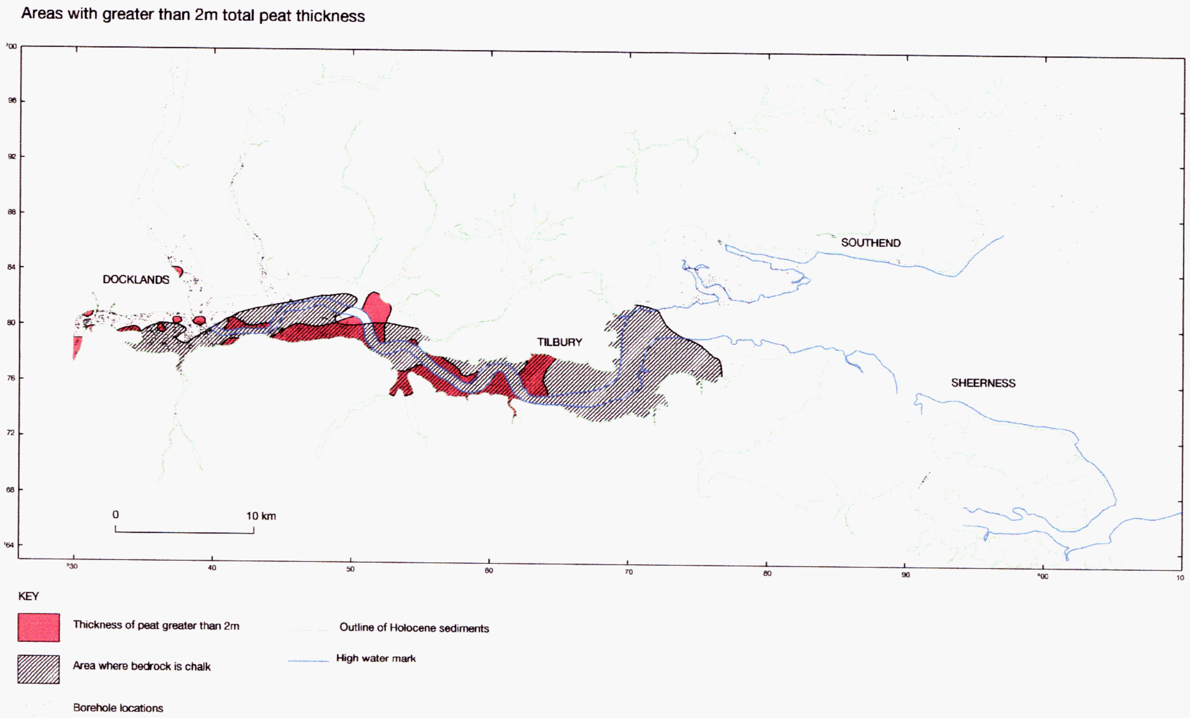


Figure 5 Generalised Peat thickness in the Thames valley

Areas in which two or more metres of peat are present extend on the south side of the River Thames from Thamesmead to Gravesend and on the north side from Rainham to Grays (see Figure 5). The principal requirement for peat to be deposited is the availability of fresh water; in general peat does not accumulate in brackish conditions. The distribution of the freshwater marshland in the Thames estuary corresponds roughly to areas where the principal aquifer (Chalk and the lower Tertiary sands) is unconfined, or is in continuity with permeable drift deposits. Peat is not present beneath the present river channel, which is incised through the Holocene deposits into either the basal gravels or bedrock. The preservation of the peat from river erosion is likely to have been greatest where the river has been incised in the Chalk and also where it may have followed the same course for the past 8000 years. This is most likely to have been the case between Erith and Gravesend.

Examples of the three-dimensional visualisations derived from the data are given in Figures 6, 7 and 8. Figure 6 shows a view of the base of the Holocene sediments in the Thames valley and, for comparison, Figure 7 presents a view of the Quaternary sediments underlying the Holocene deposits in the Thames valley. In addition, Figure 8 shows a digital terrain model draped over the three-dimensional Holocene model.

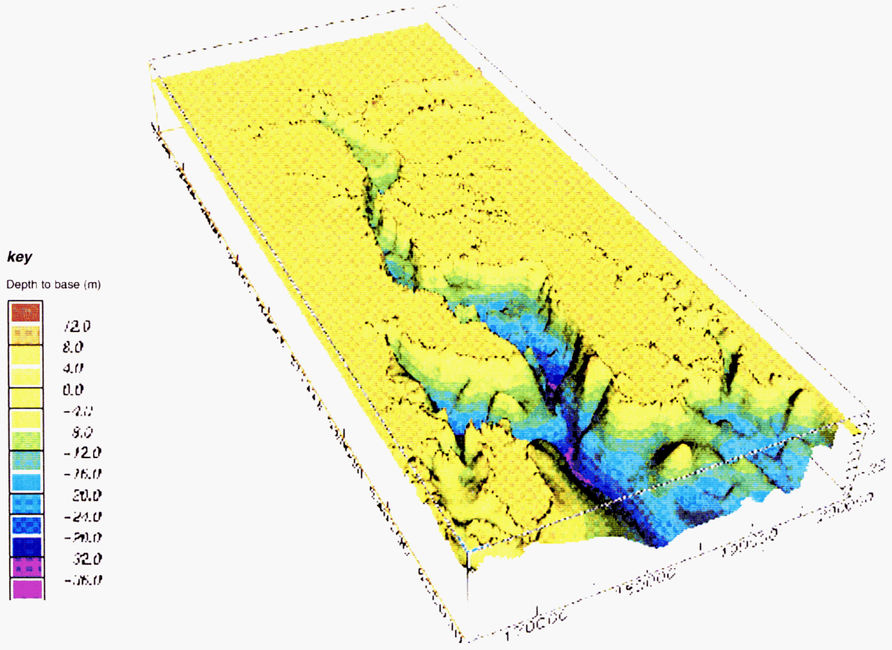


Figure 6 3-D view of the base of the Holocene sediments in the Thames valley, viewed from the south-east

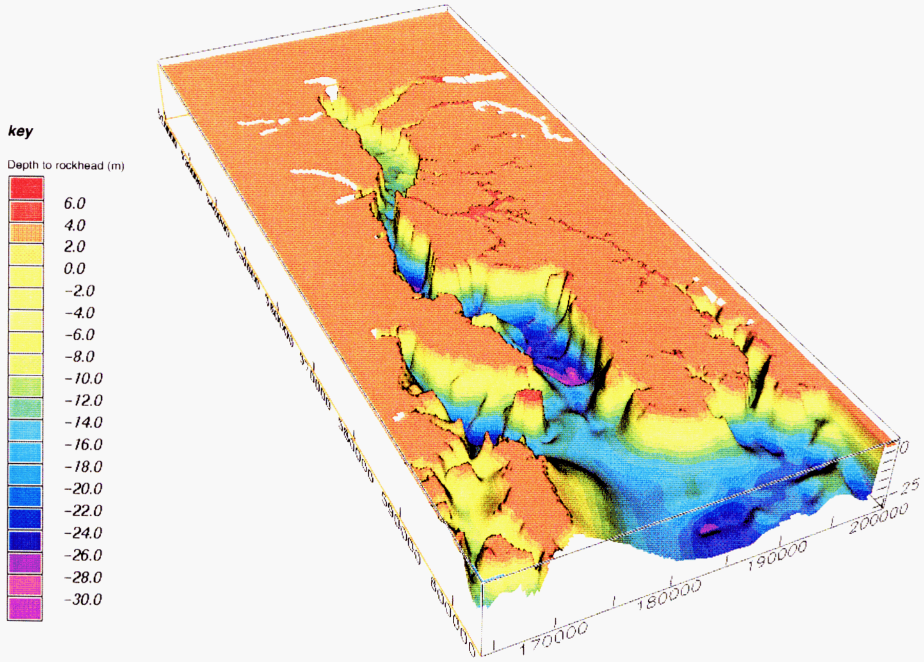


Figure 7 3-D view of the base of the Quaternary sediments underlying the Holocene deposits in the Thames valley, viewed from the south-east

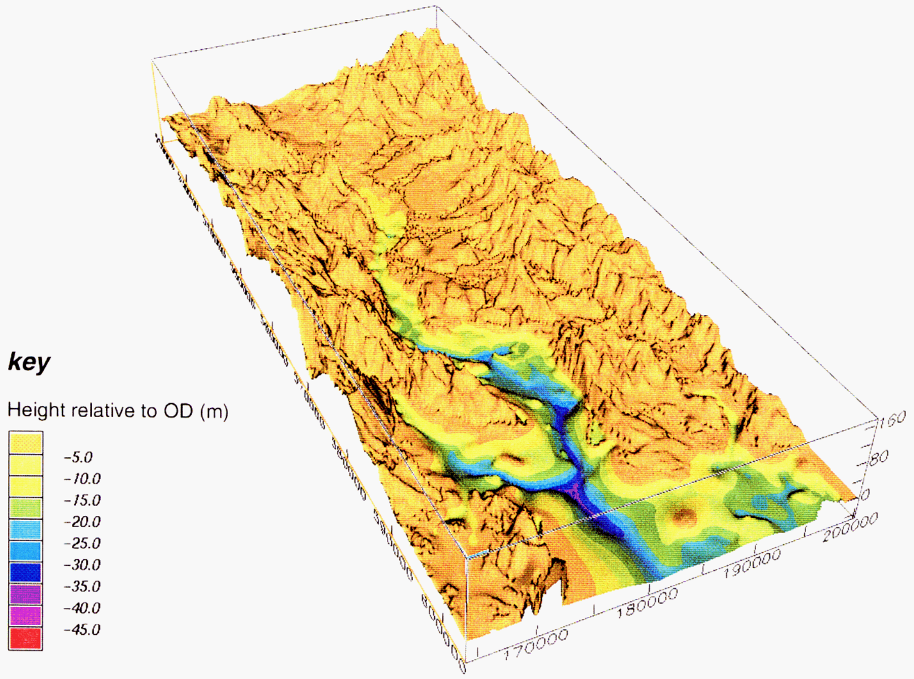


Figure 8 3-D view of the base of the Holocene sediments in the Thames valley, draped with the digital terrain model, viewed from the south-east

These illustrations show that the base of the Holocene deposits has a valley form, whereas the base of the Quaternary succession as a whole is relatively broad and flat. This indicates that the basal Quaternary gravels were laid down on a bedrock terrace, similar in form to those beneath older Quaternary river terrace deposits. Following deposition of the gravels, a relative lowering of sea level led to a certain amount of downcutting and subsequent deposition of the Holocene deposits within this valley during relatively rising sea level.

The 'regional geological model' formed from the database outputs is invaluable for visualisation and should aid further research into the changes in ground level that have taken place over the past 10 000 years.

5.3 Compaction Studies

A limited study on three borehole sequences has been carried out with a view to determining the theoretical amount of compaction of different successions in the Thames estuary. The findings of the compaction studies take the form of settlement analyses carried out for three sites, namely Tilbury, South Essex and Docklands. The results of these settlement analyses are summarised in Table 5, which shows the initial thickness (IT) and the present thickness (PT) estimated for each layer. These are given relative to a datum taken at the base of layer 1, which is coincident with an incompressible 'rockhead'.

Table 5 Summary of settlement analyses results for three sites

Tilbury			South Essex			Docklands		
Layer	**IT (m)**	**PT (m)**	**Layer**	**IT (m)**	**PT (m)**	**Layer**	**IT (m)**	**PT (m)**
Blue Clay	0.83	0.81	Silty Sand	1.40	1.38	Peaty Clay	1.37	1.35
Peat	0.96	0.38	Silty Sand	1.40	1.38	Peaty Clay	1.57	1.35
Blue Clay	3.77	3.07	Silty Clay	0.75	0.53	Peat	3.69	1.10
Clay+Peat	1.71	1.04	Silty Clay	0.75	0.53	Peat	3.38	1.10
Peat	4.69	1.52	Silty Sand	2.13	2.10	Sand+Gravl	2.78	2.75
Clay+Peat	4.36	3.05	Silty Sand	2.13	2.10	Sand+Gravl	2.78	2.75
Peat	5.38	1.75	Silty Clay	4.04	3.25	Clay+Sand	0.63	0.55
Blue Clay	2.75	1.70	Silty Clay	4.14	3.25	Clay+Sand	0.63	0.55
Peat	1.52	0.23	Sand	7.55	7.50	Sandy Clay	0.98	0.90
Loam+Peat	0.66	0.31	Gravel	2.03	2.00	Sandy Clay	0.98	0.90
Rockhead			Rockhead			Rockhead		
Total	26.63	13.86	Total	26.32	24.00	Total	18.79	13.30

As can be seen from Table 5, the site at Tilbury has settled overall from an initial thickness (IT) of 26.63 m to a present thickness (PT) of 13.86 m, which represents a compaction of 48%. Contrary to this, the site at South Essex has only settled by 9 %, from an initial thickness of 26.32 m to a present thickness of 24.00 m. The results for the third site at Docklands are somewhere in between with a settlement of 29%, from 18.79 m to 13.30 m. Based on these preliminary studies it is possible that these results can be taken forward into a model that will help to elucidate the ground level change in the region. However, considerably more work would be required on the sediments themselves, including dating, before meaningful conclusions can be reached.

6 GEODETIC RESULTS

Through this project, a geodetic observation strategy and a geodetic processing strategy were developed, tested and refined as detailed in Chapter 4. This Chapter presents the final geodetic results for the reference stations and the monitoring stations, with an assessment of the performance of these strategies.

6.1 Observations

The successful implementation of the monitoring strategy depends on the availability of GPS data from the IGS station, the reference stations and the monitoring stations.

If the IGS station is not operational on a particular day, a daily solution cannot be obtained for the reference stations, which leads to a gap in their height time series. Similarly, if a reference station is not operational, this will also lead to gaps in its height time series.

If the IGS station is not operational, but one of the three reference stations is operational, on a particular day, then it will still be possible to obtain an epochal solution for a monitoring station. However, if all three reference stations are not operational on a particular day, then an epochal solution cannot be obtained for a monitoring station. Furthermore, if one of the three reference stations is not operational this may lead to a weaker epochal solution for the monitoring station.

(i) IGS Station and Reference Stations

In the geodetic observation strategy, the role of the COGRs at the reference stations is to record continuous GPS data, ie 365 days per year, for 24 hours each day, at a 30 second epoch interval. In this context, the requirements of the project were for the scheduling, downloading, reformatting and archiving of the continuous GPS data to be automated, as far as possible. This automation was achieved through the development of a series of MS-DOS batch files, functioning around programs which form part of the IESSG GPS Analysis Software (GAS) and the Trimble RUTILS software as detailed in Chapter 4.

The efficiency of the automated procedures was assessed by dividing the monitoring period into three nine month periods; from 23 March 1997 (GPS Week 0898) to 27 December 1997 (GPS Week 0937), 28 December 1997 (GPS Week 0938) to 3 October 1998 (GPS Week 0977), 4 October 1998 (GPS Week 0978) to 3 July 1999 (GPS Week 1016). For each of these periods, Table 6 shows the total number of days that were available, the number of daily sessions that were observed and the percentage of observed sessions that were obtained. For comparison purposes, the corresponding information for the IGS station at Kootwijk is included.

Table 6 Efficiency of the geodetic observation strategy for the reference stations

Station Name	Total No of Days Available	No of Observed Daily Sessions	% Observed Sessions
0898 - 0937			
Kootwijk IGS	280	277	99
Sunbury Yard	263	241	92
Barking Barrier	247	194	79
Sheerness TG	277	255	92
0938 - 0977			
Kootwijk IGS	280	277	99
Sunbury Yard	280	277	99
Barking Barrier	280	266	95
Sheerness TG	280	277	99
0978 - 1017			
Kootwijk IGS	273	262	96
Sunbury Yard	273	263	96
Barking Barrier	273	263	96
Sheerness TG	273	268	98

From Table 6, it can be seen that the majority of problems were encountered during the first nine months of the monitoring period. In these early stages of the project, a limitation in the Trimble software meant that the receivers had to stop recording GPS data every 17 days, so that their internal memories could be cleared in order to record more GPS data. This problem was overcome in December 1997, but resulted in many gaps in the early GPS data for the reference stations. In addition to this, there were two periods when communication with the COGR at Barking Barrier was lost for up to 19 days due to problems with the telephone line.

Considering the percentage of observed sessions for the Kootwijk IGS station it would appear that an efficiency of better than 95% should be expected. For the three reference stations, this efficiency was more than achieved in the second nine months of the monitoring period, with the loss of only 3 daily observation sessions at Sunbury Yard and Sheerness TG, and the loss of a few more days of data at Barking Barrier due to power failures caused during routine electrical testing. This success rate was then maintained in the final nine months of the monitoring period, with a few additional daily observation sessions lost when the receiver firmwares were upgraded to be Y2K compatible.

(ii) Monitoring Stations

For the 22 monitoring stations at which episodic GPS measurements were planned, these were observed by using one or two 'roving' GPS receivers as detailed in Chapter 4. In this part of the geodetic observation strategy, the percentage of observed sessions was expected to be 100% unless exceptional circumstances, such as restricted access, equipment failure or changes in site conditions, prevented the GPS measurements being made.

During the 2.25 year monitoring period, nine epochs of GPS measurements were obtained at the all but one of the monitoring stations. The only exception was at Southend Pier, where epoch 7 was not measured due to the hire car being vandalised and only six hours of data were observed in epoch 8 due to early closure of the pier.

In addition, it is important to note that the original monitoring network included an additional monitoring station at Newnham Court Farm, within a few kilometres of Thurnham. However, following the installation of a new monument, and the first five epochs of GPS measurements, this station was destroyed by farming activity.

6.2 Processing

As stated in Section 6.1, the first requirement for the successful implementation of the monitoring strategy was the availability of GPS data from the IGS station, the reference stations and the monitoring stations. Once this was ensured, the second requirement was for the geodetic processing strategy to use as much of the observed data as possible to produce daily, weekly or epochal solutions.

(i) Reference Stations

In the geodetic processing strategy, using the 'Mark 3' automated procedures, the continuous GPS data from the reference stations is used to produce daily solutions for the coordinates of the reference stations in the ITRS. These daily solutions can then be used to produce height time series, from which estimates of vertical station velocities can be obtained. In this context, the requirements of the project were for the processing and analysis of the continuous GPS data to be automated, while maintaining the maximum amount of observed data.

In order to assess the efficiency of these automated procedures, Table 7 shows the total number of daily sessions that were observed for each of the reference stations, the number of days for which accepted sessional solutions were obtained and the percentage of accepted sessional solutions.

Table 7 Efficiency of the geodetic processing strategy for the reference stations

Station Name	No of Observed Daily Sessions	No of Accepted Sessional Slns	% Accepted Sessional Slns
Sunbury Yard	781	730	93
Barking Barrier	723	669	93
Sheerness TG	800	745	93

In practice, about 2% of the sessional solutions were not computed due to the unavailability of data from the Kootwijk IGS station, which was highlighted in Table 6. This leaves about 5% of the daily sessions that were not acceptable, either due to 'noisy' data or sessional solutions that were rejected following outlier detection.

Combining the information given in Tables 6 and 7 it can be seen that height estimates have been obtained for about 85 to 90% of the data that were potentially available over the 2.25 year monitoring period.

(ii) Monitoring Stations

In this part of the geodetic processing strategy, when using the 'Mark 3' automated procedures, the relatively short baselines between the reference stations and the monitoring stations have meant that it was possible to obtain 100% of the accepted sessional solutions at the majority of monitoring stations. At the monitoring stations where this has not been possible, the problems can be attributed to 'noisy' data caused by site specific effects such as interference and multipath on the GPS signals.

In total, two 3 hour sessional solutions were rejected for Tilbury TG (session 2 in epoch 2 and session 2 in epoch 5), four 3 hour sessional solutions were rejected for Isle of Thanet (sessions 1, 2 and 3 in epoch 2 and session 1 in epoch 9), one 3 hour sessional solution was rejected for Bush Hill Park GC (session 2 of epoch 9) and one 3 hour session was rejected for Sundridge Park GC (session 3 of epoch 8). These represent about 1% of the data that was observed over the 2.25 year monitoring period.

In addition to the rejected sessional solutions, it should be noted that Isle of Thanet has produced consistently 'noisy' data over all nine epochs, which is most likely due to signal interference from a nearby radio transmitter. Similarly, at Erith TG the data for epochs 7, 8 and 9 is 'noisier', due to multipath, following the installation of a lamp post adjacent to the station some time between epochs 6 and 7.

6.3 Height Time Series

Following the observation and processing of the continuous and episodic GPS data, a series of daily coordinate estimates were obtained for the reference stations and a series of epochal coordinate estimates were obtained for the monitoring stations. Using the 'Mark 3' automated procedures these coordinate estimates have been computed in the latest realisation of the ITRS, namely ITRF97, and are time-tagged to their epoch of observation, eg 1998.50 corresponds to Julian day 183 of 1998, ie 2 July 1998.

From the daily / epochal coordinate estimates it is possible to produce coordinate time series, which illustrate the change in a station's coordinates with time. For this project, where changes in ground level are being monitored, the height component is the most important, so height time series for each station were formed.

With a relatively short monitoring period, such as the 2.25 years associated with this project, it is possible to compute a time-averaged mean height, from which estimates for the quality of the height time series can be obtained, as outlined in Appendix B. Ultimately, with an increased monitoring period, it will be possible to use these height time series to derive estimates of vertical station velocities in the ITRF97, from which indications of changes in ground level can be inferred at all stations.

Some preliminary indications of changes in ground level are presented in Chapter 7. This Chapter concentrates on assessing the performance of the geodetic processing strategy through estimates for the quality of the height time series obtained.

(i) Reference Stations

The height time series for the three reference stations are given in Appendix C as Figures C1 to C3 inclusive. Here it is important to note that, for clarity of presentation, standard error bars have not been included in these figures. Table 8 presents values for the standard deviation of a daily height estimate from the time-averaged mean height and the precision of the time-averaged mean height for the three reference stations.

Table 8 Height standard deviations and precisions for the reference stations

Station Name	Number of Daily Solutions	Daily Height SD (mm)	Height Precision (mm)
Sunbury Yard	730	10.0	0.37
Barking Barrier	669	9.3	0.36
Sheerness TG	745	11.4	0.42

From Table 8, it can be seen that values of 9 to 11 mm have been obtained for the standard deviations of a daily height estimate from the time-averaged mean. These are equivalent to standard deviations of a weekly height estimate from the time-averaged mean of 5 to 6 mm. Furthermore, through the time-averaging of errors in the daily height estimates the precision of the time-averaged mean heights for the three reference stations are about 0.4 mm.

From Figures C1 to C3, it is possible to see some apparent seasonal and annual variations in the height time series. These variations have also been observed at other COGRs operating in networks throughout the world (Beutler et al 1998). At this stage it is not clear whether these variations are an artefact of GPS processing or whether they are true indications of changes in height on seasonal and annual time scales. In either case, it is important to note that the presence of such variations will limit the precision of any estimates of vertical station velocities obtained from both continuous and episodic GPS data. It is recommended, therefore, that future research is required in order to isolate these seasonal and annual effects in height time series using time series analysis. This would include an analysis of the height time series themselves, but would also include an analysis of other related time series for physical processes such as changes in air pressure, air temperature and groundwater levels. In addition to these temporal effects, it would also be useful to investigate any correlations with events such as storm surges and engineering activities (eg dredging, piling).

As far as this project is concerned, it can be concluded that when using continuous GPS data, with the geodetic processing strategy that has been developed, it is possible to obtain standard deviations of a daily height estimate from the time-averaged mean of ± 10 mm.

Over the 2.25 year monitoring period, these are equivalent to precisions for the time averaged mean height of ± 0.4 mm, and would enable vertical station velocities to be estimated to a precision of ± 2.0 mm/yr (see Appendix B).

Through continued monitoring, a standard deviation of ± 10 mm would enable vertical station velocities of 1 mm/yr to be estimated to a required precision of ± 0.4 mm/yr, with a monitoring period of 6 to 7 years.

(ii) Monitoring Stations

The height time series for the 22 monitoring stations are given in Appendix D as Figures D1 to D22 inclusive. Table 9 presents the standard deviation of an epochal height estimate from the time-averaged mean height and the precision of the time-averaged mean height for the 22 monitoring stations.

Table 9 Height standard deviations and precisions for the monitoring stations

Station Name	Number of Epochal Slns	Epochal Height SD (mm)	Height Precision (mm)
Richmond TG	9	6.1	2.04
Tower Pier TG	9	9.6	3.21
Silvertown TG	9	6.2	2.07
Erith TG	9	8.5	2.82
Tilbury TG	9	6.4	2.12
Southend Pier TG	8	10.5	3.73
Shirburn Hill	9	4.9	1.65
Dunstable Down	9	11.7	3.90
Heath Farm	9	7.6	2.55
Mascalls	9	19.4	6.47
Isle of Thanet	8	11.2	3.97
Thurnham	9	3.7	1.24
Rowdow Hill	9	5.9	1.98
Riddlesdown Park	9	6.2	2.06
Hindhead	9	5.0	1.67
Bush Hill Park GC	9	6.2	2.06
Sundridge Park GC	9	7.1	2.38
Mill Plane	9	5.1	1.70
Dunton Hills	9	16.6	5.54
Gravesend Grammar School	9	4.5	1.50
Grain	9	7.2	2.40
Greenwich Park	9	4.5	1.50

From Table 9, it can be seen that values of 4 to 10 mm have been obtained for the standard deviations of an epochal height estimate from the time-averaged mean at 17 of the 22 monitoring stations. These are equivalent to precisions of the time-averaged mean heights of about 1.3 to 3.3 mm. Furthermore, it can be seen that values of 10 to 12 mm have been obtained for the standard deviations of an epochal height estimate from the time-averaged mean at 3 of the 22 monitoring stations. These are equivalent to precisions of the time-averaged mean heights of about 3.3 to 4.0 mm.

The two monitoring stations with higher standard deviations are Mascalls and Dunton Hills. Considering, Figures C10 and C19, the height time series for Mascalls and Dunton Hills appear to exhibit seasonal variations. These variations are consistent with the role of these two monitoring stations in assessing the effects of the swell-shrink of London Clay, and are discussed further in Chapter 7, Section 7.7.

Based on the results for the monitoring stations, when using episodic GPS data with the geodetic processing strategy that has been developed, it is possible to obtain standard deviations of an epochal height estimate from the time-averaged mean of better than 12 mm. These are, at worst similar in magnitude to, and at best three times as good as, the standard deviations of the daily height estimates obtained for the reference stations.

By comparing the precisions of the time-averaged mean heights obtained for the reference stations with those obtained for the monitoring stations, it is clear that the limited number of epochal solutions leads to a precision that is three to ten times worse over the same monitoring period.

As far as this project is concerned, it can be concluded that when using episodic GPS data, with the geodetic processing strategy that has been developed, it is possible to obtain standard deviations of an epochal height estimate from the time-averaged mean of ± 5 to 10 mm.

Over the 2.25 year monitoring period, these would enable vertical station velocities to be estimated to a precision of ± 2.2 to 4.4 mm/yr (see Appendix B).

Through continued monitoring, a standard deviation of ± 5 mm would enable vertical station velocities of 1 mm/yr to be estimated to a required precision of ± 0.4 mm/yr, with a monitoring period of 7 to 8 years. This is only slightly more than the 6 to 7 years required when using continuous GPS data. However, with a standard deviation of an epochal height estimate from the time-averaged mean of ± 10 mm, an increased monitoring period of 12 years would be required (see Appendix B).

7 GEODETIC/GEOLOGICAL INTERPRETATION

Based on the geodetic results outlined in Chapter 6, changes in ground level can be inferred from the vertical movements of some stations in the monitoring network. Where evidence for a trend in vertical movement has been identified at a station or a group of stations, an interpretation of this trend has been attempted in terms of regional and local geology. However, it is important to note that caution has been exercised when interpreting these trends as the monitoring period is extremely short in geological terms.

The interpretations are provided in terms of the station roles defined in Table 2, given in Section 4.1 of Chapter 4.

7.1 Reference Stations

The height time series for the three reference stations, given in Appendix C, are re-presented in Figure 9 as arbitrary values for comparison purposes.

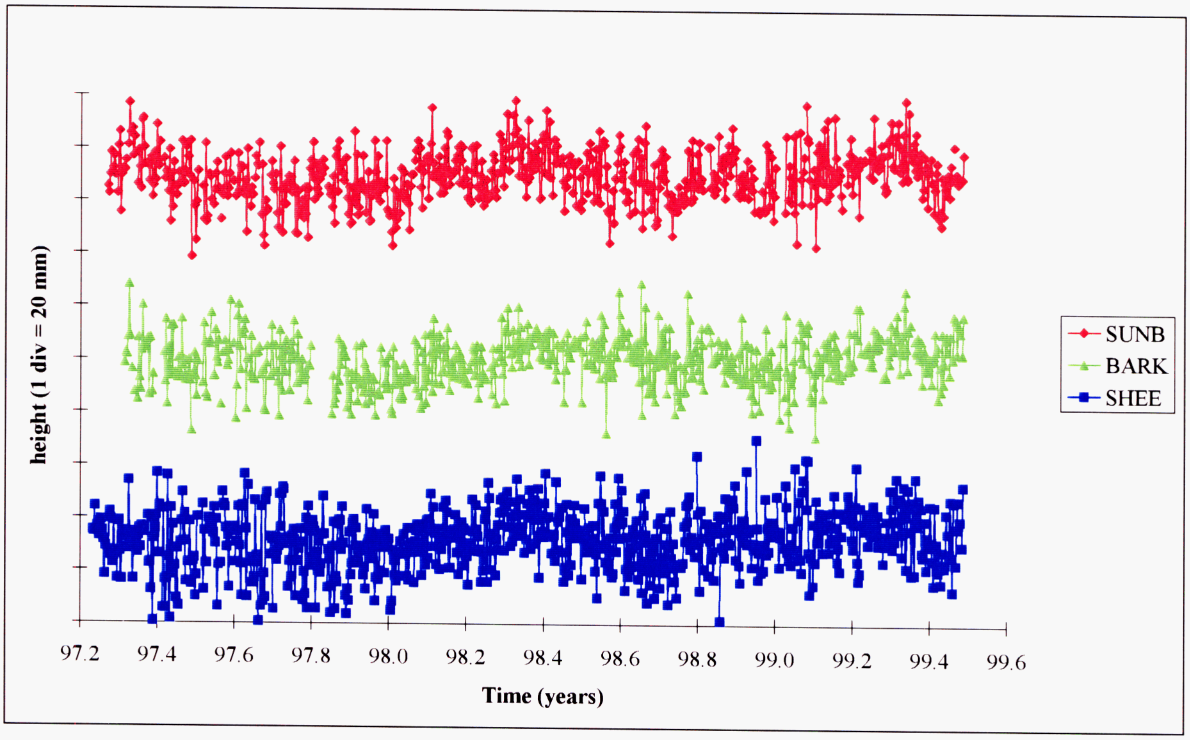


Figure 9 Height time series for the three reference stations

As stated in Section 6.3 (i), based on only 2.25 years of continuous GPS data, any estimate for the vertical station velocities of the reference stations would have a precision of about 2.0 mm/yr. Considering the small movements expected at these reference stations, it can be concluded that the 2.25 year monitoring period is not sufficient to be able to compute a reliable estimate of the vertical station velocities for each of the individual reference stations. However, on the assumption that certain systematic biases are common to the three reference stations, it should be possible to obtain an indication of their relative movements.

Using the height time series given in Appendix C, the daily height estimates for Barking Barrier and Sheerness TG have been differenced from the daily height estimates for Sunbury

Yard in order to produce time series of height differences between the three reference stations. The height difference time series for Barking Barrier minus Sunbury Yard is given in Figure 10, and the height difference time series for Sheerness TG minus Sunbury is given in Figure 11.

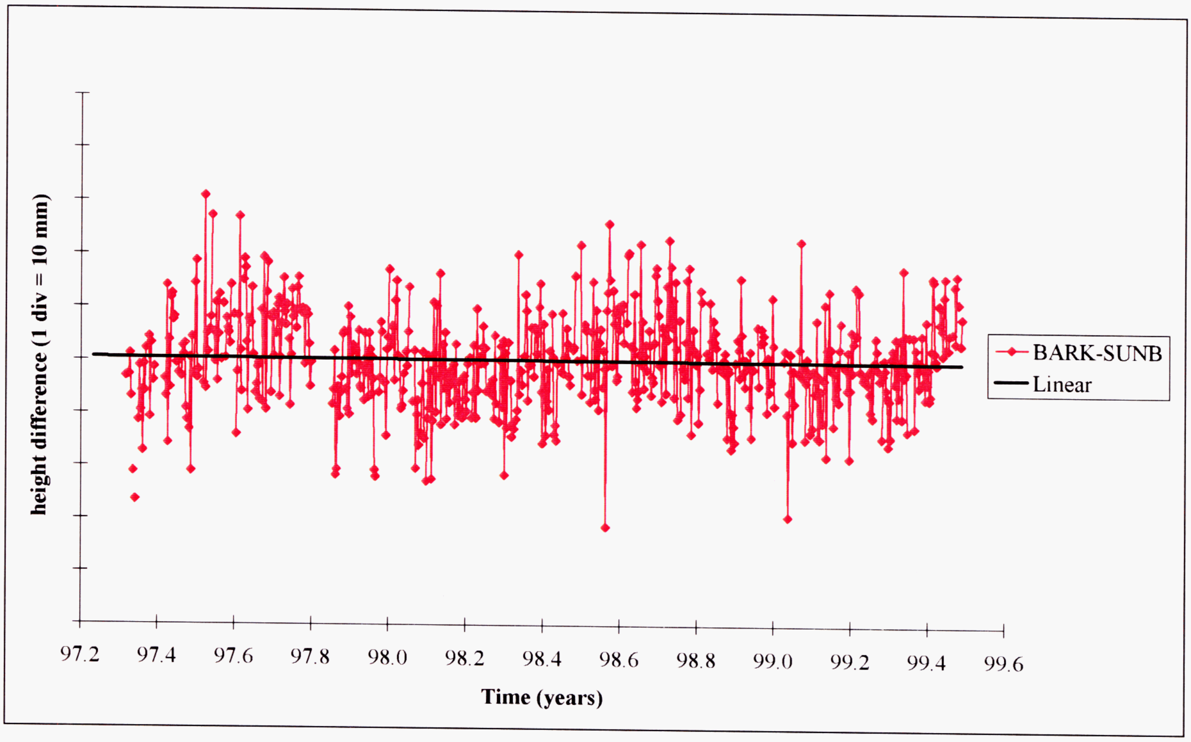


Figure 10 Height difference time series for Barking Barrier minus Sunbury Yard

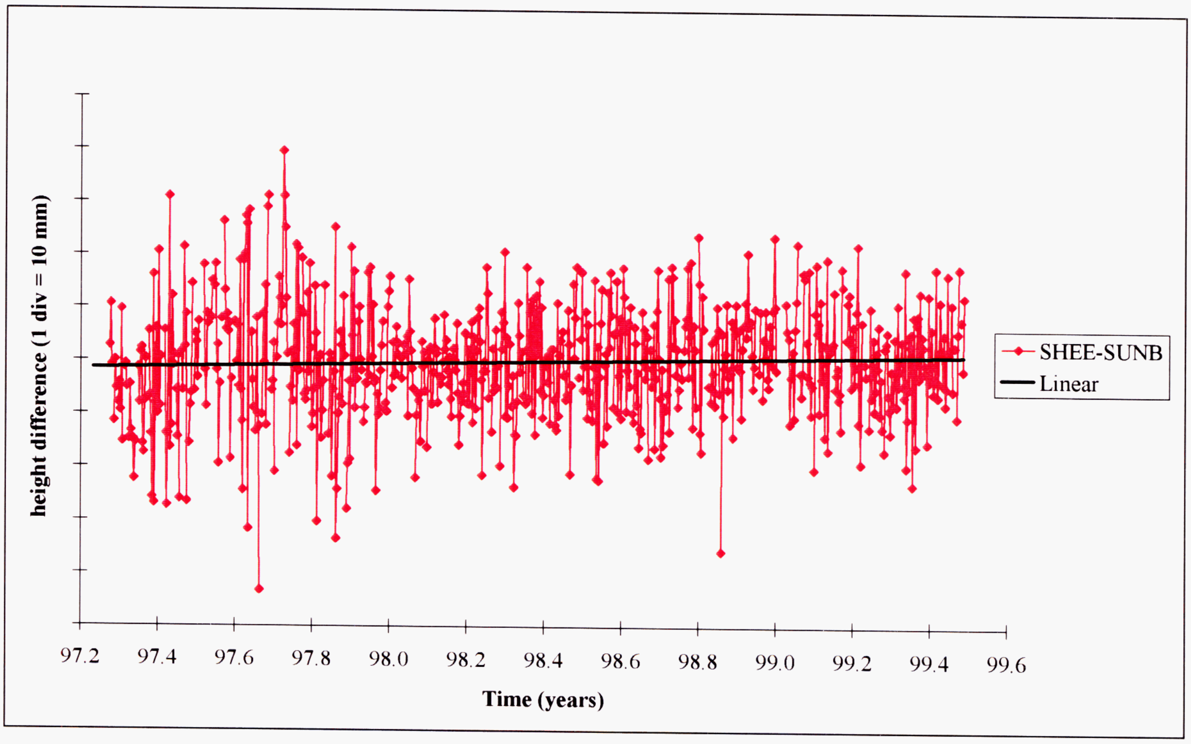


Figure 11 Height difference time series for Sheerness TG minus Sunbury Yard

A closer inspection of the height time series for Barking Barrier, given in Figure 9, suggests that there is an apparent annual cyclic trend at this station, with a minima at 98.00 and 99.00, maxima at 97.50 and 98.50 and an amplitude of about 5 mm. Similar annual cyclic trends may also be seen in the height time series for Sunbury Yard and Sheerness TG, although the amplitudes here are only about 1 or 2 mm and the minima and maxima appear about two months earlier.

Comparing Figures 10 and 11, it can be seen that the annual variations in height are not eliminated in Figure 10 but are mostly eliminated in Figure 11. This confirms that the annual variations are common to Sheerness TG and Sunbury Yard, but suggests that there are additional effects taking place at Barking Barrier. The most obvious explanation for the cause of these additional effects is a thermal expansion of the concrete tower that is part of the Barking Barrier structure, and on which the GPS antenna is located.

Figures 10 and 11 also include best-fit linear trends through the height difference time series. In the case of Figure 10, the linear trend is – 0.1 mm/yr, which suggests that over the 2.25 year monitoring period there have been no significant changes in ground level between the reference stations at Barking Barrier and Sunbury Yard. In the case of Figure 11, the trend is + 1.2 mm/yr, which suggests that over the 2.25 year monitoring period, the reference station at Sheerness TG has risen by about 2.7 mm in total with respect to the reference station at Sunbury Yard.

This apparent rise of the reference station at Sheerness TG may be an indication of a change in regional ground level in an east-west direction, or could be a more local effect. At this stage, it is not possible to evaluate this change in ground level in geological terms as there is uncertainty about the nature of the foundation conditions on which the Sheerness TG is sited.

7.2 Links to Sea Level

In the monitoring network design, six monitoring stations were established at tide gauges, namely Richmond TG, Tower Pier TG, Silvertown TG, Erith TG, Tilbury TG and Southend Pier TG, to provide a link to sea level.

As stated in Section 6.3 (ii), based on only 2.25 years of continuous GPS data, any estimate for the vertical station velocities of these ‘tide gauge monitoring stations’ would have a precision of about 2.2 to 4.4 mm/yr. Considering the small movements expected at these monitoring stations, it can be concluded that the 2.25 year monitoring period was not sufficient to be able to compute a reliable estimate of the vertical station velocities for each of these stations. Therefore, in this section, the height time series given in Appendix D are re-presented as two figures for comparison purposes only.

Figure 12 shows the height time series for the three ‘western tide gauge monitoring stations’, moving from west to east, namely Richmond TG (RICH), Tower Pier TG (TOPR) and Silvertown TG (SILV). Figure 13 shows the height time series for the three ‘eastern tide gauge monitoring stations’, moving from west to east, namely Erith TG (ERIT), Tilbury TG (TILB) and Southend Pier TG (SOPR). In these figures, the height time series are presented as arbitrary values for display purposes.

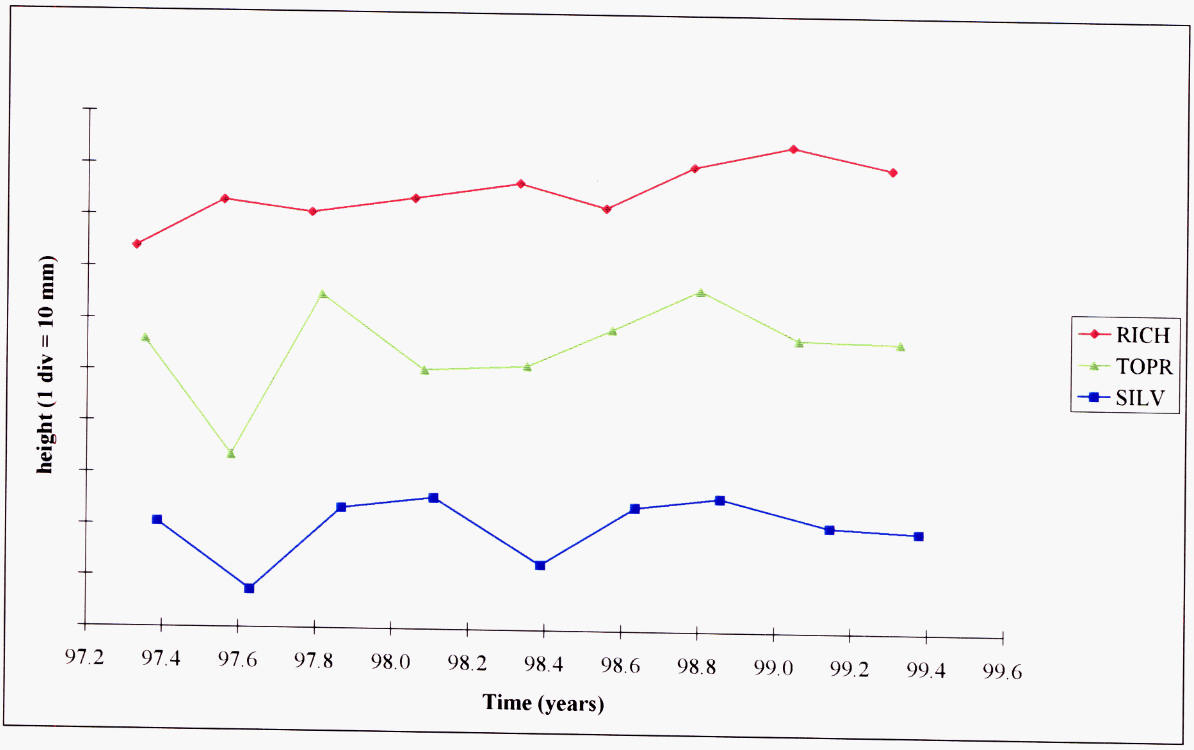


Figure 12 Height time series for the 'western tide gauge monitoring stations'

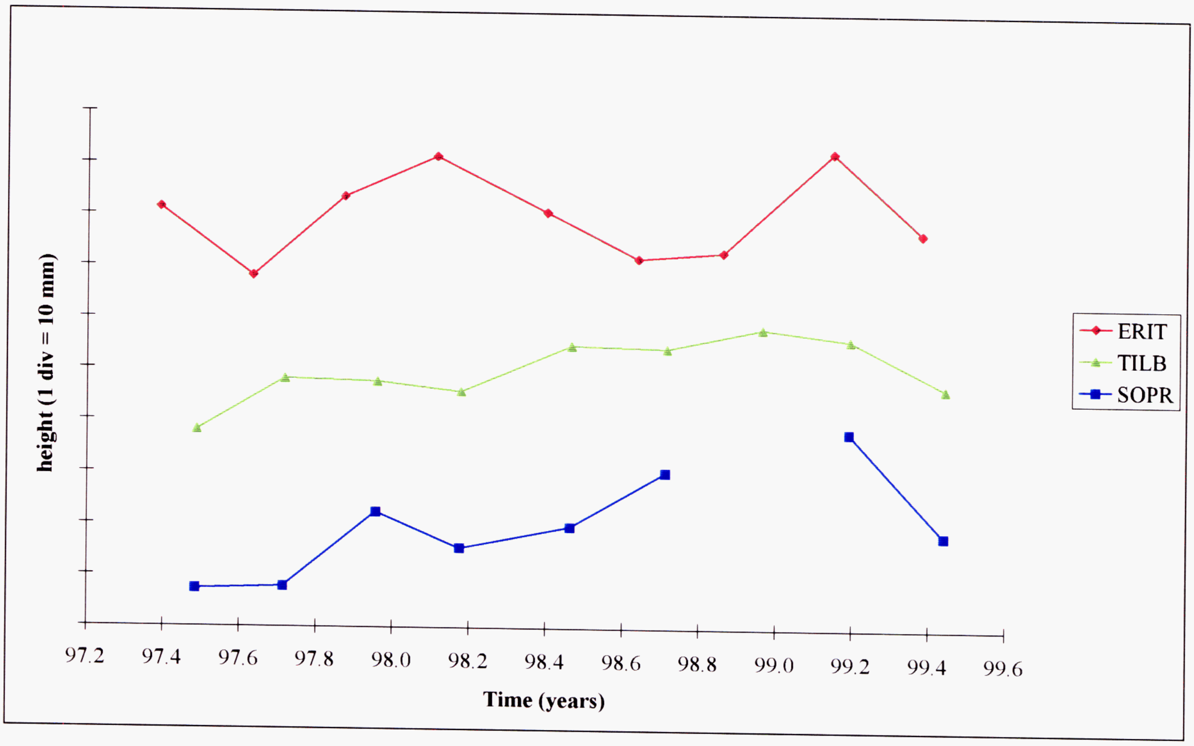


Figure 13 Height time series for the 'eastern tide gauge monitoring stations'

Considering Figures 12 and 13, it would appear that the heights of the 'tide gauge monitoring stations' vary from epoch to epoch. It is important to note that these variations in height are not indications of changes in ground level, but simply reflect the quality of the individual epochal height estimates. With this in mind, it is important not to 'over interpret' these height time series at this stage. Instead, exercising caution, it can be concluded that these height time series confirm that there have been no significant changes in ground level at the six 'tide gauge monitoring stations' over the 2.25 year monitoring period.

7.3 London basin Tectonic Activity

In the monitoring network design, eight monitoring stations were included in order to monitor any tectonic activity associated with the London basin. These were Shirburn Hill, Dunstable Down, Heath Farm, Isle of Thanet, Thurnham, Rowdow Hill, Riddlesdown and Hindhead.

As stated in Section 6.3 (ii), based on only 2.25 years of continuous GPS data, any estimate for the vertical station velocities of these 'regional monitoring stations' would have a precision of about 2.2 to 4.4 mm/yr. Considering the small movements expected at these monitoring stations, it can be concluded that the 2.25 year monitoring period was not sufficient to be able to compute a reliable estimate of the vertical station velocities for each of these stations. Therefore, in this section, the height time series given in Appendix D are re-presented as two figures for comparison purposes only.

Figure 14 shows the height time series for the three 'northern regional monitoring stations', moving from west to east, namely Shirburn Hill (SHHL), Dunstable Down (DUDO) and Heath Farm (HEFM). Figure 15 shows the height time series for the four 'southern regional monitoring stations', moving from west to east, namely Hindhead (HIND), Riddlesdown (RIDD), Rowdow Hill (ROHL) and Thurnham (THUR). Here it is important to note that the Isle of Thanet has not been included due to the poor quality of its data, highlighted by the large standard error bars in Figure D11 of Appendix D. In Figures 14 and 15, the height time series are presented as arbitrary values for display purposes.

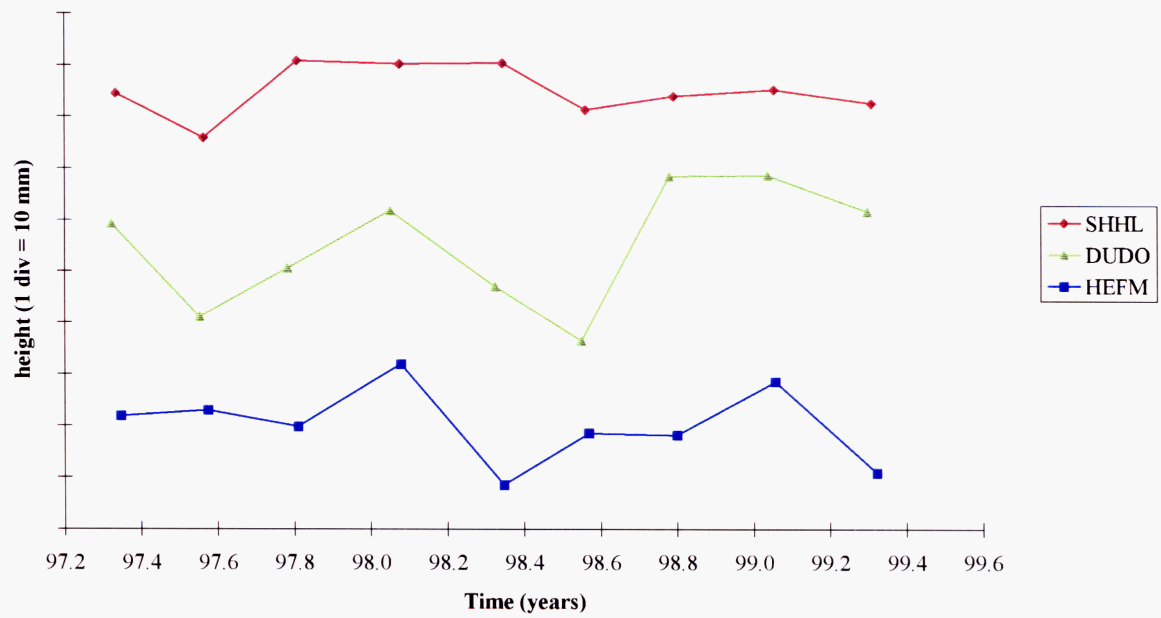


Figure 14 Height time series for the 'northern regional monitoring stations'

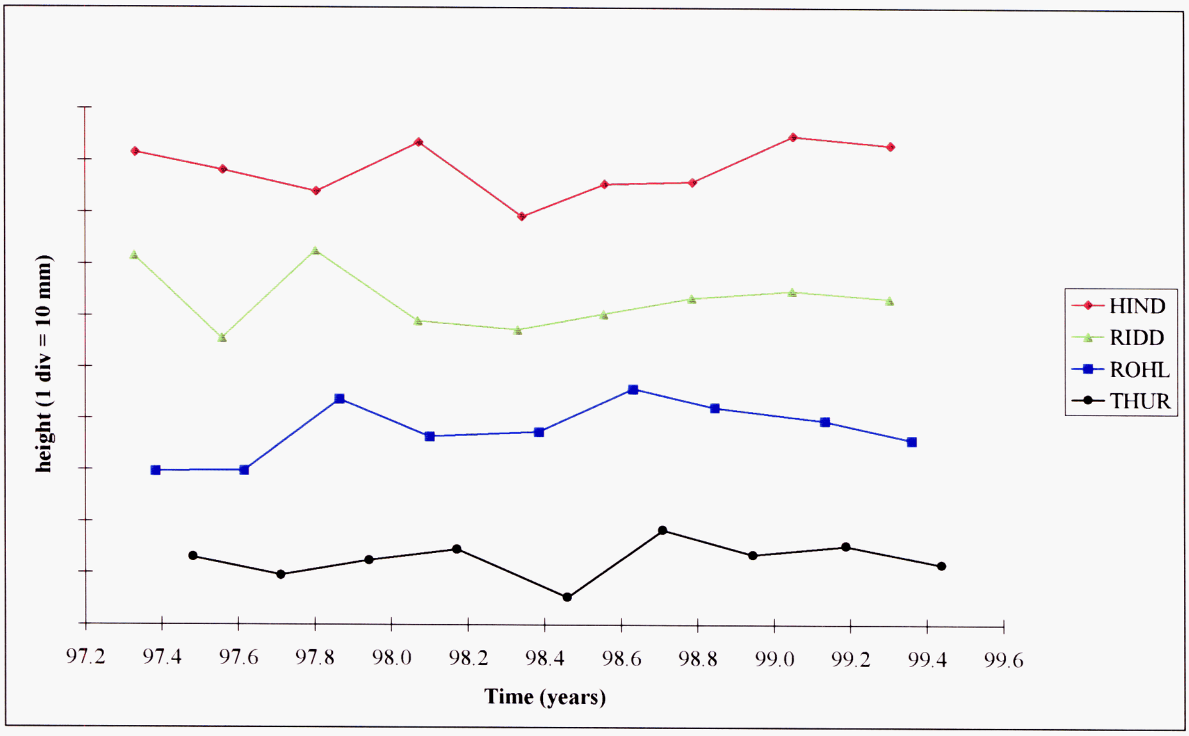


Figure 15 Height time series for the 'southern regional monitoring stations'

Considering Figures 14 and 15, it would appear that the heights of the 'regional monitoring stations' vary from epoch to epoch. It is important to note that these variations in height are not indications of changes in ground level, but simply reflect the quality of the individual epochal height estimates. With this in mind, it is important not to 'over interpret' these height time series at this stage. Instead, exercising caution, it can be concluded that these height time series confirm that there have been no significant changes in ground level at the seven 'regional monitoring stations' over the 2.25 year monitoring period.

7.4 Greenwich Fault

From the desk study at the beginning of the project, it was proposed that the monitoring of ground movements on a sub-regional scale due to activity on the Greenwich fault should be carried out. In the network design, two monitoring stations were included for this purpose, namely Sundridge Park GC and Greenwich Park. These were set up as a pair to enable relative movements to be measured over a short baseline.

The height time series for these two monitoring stations are given in Appendix D, as Figures D17 and D22. In this section, these two height time series are presented together, along with a height difference time series computed by differencing the epochal height estimates for Sundridge Park GC (SPGC) from the epochal height estimates for Greenwich Park (GRPK).

Figure 16 shows the height time series and the height difference time series for these two stations. In this figure, the height time series and height difference time series are presented as arbitrary values for display purposes only.

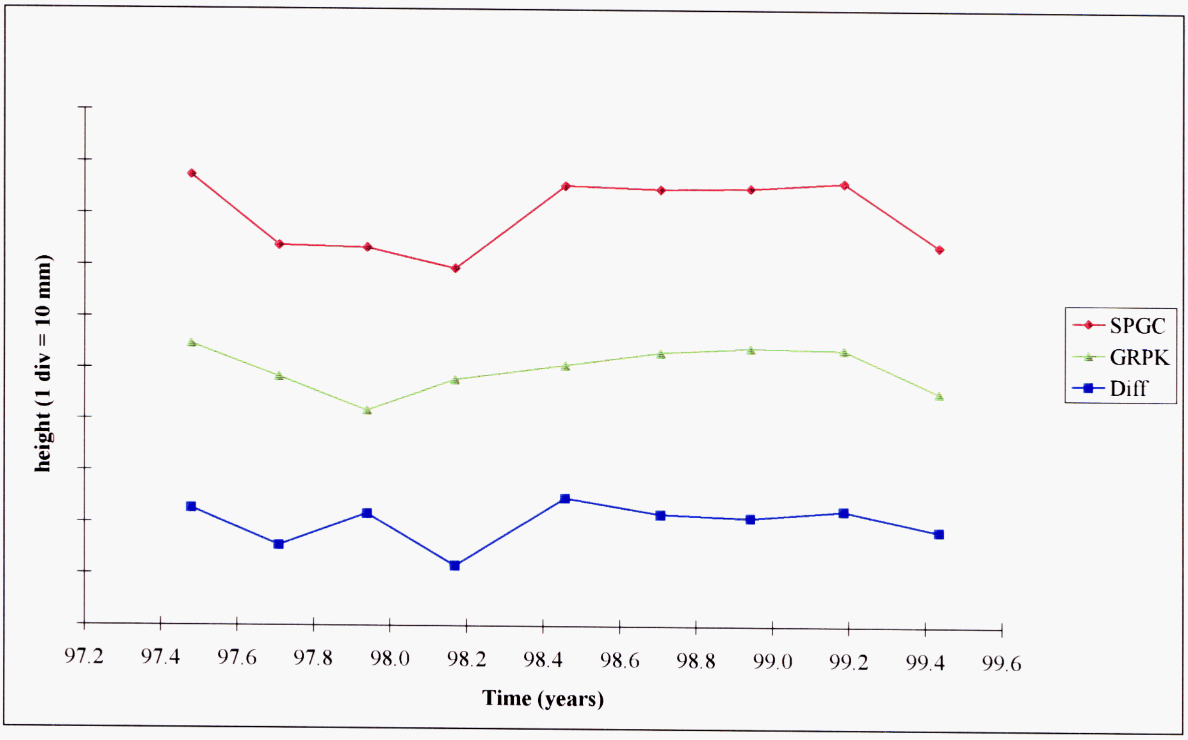


Figure 16 Height and height difference time series for the Greenwich fault monitoring stations

From Figure 16, it can be seen that the variations in the two height time series are correlated, as would be expected with GPS over such a short baseline. This means that by forming the height difference time series, any common errors in the two height time series should be differenced away, leading to an improved estimate of the relative change in height.

From the height difference time series there is some evidence to suggest that the monitoring station at Sundridge Park GC has 'risen' relative to the monitoring station at Greenwich Park over the 2.25 year monitoring period. A best-fit linear trend through the height difference time series gives a value for the relative station velocities of + 0.9 mm/yr. This is interesting but it is not statistically significant. After such a short monitoring period, therefore, it would be unwise to attribute the change in height difference to ground movement caused by the Greenwich fault.

7.5 Aquifer Recharge

From the desk study at the beginning of the project, it was proposed that the monitoring of ground movements on a sub-regional scale due to aquifer recharge should be carried out. In the network design, two monitoring stations were included for this purpose, namely Bush Hill Park GC and Mill Plane. These were set up as a pair to enable relative movements to be measured over a short baseline.

The height time series for these two monitoring stations are given in Appendix D, as Figures D16 and D18. In this section, these two height time series are presented together, along with a height difference time series computed by differencing the epochal height estimates for Bush Hill Park GC (BPGC) from the epochal height estimates for Mill Plane (MIPL).

Figure 17 shows the height time series and the height difference time series for these two stations. In this figure, the height time series and height difference time series are presented as arbitrary values for display purposes only.

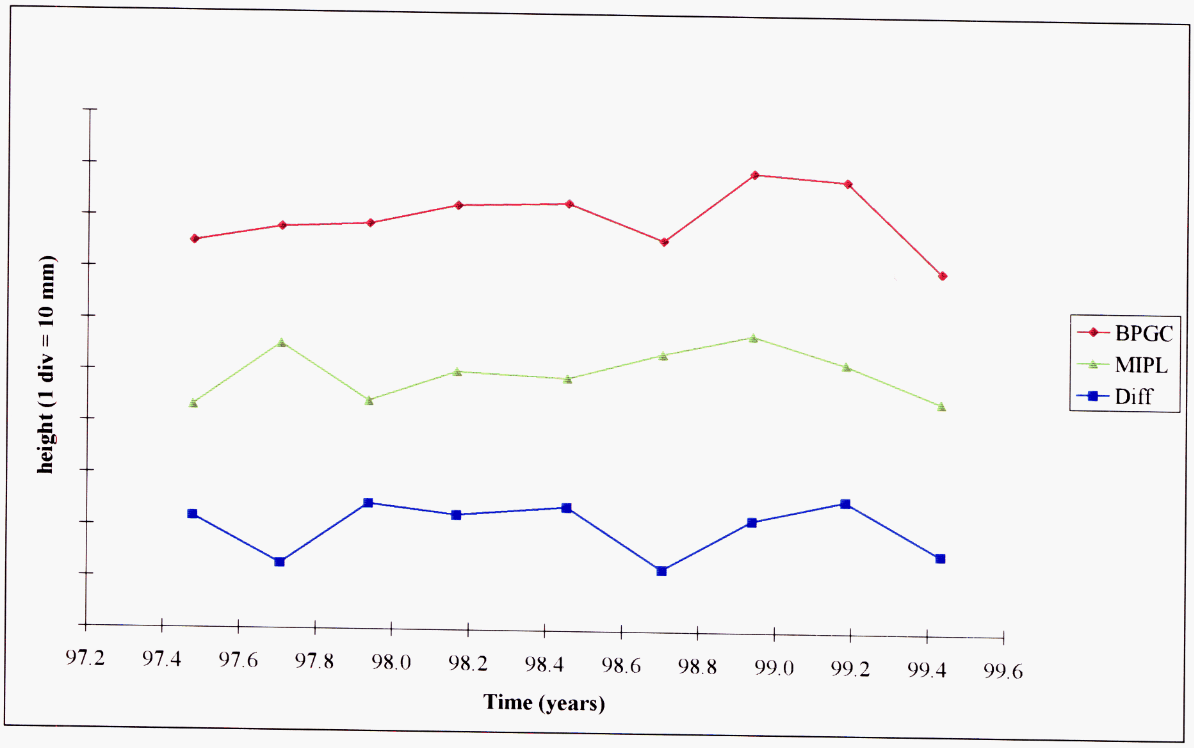


Figure 17 Height and height difference time series for the aquifer recharge monitoring stations

From Figure 17, it can be seen that the variations in the two height time series are correlated, as would be expected with GPS over such a short baseline. This means that by forming the height difference time series, any common errors in the two height time series should be differenced away, leading to an improved estimate of the relative change in height.

A best-fit linear trend through the height difference time series gives a value for the relative station velocities of - 0.3 mm/yr. Therefore, from the height difference time series for the 2.25 year monitoring period there is no evidence to suggest that aquifer recharge has caused ground movements on a sub-regional scale at these two monitoring stations.

7.6 Alluvial Compaction

From the desk study at the beginning of the project, it was proposed that the monitoring of ground movements due to alluvial compaction should be carried out on a local scale. For this purpose, the 'tide gauge monitoring stations' at Tilbury TG and Southend Pier TG were paired with monitoring stations at Gravesend Grammar School and Grain respectively.

The height time series for these four monitoring stations are given in Appendix D, as Figures D5, D6, D20 and D21 respectively. In this section, the height time series for the monitoring station pairs are presented together, along with a height difference time series. Figure 18 shows the height time series and the height difference time series for Tilbury TG and Gravesend Grammar School. Figure 19 shows the height time series and the height difference time series for Southend Pier TG and Grain. In these figures, the height time series and height difference time series are presented as arbitrary values for display purposes only.

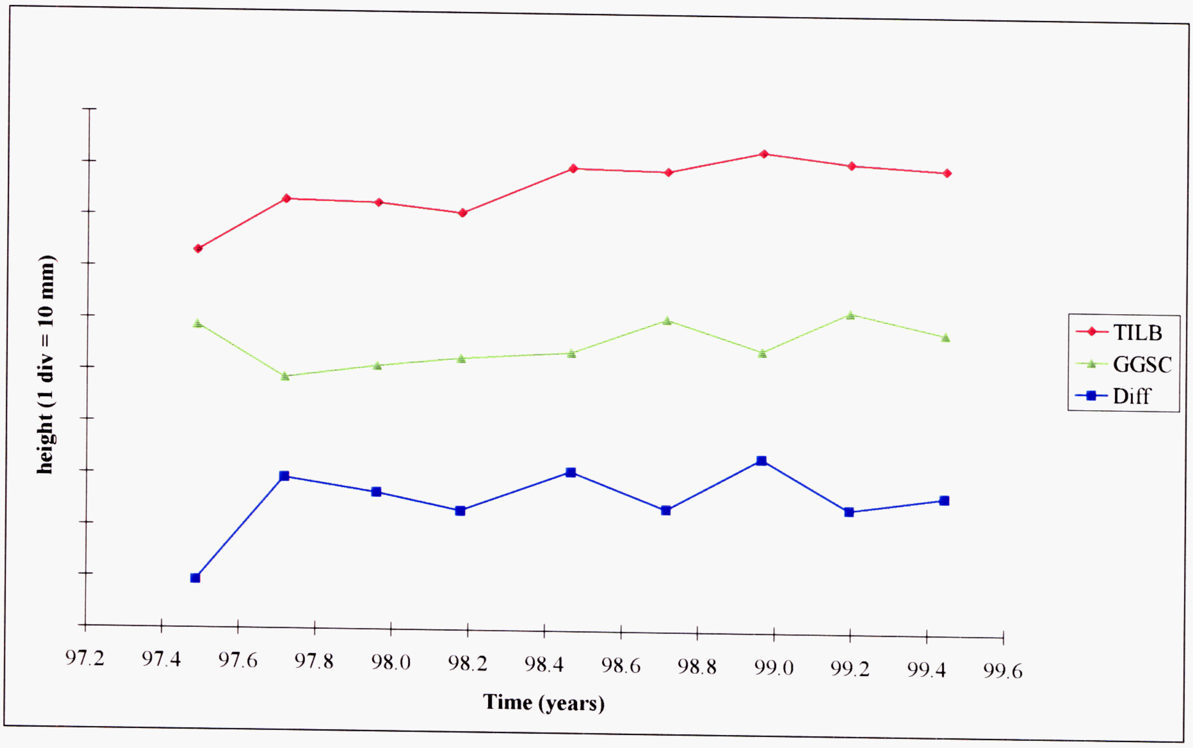


Figure 18 Height and height difference time series for Tilbury TG and Gravesend Grammar School

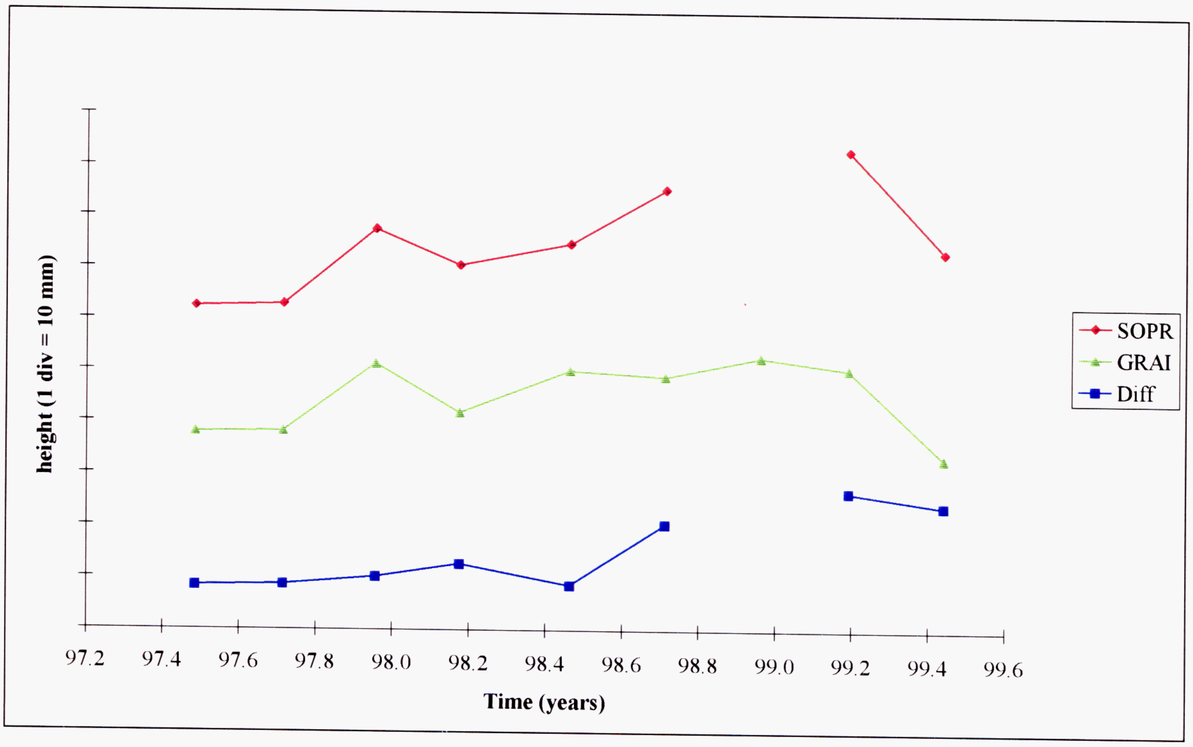


Figure 19 Height and height difference time series for Southend Pier TG and Grain

From both Figures 18 and 19, it can be seen that the variations in the height time series are correlated for both short baselines. This means that by forming the height difference time series, any common errors in the two height time series should be differenced away, leading to improved estimates for the relative changes in height.

From the two height difference time series there is some evidence to suggest that the two 'tide gauge monitoring stations' on the north side of the Thames estuary have 'risen' with respect to the two monitoring stations on the south side of the Thames estuary, over the 2.25 year monitoring period. A best-fit linear trend through the height difference time series gives a value for the relative station velocities of + 4.5 mm/yr for Tilbury TG relative to Gravesend Grammar School and + 8.0 mm/yr for Southend Pier TG relative to Grain.

From a geodetic point of view, the height difference time series shown in Figures 18 and 19 are interesting and the station velocities would appear to be statistically significant. From a geological point of view these are also some of the most interesting results. Although it is entirely speculative, because of the short monitoring period, the relative rise of sites on the north side of the Thames estuary compared to the south may relate to tectonic activity. Alternatively, the different foundation conditions at each site could account for the relative movements observed. For instance, Tilbury TG is resting on alluvium and is thus potentially more unstable than Gravesend Grammar School which is sited on chalk. Similarly, Grain is on gravel whereas the foundation of Southend Pier is uncertain, but may be in London Clay, gravel or alluvium.

7.7 London Clay Swell-Shrink

From the desk study carried out at the beginning of the project, it was proposed that the monitoring of ground movements due to the swell-shrink of London Clay on a local scale should be carried out. In the network design, the monitoring stations at Mascalls and Dunton Hills were selected for this purpose, with an additional monitoring station installed as the Dunton Hills Aux to enable an independent estimate of changes in ground level at this site using precise levelling.

It was noted in Section 6.3 (ii), that the standard deviation of an epochal height estimate from the time-averaged mean height were the highest for Mascalls and Dunton Hills. Considering the height time series for these two stations, presented in Appendix D as Figure D10 and D19, it is clear that the high standard deviations are due to seasonal variations in the height time series.

From Figures D10 and D19, it can be seen that over the last 2.25 years, the Mascalls and Dunton Hills monitoring stations have

- first subsided by about 12 and 20 mm respectively between May and November 1997, due to shrinking of the London Clay,
- then risen by 38 and 10 mm respectively between November 1997 and May 1998, due to swelling of the London Clay,
- then subsided again by 43 and 22 mm respectively between May and August 1998, due to shrinking of the London Clay, and
- then risen again by 54 and 48 mm respectively between August 1998 and May 1999, due to swelling of the London Clay.

In this section, the height time series for Mascalls and Dunton Hills are presented together in Figure 20 for comparison purposes. In this figure, the height time series and height difference time series are presented as arbitrary values for display purposes only.

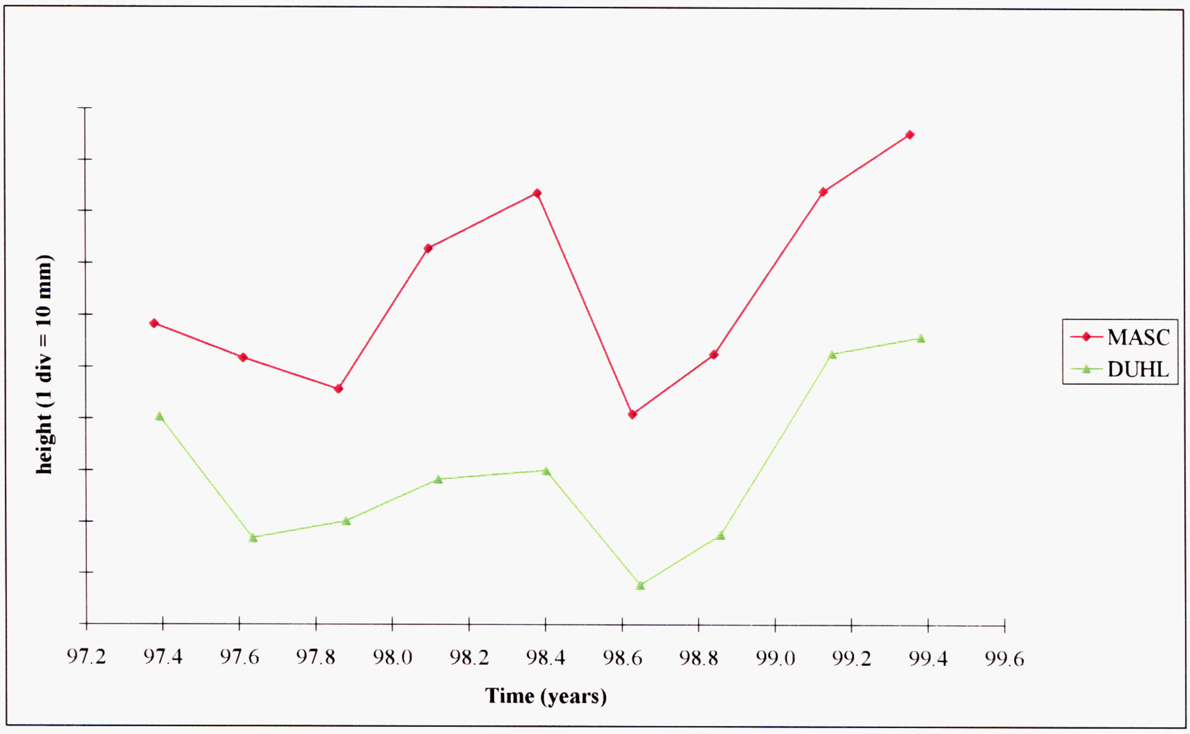


Figure 20 Height time series for the London clay swell-shrink monitoring stations

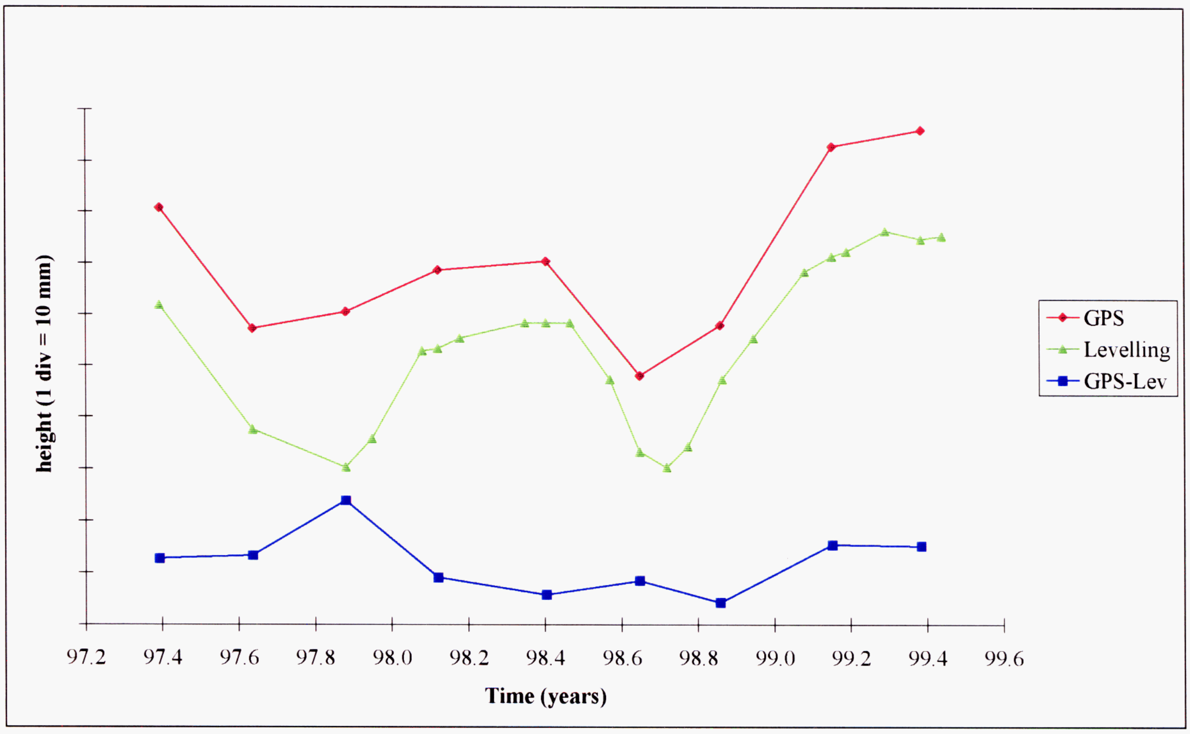


Figure 21 Height time series for Dunton Hills based on GPS and precise levelling

From Figure 20, it is remarkable that although there are seasonal variations in ground level of about 50 mm, the two height time series are still correlated.

Further investigations of the swell-shrink of London Clay at Dunton Hills were enabled through a series of episodic levelling measurements between this station and Dunton Hills Aux, that was assumed to be 'stable'. The results for the episodic GPS measurements are compared with those from the precise levelling in Figure 21. In this figure, it can be seen that the local precise levelling results confirm the pattern of swell-shrink indicated by the episodic GPS measurements at Dunton Hills, with the standard deviation for the height difference time series being only 6 mm.

From a geodetic point of view, the results shown in Figure 21 confirm that the changes in ground level are due to the swelling and shrinking of the London Clay. From a geological point of view the results shown in Figure 20 are very interesting, and are in accordance with results obtained by independent research carried out specifically to investigate this problem (BRE 1980a, 1980b, 1981; Driscoll 1983, 1984).

8 CONCLUSIONS AND RECOMMENDATIONS

The aim of the project was to develop a generic strategy for monitoring small changes in ground level within regions of up to 100 x 100 km in extent, and providing an interpretation of such changes in terms of local and regional geology. This aim has been achieved through the development of a monitoring strategy based around a monitoring network, a geodetic observation strategy, a geodetic processing strategy and a geological database.

Through the pilot study in the Thames region, the following conclusions can be made regarding the monitoring strategy developed as part of this project:

(i) Using continuous GPS data at a reference station, it is possible to obtain standard deviations of a daily height estimate from the time-averaged mean of ± 10 mm. Over the 2.25 year monitoring period, these are equivalent to precisions for the time averaged mean height of ± 0.4 mm. In the longer term, these standard deviations will enable vertical station velocities of 1 mm/yr to be estimated to a required precision of ± 0.4 mm/yr, with a monitoring period of 6 to 7 years.

(ii) Continuous GPS data appears to be sensitive to small variations in height on seasonal and annual time scales. These variations are currently one of the 'hot research topics' in high precision GPS and it is recommended that future research is required in order to isolate these seasonal and annual effects in height time series.

(iii) Using episodic GPS data at a monitoring station, in association with continuous GPS data from a reference station, it is possible to obtain standard deviations of an epochal height estimate from the time-averaged mean of ± 5 to 10 mm. Over the 2.25 year monitoring period, these are equivalent to precisions for the time averaged mean height of ± 1.3 to 3.3 mm. In the longer term, these standard deviations will enable vertical station velocities of 1 mm/yr to be estimated to a required precision of ± 0.4 mm/yr, with a monitoring period of 7 to 12 years.

The pilot study has rationalised the understanding of current changes in ground level in the Thames region. Specifically, over the 2.25 year monitoring period, it has been shown that:

(i) In relation to changes in sea level, there have been no significant changes in ground level at tide gauges along the Thames estuary.

(ii) There have been no significant changes in ground level due to tectonic activity associated with the London basin and the Greenwich fault.

(iii) There have been no significant changes in ground level due to aquifer recharge in the Enfield-Haringey area.

(iv) There is some evidence for tectonic activity in the east of the Thames estuary, with the north side rising relative to the south side.

(v) There are significant seasonal changes in ground level of up to 50 mm where London Clay is at the surface, but these movements are not apparent where London Clay is overlaid by other deposits.

As a result of this project, the IESSG and the BGS have put in place a monitoring network that can be used by the Agency for the continued monitoring of long term changes in ground level in the Thames region. Furthermore, the monitoring strategy that has been developed is not specific to the Thames region and could be used by the Agency in any other regions where changes in ground level are of concern. For any region, a monitoring period of 6 to 12 years would be required in order to detect millimetric changes in ground level.

REFERENCES

Ashkenazi, V and Ffoulkes-Jones, G H (1990) Millimetres over hundreds of kilometres by GPS. *GPS World,* Vol **1**, No **6**.

Ashkenazi, V, Jones, D E B, Lowe, D P and Woodhams, J W (1993) Reservoir deformation monitoring by GPS satellites. *Surveying World,* September 1993.

Ashkenazi V and Roberts G W (1997) Experimental monitoring of the Humber Bridge with GPS. Proceedings of the Institution of Civil Engineers, Vol **120**, Issue **4**, 177-182.

Ashkenazi, V, Bingley, R M, Dodson, A H, Penna, N T and Baker, T F (1998) Monitoring Tide Gauge Heights in the UK with GPS. *Proceedings of Commission 5 of the FIG '98 Congress*, Brighton, UK, 291-303.

Baker, T F (1984) Tidal deformations of the Earth. Sci Prog, No **69**, Oxford.

Baker, T F, Curtis, D J and Dodson, A H (1995) Ocean tide loading and GPS. *GPS World,* March 1995, 54-59.

Beamson, G A (1995) Precise height determination of tide gauges using GPS. *PhD Thesis,* University of Nottingham.

Beutler, G (1994) Development of the IGS. *IGS 1994 Annual Report,* IGS Central Bureau, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, 3-9.

Beutler, G, Rothacher, M, Springer, T, Kouba, J and Neilan, R (1998) The International GPS Service (IGS): an interdisciplinary service in support of Earth sciences. *Proceedings of the 32nd COSPAR Scientific Assembly*, Nagoya, Japan.

Bevis, M, Bock, Y, Fang, P, Reilinger, R, Herring, T, Stowell, J and Smalley, R (1997) Blending old and new approaches to regional GPS geodesy. *EOS Transactions,* American Geophysical Union, Vol **78**, No 6, 61-66.

BIFROST (1996) GPS measurements to constrain geodynamic processes in Fennoscandia. *EOS Transactions,* American Geophysical Union, Vol **77**, No 35, 337-341.

Boucher, C and Altamimi, Z (1996) International Terrestrial Reference Frame. *GPS World,* September 1996, 71-74.

Brackley, I J A (1975) The inter-relationship of the factors affecting heave of an expansive, unsaturated, clay soil. *PhD Thesis*, University of London, 159-166.

Bristow, C R (1983) The stratigraphy and structure of the Red Crag of Mid-Suffolk, England. *Proceedings of the Geologists'Association*, Vol **94**, 1-12.

Building Research Establishment (1980a) Low rise buildings on shrinkable clay soils: part 1, *Digest 240*, HMSO, London.

Building Research Establishment (1980b) Low rise buildings on shrinkable clay soils: part 2, *Digest 241*, HMSO, London.

Building Research Establishment (1981) Assessment of damage in low rise buildings, *Digest 251*, HMSO, London.

Bridgland, D R and D'Olier, B (1995) The Pleistocene evolution of the Thames and Rhine drainage systems in the southern North Sea basin, in Island Britain: a Quaternary perspective, Preece, R C (editor),_*Geological Society Special Publication,* No **96**, 27-45.

Bruyninx, C, Dousa, J, Ehrnsperger, W, Fachbach, N, Stangl, G, Ferraro, C, Fermi, M, Nardi, A, Sciaretta, C, Vespe, F, Figurski, M, Piraszewski, M, Rogowski, J, Johansson, J, Springer, T A, Beutler, G, Brockmann, E, Gurtner, W, Rothacher, M, Schaer, S, Weber, G, Wiget, W and Wild, U (1997) The EUREF associate analysis centre. *IGS 1996 Annual Report,* IGS Central Bureau, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, 271-309.

Devoy, R J N (1979) Flandrian sea level changes and vegetational history of the lower Thames estuary. *Philosophical Transactions of the Royal Society of London Series B,* **285**, 355-410.

Devoy, R J N (1982) Analysis of the geological evidence for Holocene sea-level movements in south-east England. *Proceedings of the Geologists' Association,* **93**, 65-90.

Dixon, T H (1991) An introduction to the Global Positioning System and some geological applications. *Reviews f Geophysics*, **29, 2**, 249-276.

Dodson, A H (1986) Refraction and propagation delays in space geodesy. *International Journal Of Remote Sensing*, Vol **7**, No **4**, 515-524.

Dodson, A H, Hill, C J and Shardlow, P J (1992) The effect of atmospheric refraction on GPS measurements. In *Proceedings of the 5th International Seminar on GPS* (Nottingham 1992).

Dodson, A H, Shardlow, P J, Hubbard, L C M, Elgered, G and Jarlemark, P O J (1996) Wet tropospheric effects on precise relative GPS height determination. *Journal of Geodesy,* **70**, 188-202.

Driscoll, R (1983) The influence of vegetation on the swelling and shrinking of clay soils in Britain. *Géotechnique*, Vol **33**, 93-105.

Driscoll, R (1984). The effects of clay soil volume changes on low-rise buildings. In *Ground Movements and their Effects on Structures*, Surrey University Press.

Greensmith, J T and Tucker, E V (1980). Evidence for differential subsidence on the Essex coast. *Proceedings of the Geologists' Association,* **91**, 169-175.

Hobbs, P R N, Yeow, H, Horseman, S T and Jackson, P D (1982) Swelling properties of the mudrocks at Harwell. *Radioactive Waste Disposal Research Series.* BGS Report ENPU 82-11.

IPCC (1990) The Intergovernmental Panel on Climate Change scientific assessment. Edited by Houghton, J T, Jenkins, G J and Ephraums, J J. *Cambridge University Press,* 365 pp.

IPCC (1995) Climate Change 1995. The science of climate change, contribution of working group I to the second assessment report of the Intergovernmental Panel on Climate Change. Edited by Houghton, J T, Meira Filho, L G, Callander, B A, Harris, N, Kattenberg, A, and Maskell, K. *Cambridge University Press*, 572 pp.

Kelsey, J (1972) Geodetic aspects concerning possible subsidence in south-eastern England. *Philosophical Transactions of the Royal Society*, London, **A272**, 141-149.

Kouba, J and Mireault, Y (1997) Analysis coordinator report. *IGS 1996 Annual Report,* IGS Central Bureau, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, 55-100.

Long, A J and Tooley, M J (1994) Holocene sea-level and crustal movements in Hampshire and Southeast England, United Kingdom. Chapter 41 in *Journal of Coastal Research Special Issue No.17: Holocene Cycles: Climate, Sea levels and Sedimentation.*

Long, A J (1995) Sea-level and crustal movements in the Thames estuary, Essex and Kent. In t*he Quaternary of the Lower Reaches of the Thames*, edited by D R Bridgland, P Allen and B A Haggart, Quaternary Research Association: Durham, 99-105.

Maddy, D (1997) Uplift driven valley incision and river terrace formation in southern England. *Journal of Quaternary Science*, **12**, 539-545.

Marsland, A (1986) The flood plain deposits of the Lower Thames. *Quarterly Journal of Engineering Geology*, Vol **19**, 223-247.

McCarthy, D D (1992) IERS standards 1992. *International Earth Rotation Service (IERS) Technical Note 13,* Observatoire de Paris.

McEntee, J M (1984) The influence of vegetation on the swelling and shrinking of clays. In: *Discussion on the Fourth Géotechnique Symposium Géotechnique*, Vol **34**, 151-153.

Muir Wood, R (1990) London: not waving but drowning. *Terra Nova*, **2(3)**, 284-291.

Neilan (1995) The organisation of the IGS. *IGS 1994 Annual Report,* IGS Central Bureau, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, 11-23.

O'Shea, M J, Baxter, K M and Charalambous, A N (1995) The hydrogeology of the Enfield-Haringey artificial recharge scheme, north London. *Quarterly Journal of Engineering Geology*, **28**, S115-129.

Penna, N T (1997) Monitoring land movement at UK tide gauge sites using GPS. *PhD Thesis,* University of Nottingham.

Rothacher, M, Schaer, S, Mervart, T L, and Beutler, G (1995) Determination of antenna phase centre variations using GPS data. In *Proceedings of the 1995 IGS Workshop,* (Potsdam 1995).

Schupler, B R and Clark, T A (1991) How different antennas affect the GPS observable. *GPS World,* November/December 1991.

Shennan, I (1989) Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science*, **4**, 77-89.

Spurrell, F J C (1889). On the estuary of the Thames and its alluvium. *Proceedings of the Geologists' Association,* **11**, 210-230.

Stewart, M P, Ffoulkes-Jones, G H, Chen, W, Ochieng, W Y, Shardlow, P J, and Penna, N T (1997) GPS Analysis Software (GAS) version 2.4 user manual. *IESSG Publication,* University of Nottingham.

Wilson, G and Grace, H (1942) The settlement of London due to underdrainage of the London Clay. *Journal of the Institution of Civil Engineers*, Vol **19**, 100-127.

Woodworth, P L and Jarvis, J (1991) A feasibility study of the use of short historical and short modern tide gauge records to investigate long term sea level changes in the British Isles *Proudman Oceanographic Laboratory Internal Document*, **23**.

Woodworth, P L, Tsimplis, M N, Flather, R A and Shennan, I (1999) A review of the trends observed in British Isles mean sea level data measured by tide gauges *Geophysical Journal International*, **136**, 651-670.

Worssam, B C (1963). Geology of the country around Maidstone. *Memoir of the Geological Survey.*

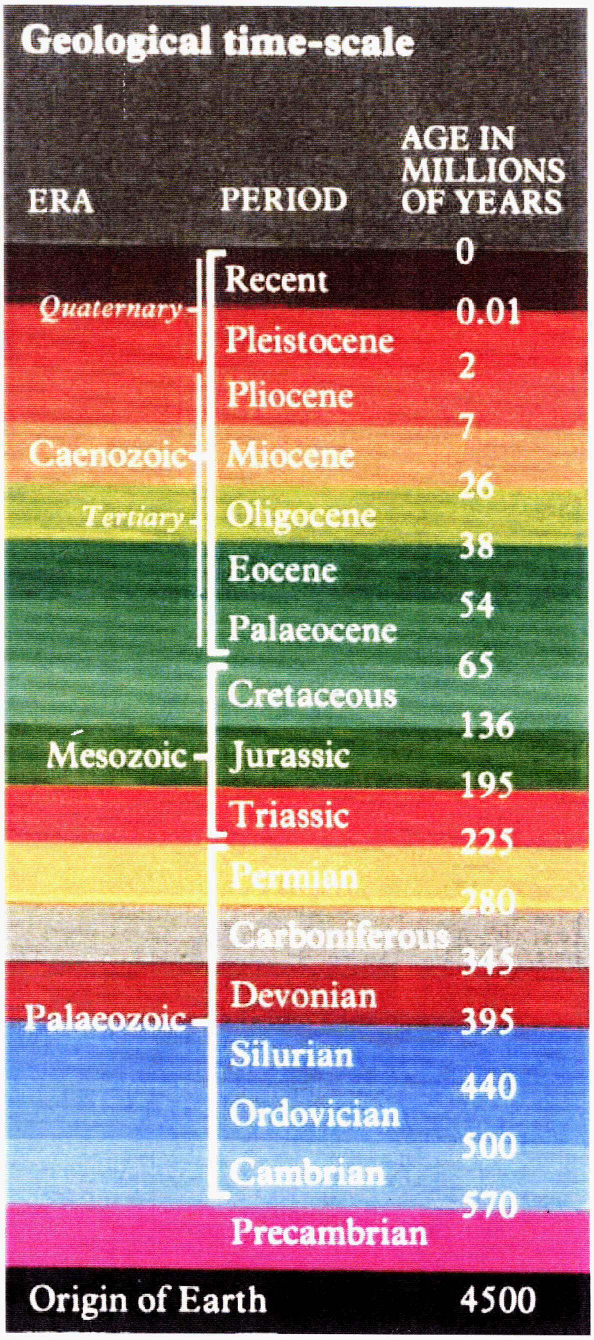
ACKNOWLEDGEMENTS

The R&D project detailed in this report was funded by the Environment Agency (Project WS-i698) and the Natural Environment Research Council (Grant Reference GR3/C0003), through the NERC CONNECT B scheme. The Berntsen Survey Monuments used for the new monitoring stations were supplied by Holtwood Marketing Ltd, for which the authors would like to acknowledge Mr Nigel Ward. The authors would also like to acknowledge other IESSG colleagues who have contributed directly to this work, including Dr G A Beamson, Mr K H Gibson, Mr A D Nesbitt and Dr S J Waugh. In addition, the authors would like to acknowledge the following BGS personnel; K A Booth and M Garcia Bajo (database and modelling), C J Evans (review of papers on ground movement), A J Humpage (engineering geology of swell-shrink), P R N Hobbs (theoretical work on sediment compaction) and R Wingfield (glacio-isostacy). Finally, the authors would like to acknowledge the contributions of Mr Dick Greenaway, Mr Keith Nursey and Dr David Bedlington of the Agency.

R A Ellison and A N Morigi publish with permission of the Director, British Geological Survey.

APPENDIX A

GEOLOGICAL TIME SCALE



Geological time-scale

ERA		PERIOD	AGE IN MILLIONS OF YEARS
			0
Caenozoic	*Quaternary*	Recent	
			0.01
		Pleistocene	
			2
	Tertiary	Pliocene	
			7
		Miocene	
			26
		Oligocene	
			38
		Eocene	
			54
		Palaeocene	
			65
Mesozoic		Cretaceous	
			136
		Jurassic	
			195
		Triassic	
			225
Palaeozoic		Permian	
			280
		Carboniferous	
			345
		Devonian	
			395
		Silurian	
			440
		Ordovician	
			500
		Cambrian	
			570
		Precambrian	
Origin of Earth			4500

APPENDIX B

PRECISION MEASURES USED

(i) Standard deviation and precision of the time-averaged mean

In this report, the standard deviation (σ_i) of an epochal / daily / weekly coordinate estimate from the time-averaged mean coordinate has been computed as

$$\sigma_i = \sqrt{\frac{\sum_{i=1}^{i=n}(X_i - X_m)^2}{(n-1)}}$$

The precision (σ_m) of a time-averaged mean coordinate (assuming a lack of correlation between the epochal / daily / weekly solutions and the elimination of systematic biases) has been computed as

$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{i=n}(X_i - X_m)^2}{n(n-1)}} = \sigma_i / \sqrt{n}$$

where

X_i = Coordinate value from an epochal / daily / weekly solution
X_m = Time-averaged mean coordinate value
n = Number of epochal / daily / weekly solutions

For the reference stations it is important to note that the standard deviation of a weekly solution from the time-averaged mean will be 2.646 (ie $\sqrt{7}$) times better than the standard deviation of a daily solution from the time-averaged mean. However, the precision of the time-averaged mean will be the same for a series of daily or weekly solutions averaged over the same observation period.

(ii) Precision of a velocity

In this report, estimates for the precision of a velocity (σ_v) in mm/yr have been computed following Dixon (1991) as

$$\sigma_v = \sigma_i \cdot \frac{1}{T} \cdot \sqrt{\frac{12\frac{T}{dt}}{(1+\frac{T}{dt})(2+\frac{T}{dt})}}$$

where

σ_i = Standard deviation (σ_i) of an epochal / daily coordinate estimate (mm)
T = Length of the monitoring period (yr)
dt = Time interval between monitoring epochs (yr)

For the monitoring stations, the time interval between monitoring epochs has been taken as 1/4 years, ie once every three months. However, for the reference stations it is important to note that the time interval between epochs has been taken as 1/26 years as opposed to 1/365 years to account for the correlations between daily coordinate estimates.

APPENDIX C

REFERENCE STATION HEIGHT TIME SERIES

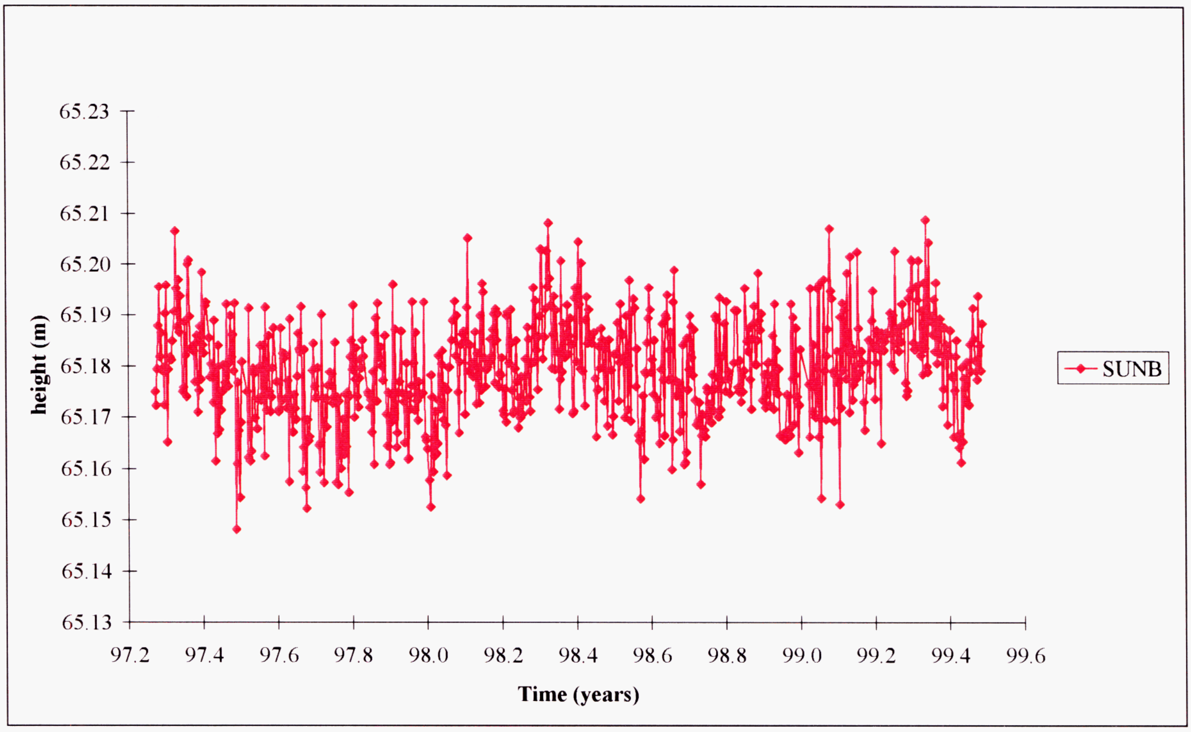


Figure C1 **Sunbury Yard reference station daily height time series**

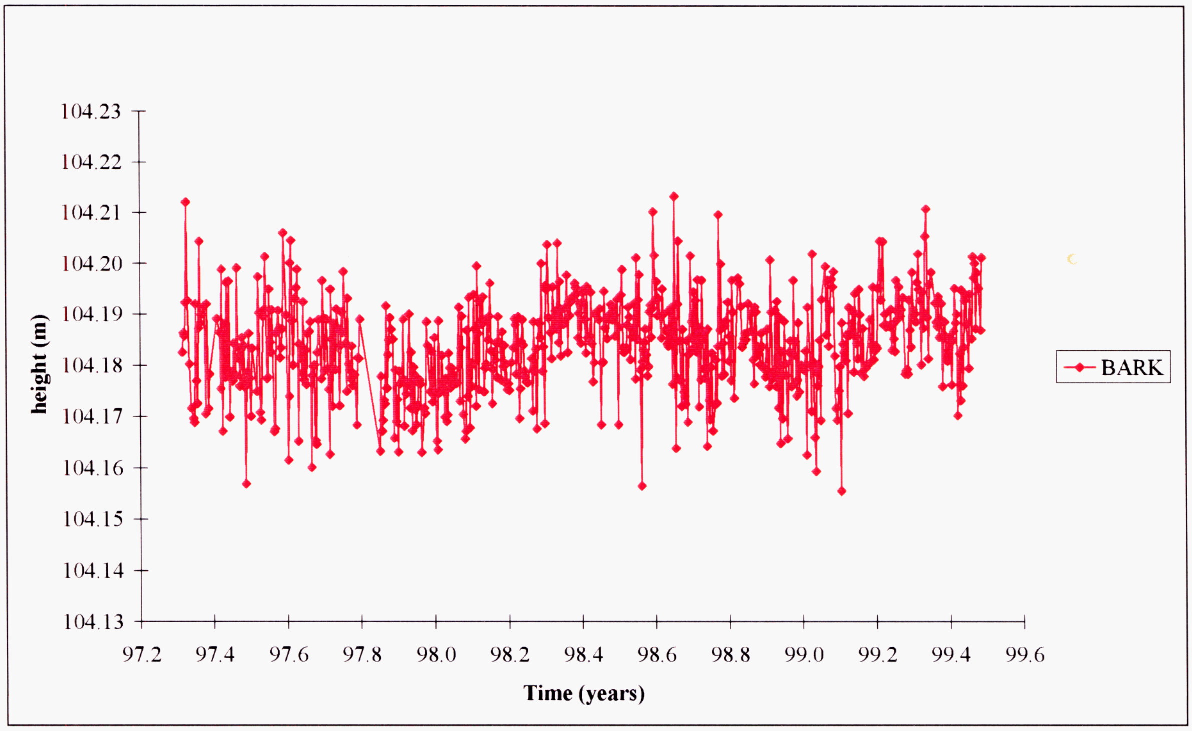


Figure C2 **Barking Barrier reference station daily height time series**

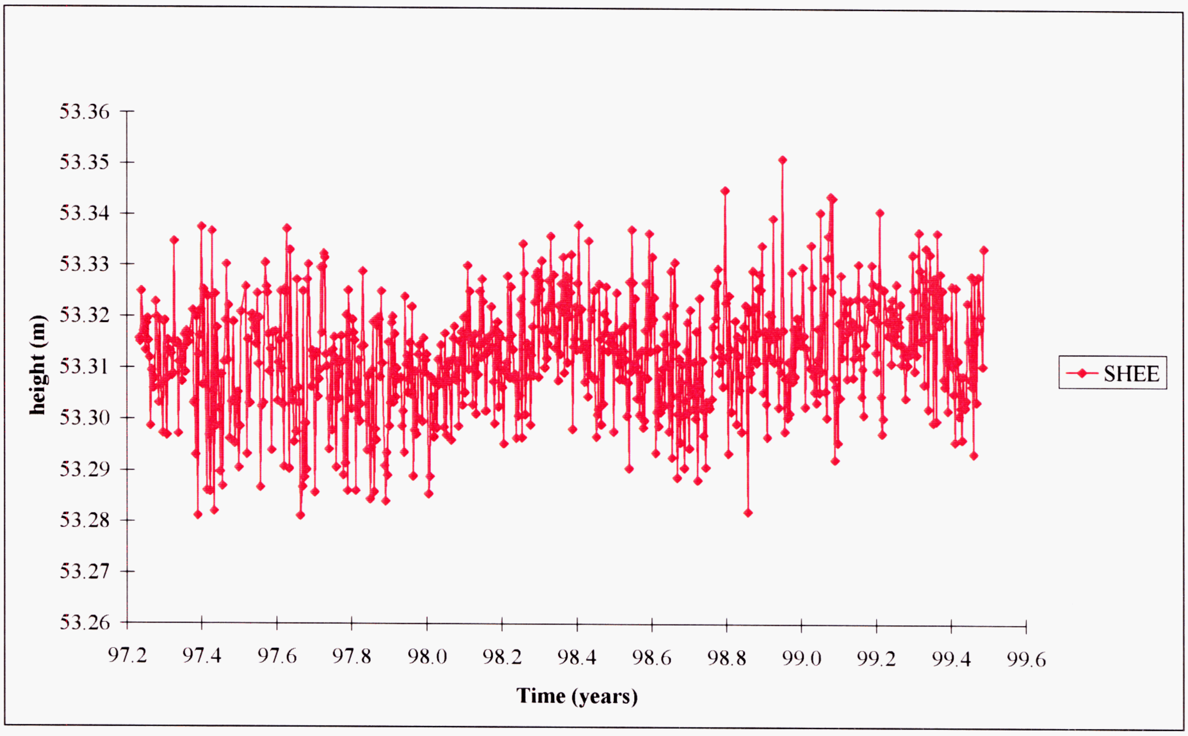


Figure C3 Sheerness TG reference station daily height time series

APPENDIX D

MONITORING STATION HEIGHT TIME SERIES

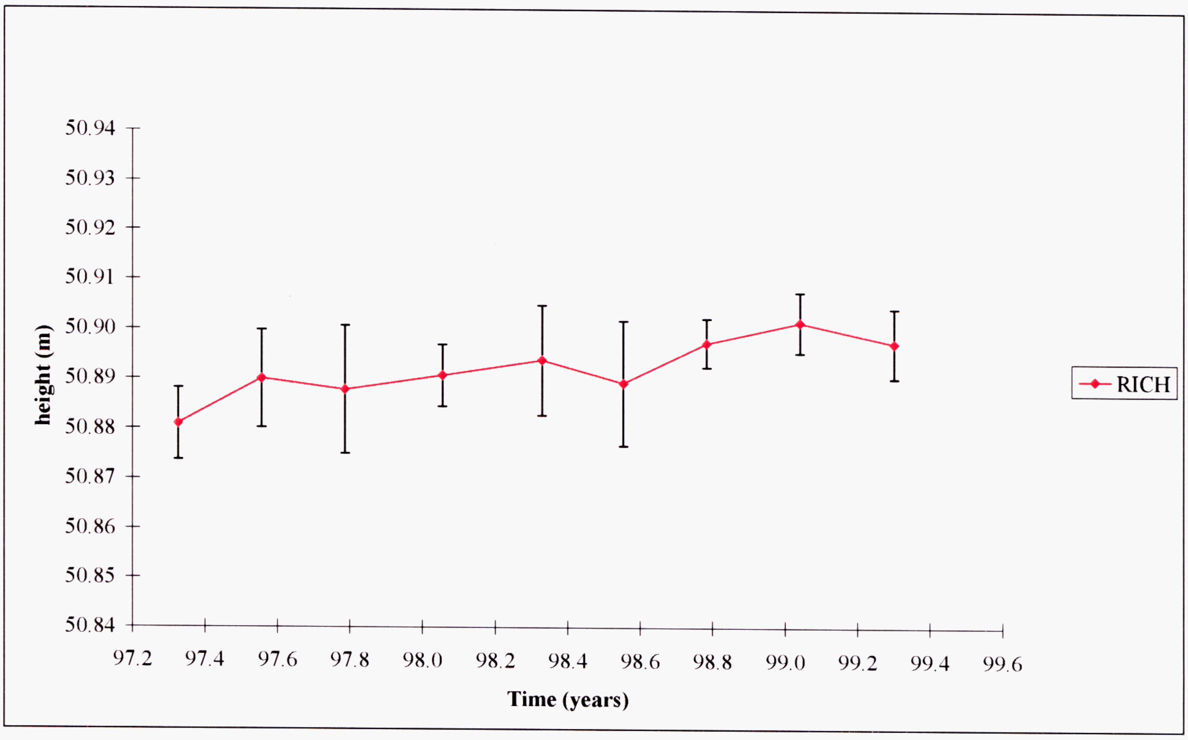


Figure D1 Richmond TG monitoring station epochal height time series (with standard errors)

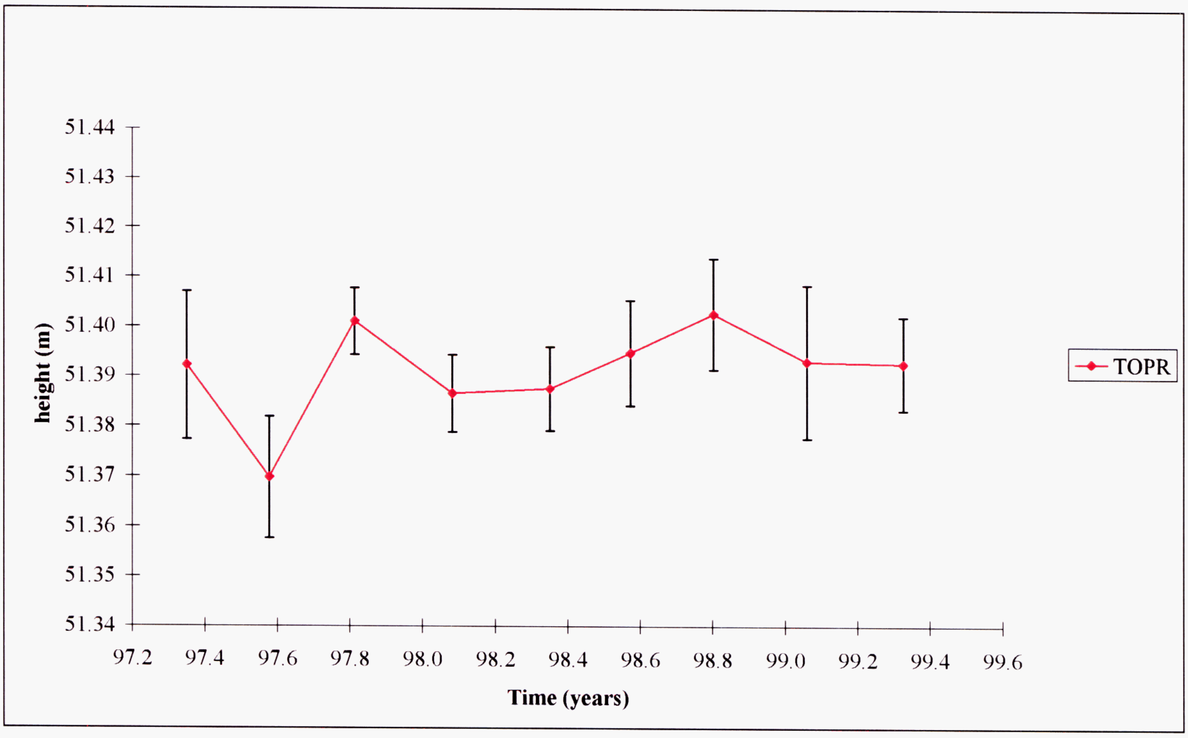


Figure D2 Tower Pier TG monitoring station epochal height time series (with standard errors)

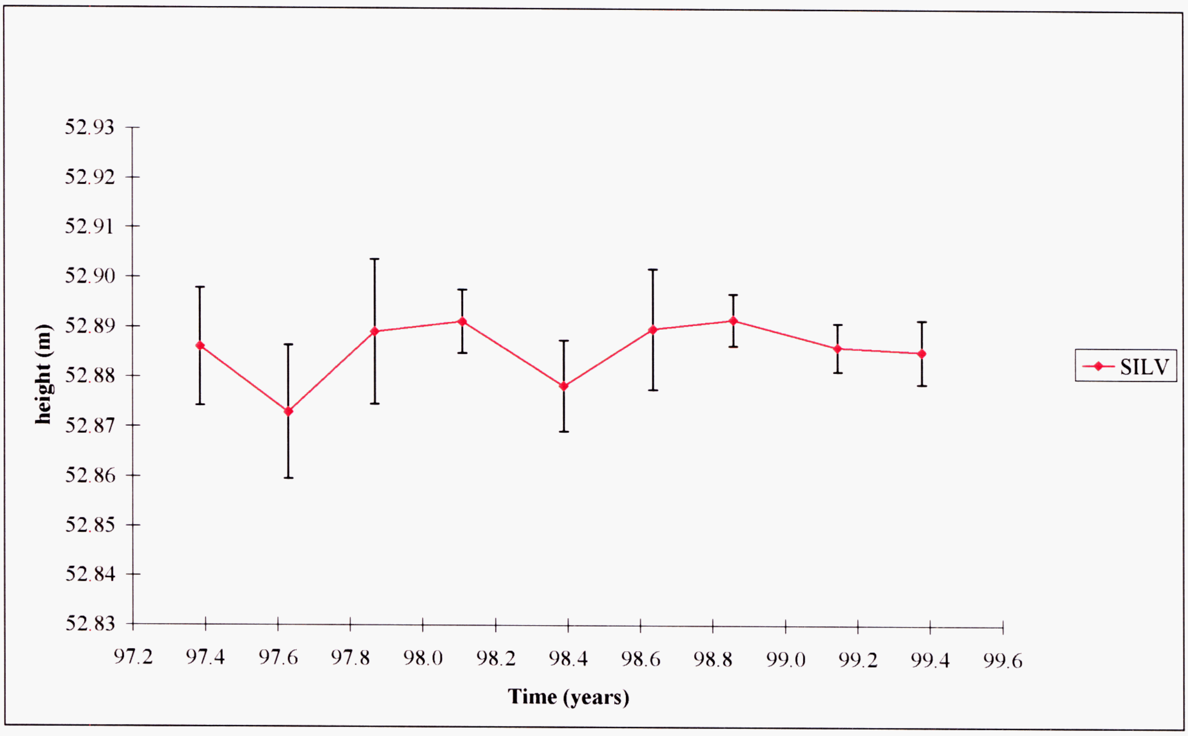


Figure D3 Silvertown TG monitoring station epochal height time series (with standard errors)

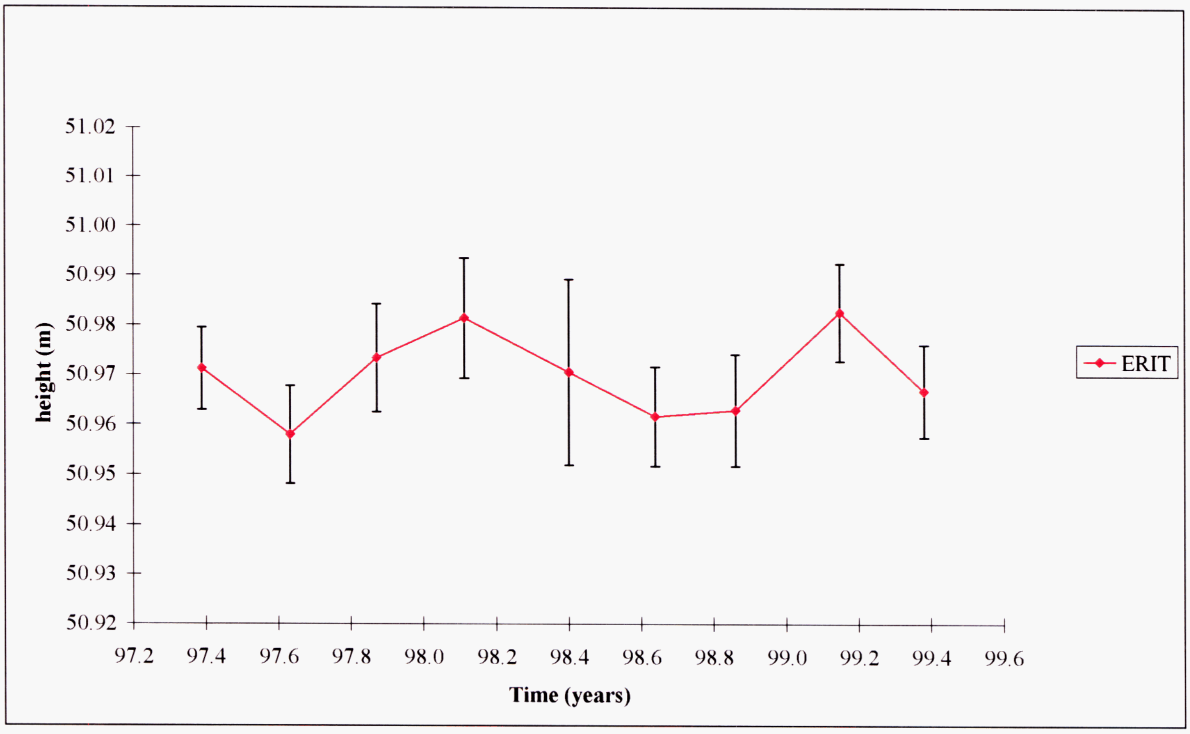


Figure D4 Erith TG monitoring station epochal height time series (with standard errors)

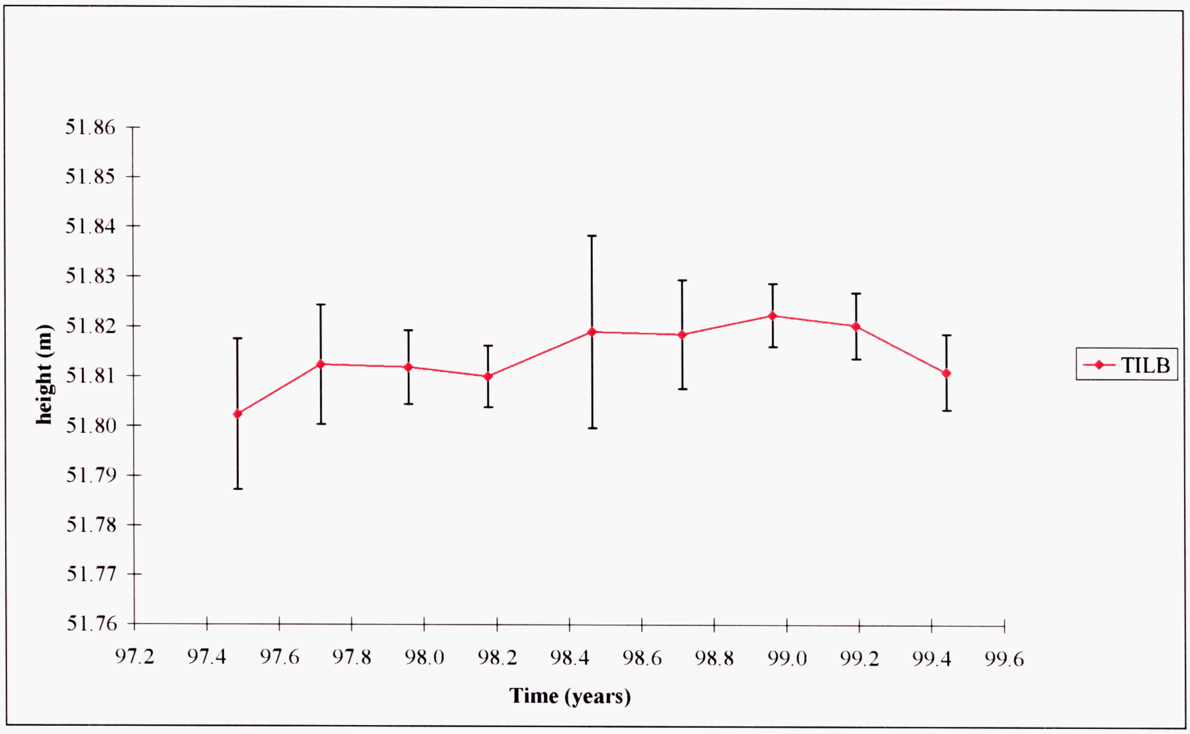


Figure D5 Tilbury TG monitoring station epochal height time series (with standard errors)

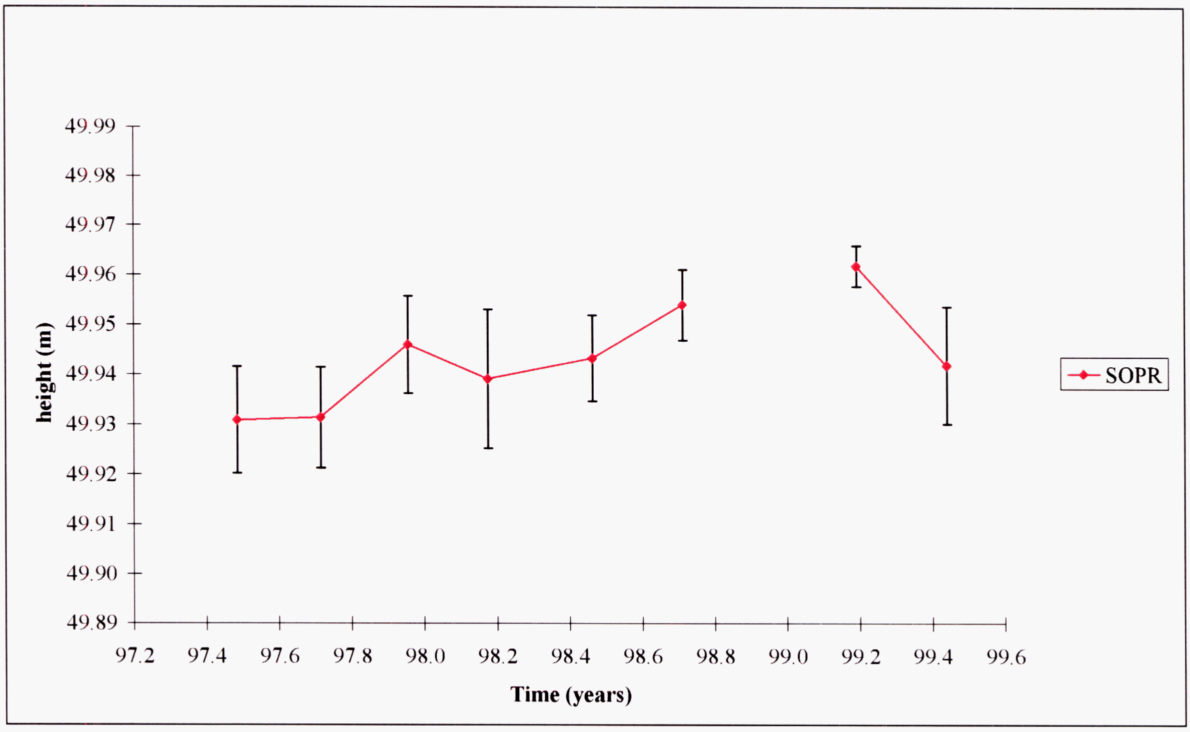


Figure D6 Southend Pier TG monitoring station epochal height time series (with standard errors)

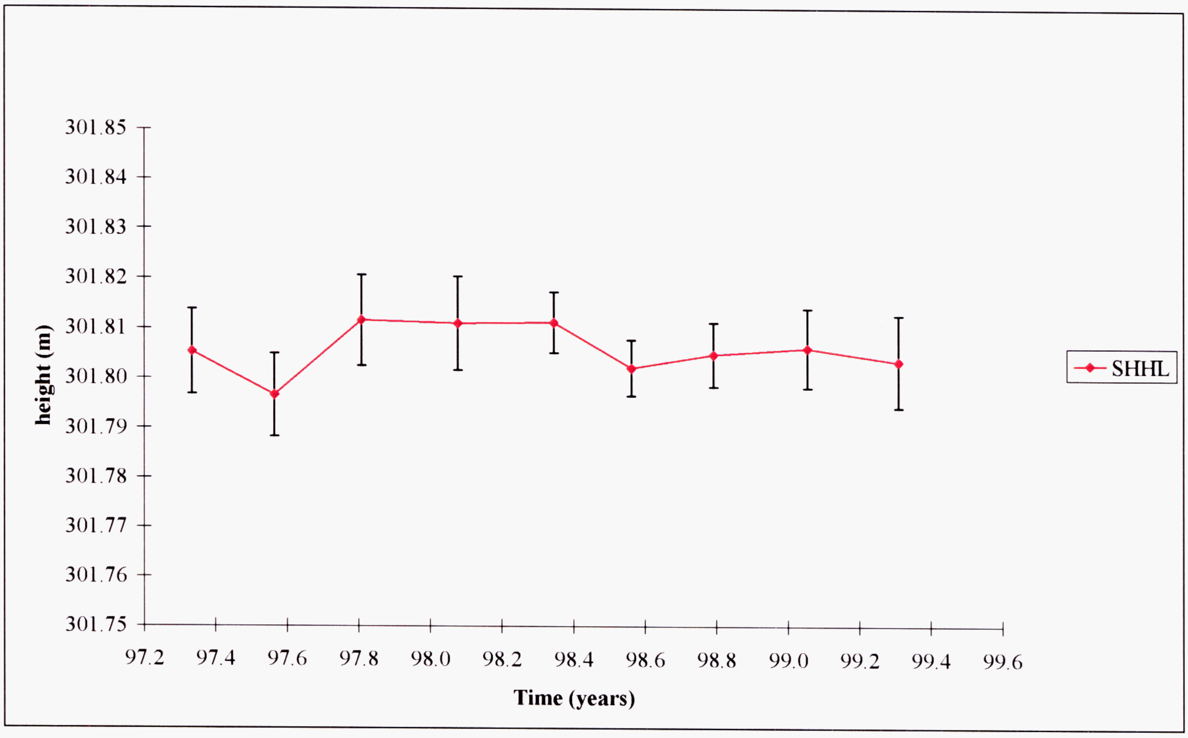


Figure D7 Shirburn Hill monitoring station epochal height time series (with standard errors)

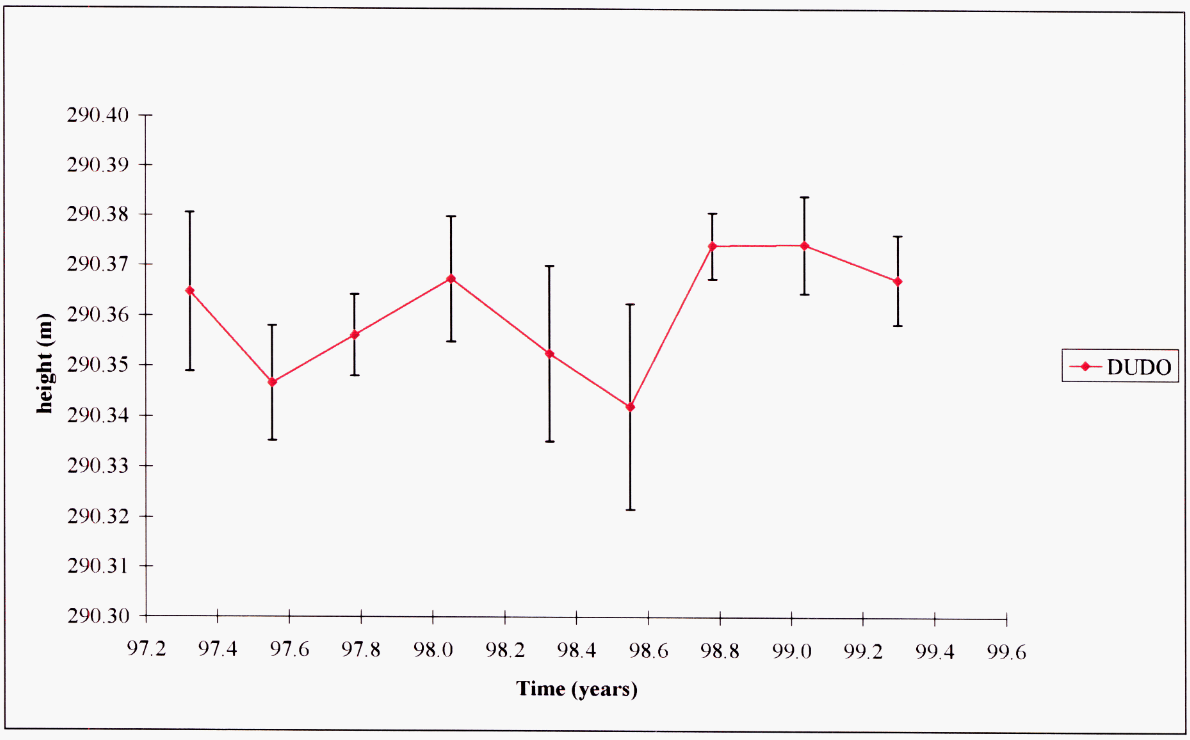


Figure D8 Dunstable Down monitoring station epochal height time series (with standard errors)

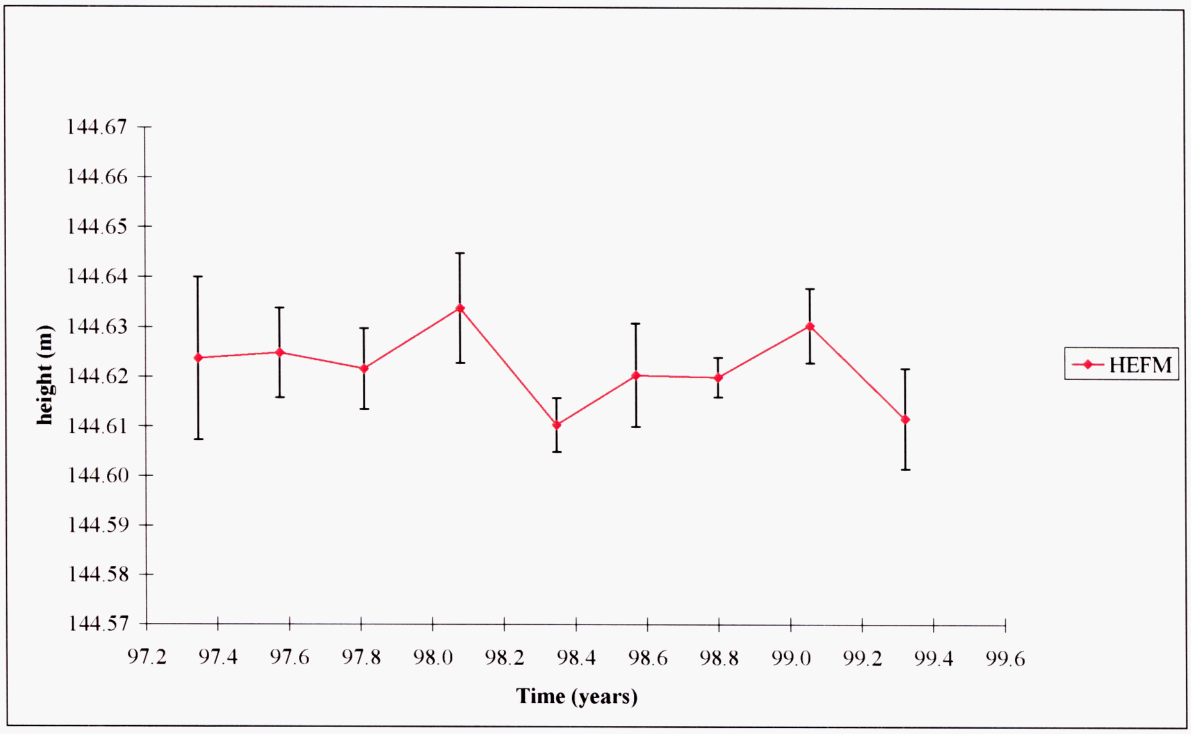


Figure D9 **Heath Farm monitoring station epochal height time series (with standard errors)**

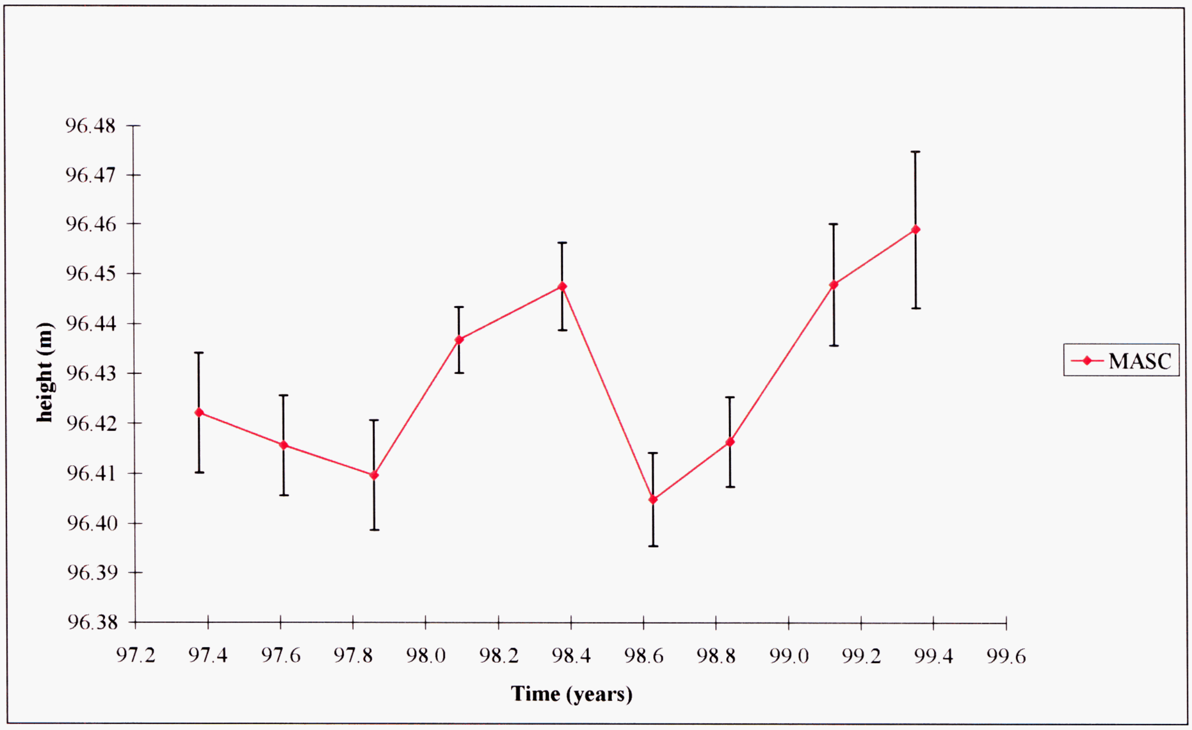


Figure D10 **Mascalls monitoring station epochal height time series (with standard errors)**

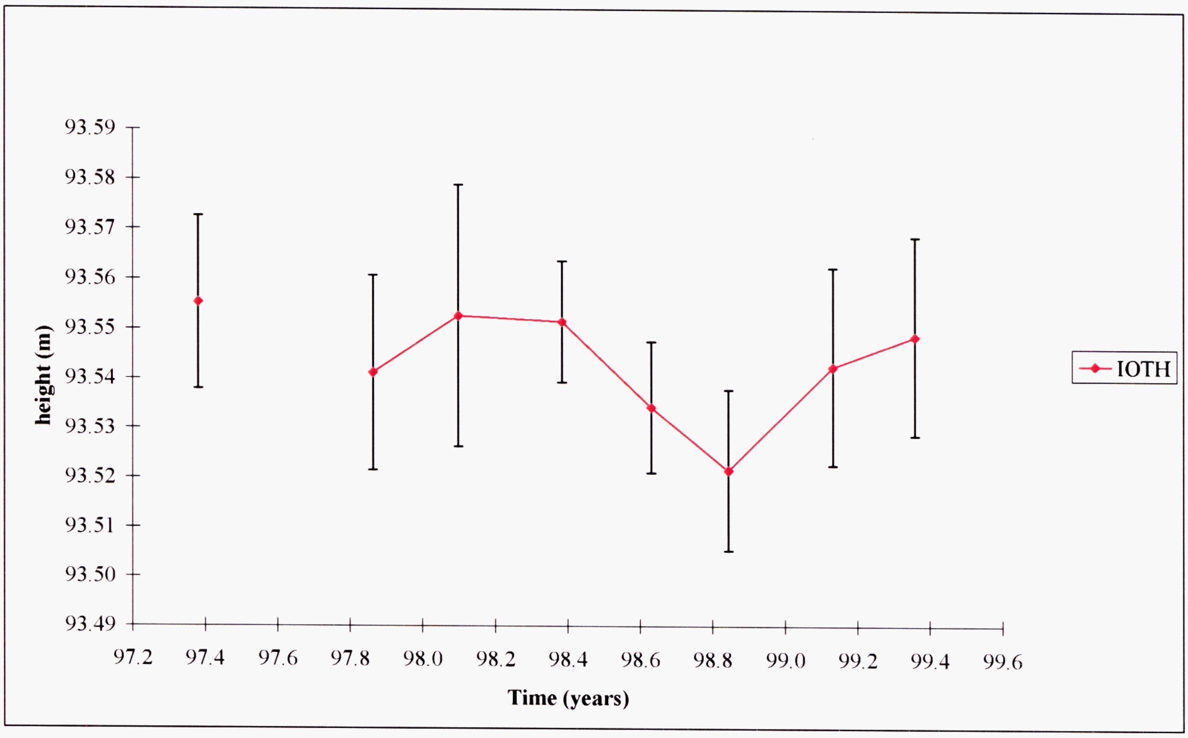


Figure D11 **Isle of Thanet monitoring station epochal height time series (with standard errors)**

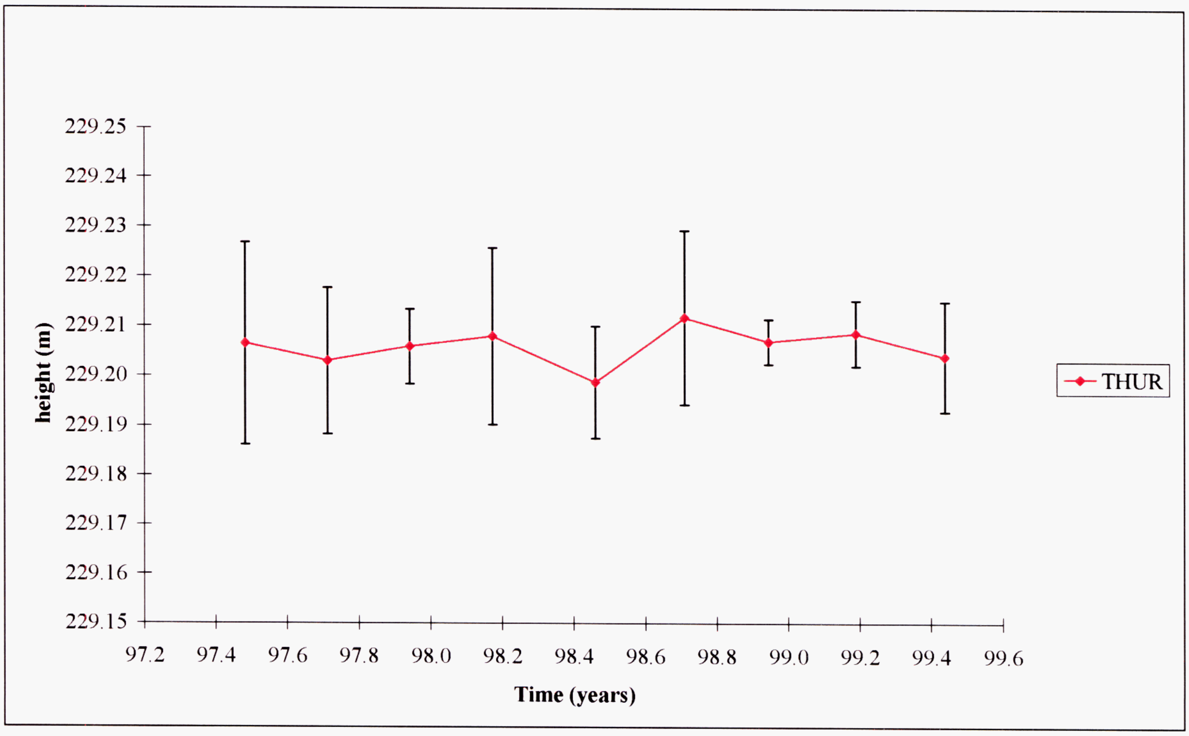


Figure D12 **Thurnham monitoring station epochal height time series (with standard errors)**

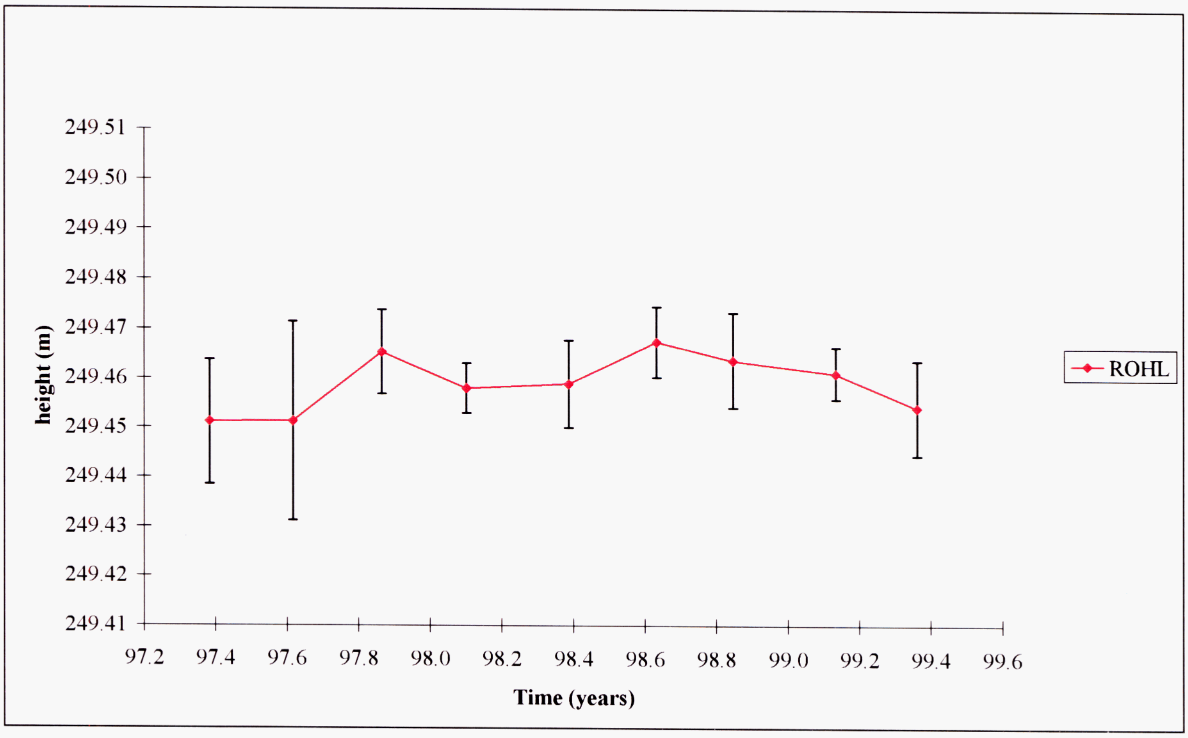


Figure D13 Rowdow Hill monitoring station epochal height time series (with standard errors)

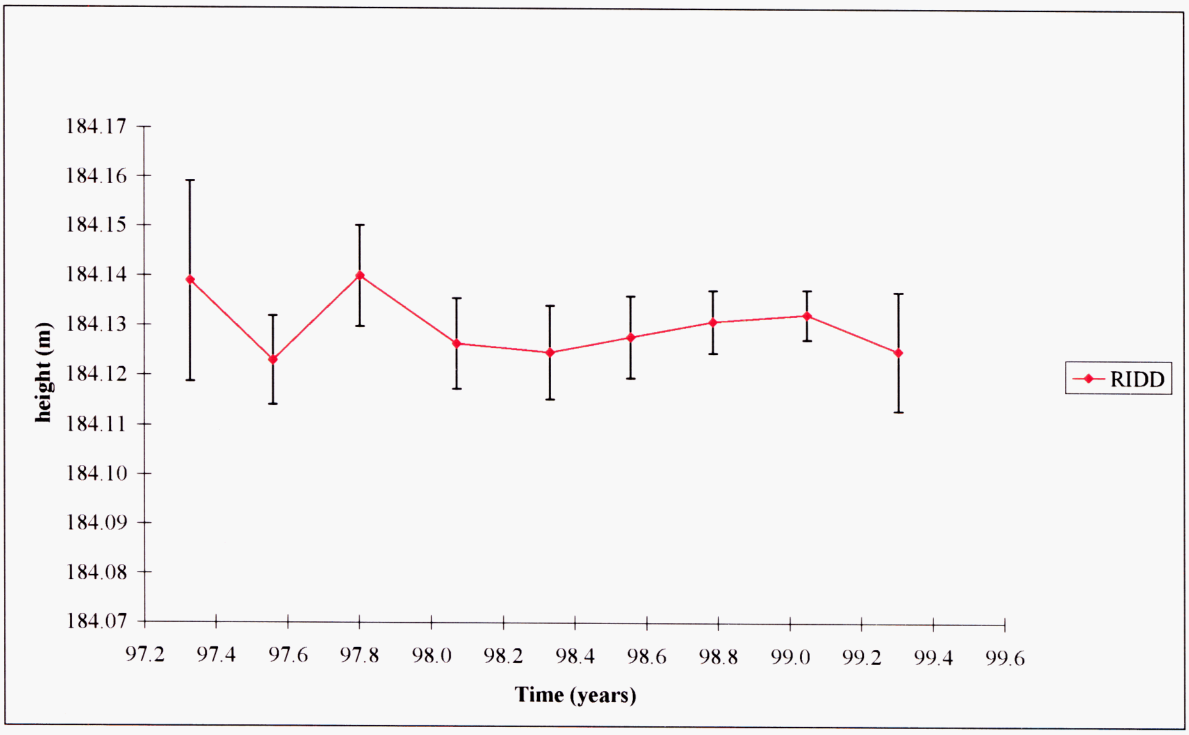


Figure D14 Riddlesdown Park monitoring station epochal height time series (with standard errors)

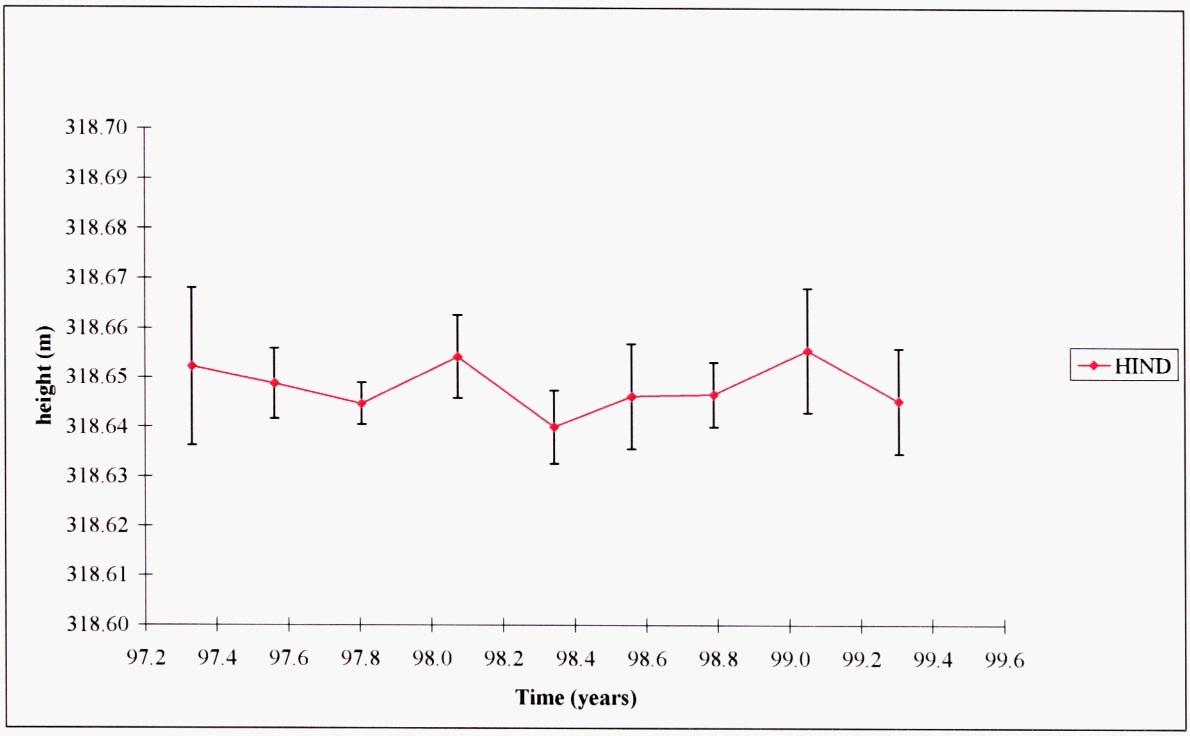


Figure D15 Hindhead monitoring station epochal height time series (with standard errors)

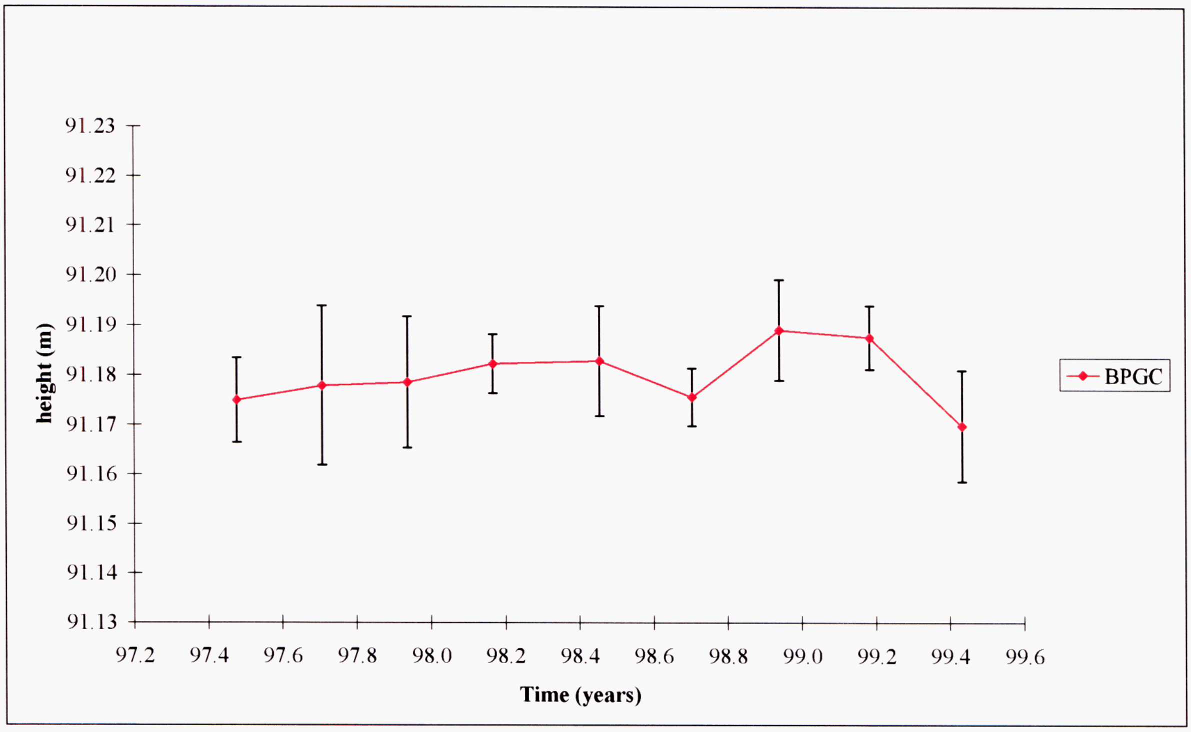


Figure D16 Bush Hill Park GC monitoring station epochal height time series (with standard errors)

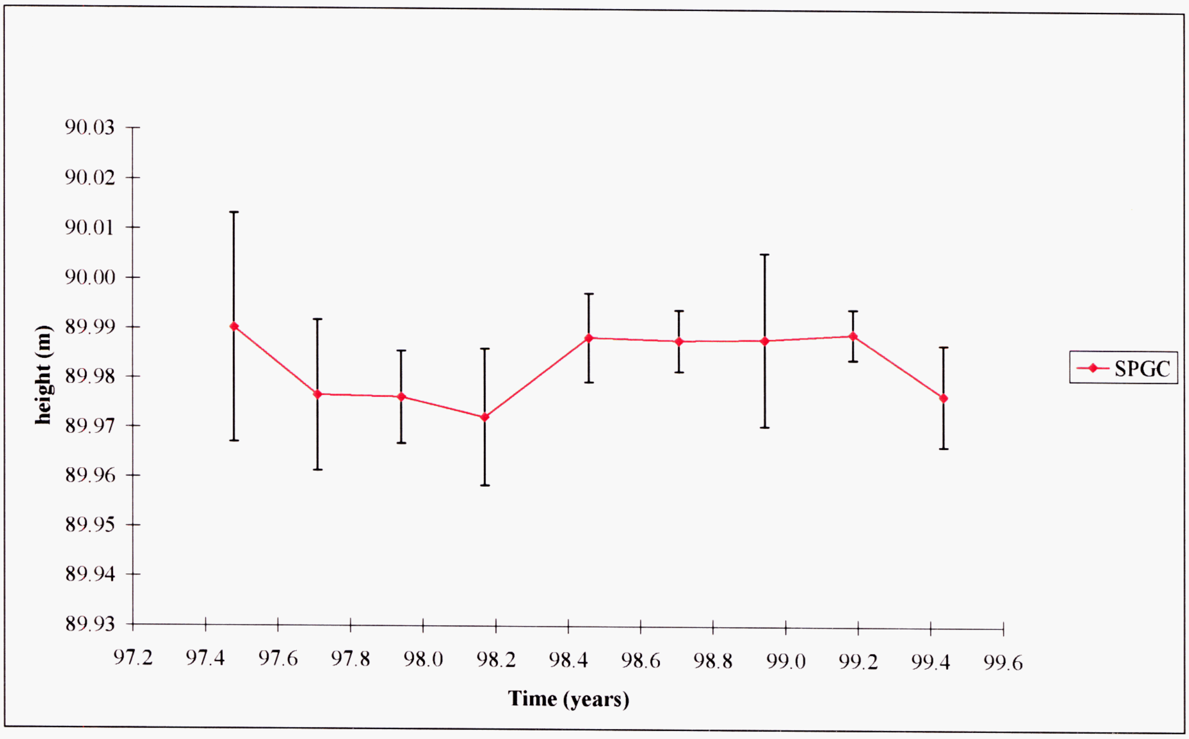


Figure D17 **Sundridge Park GC monitoring station epochal height time series (with standard errors)**

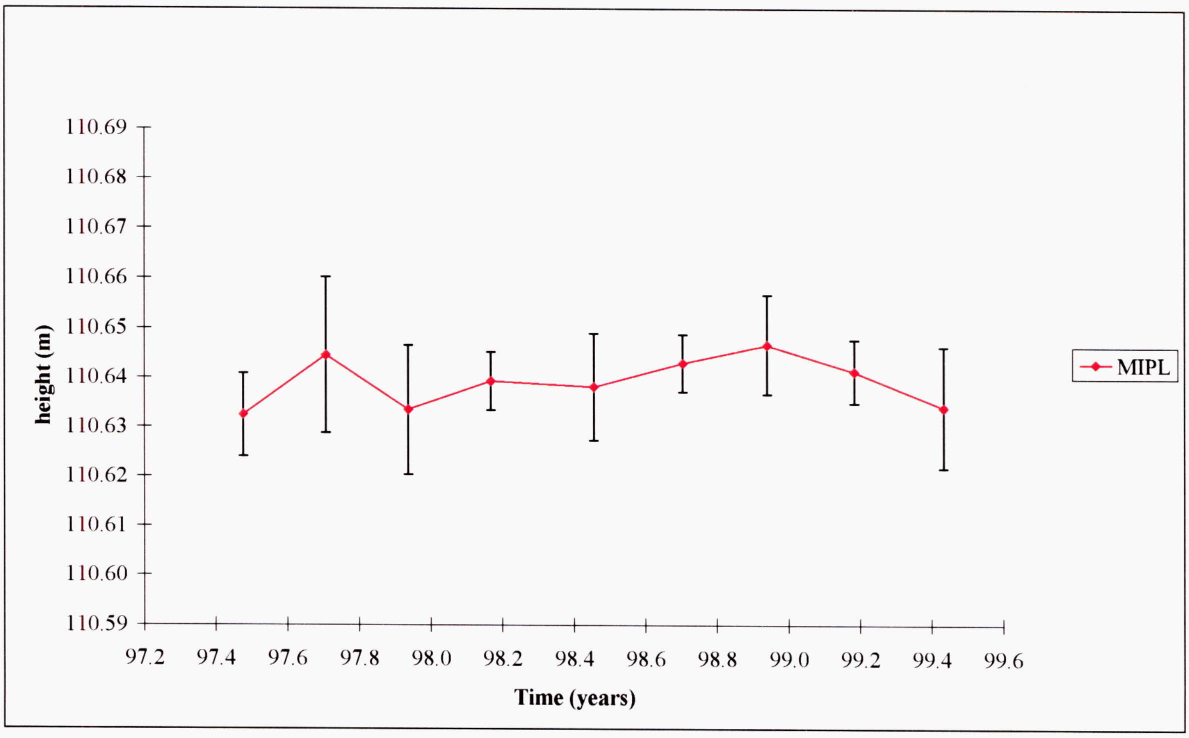


Figure D18 **Mill Plane monitoring station epochal height time series (with standard errors)**

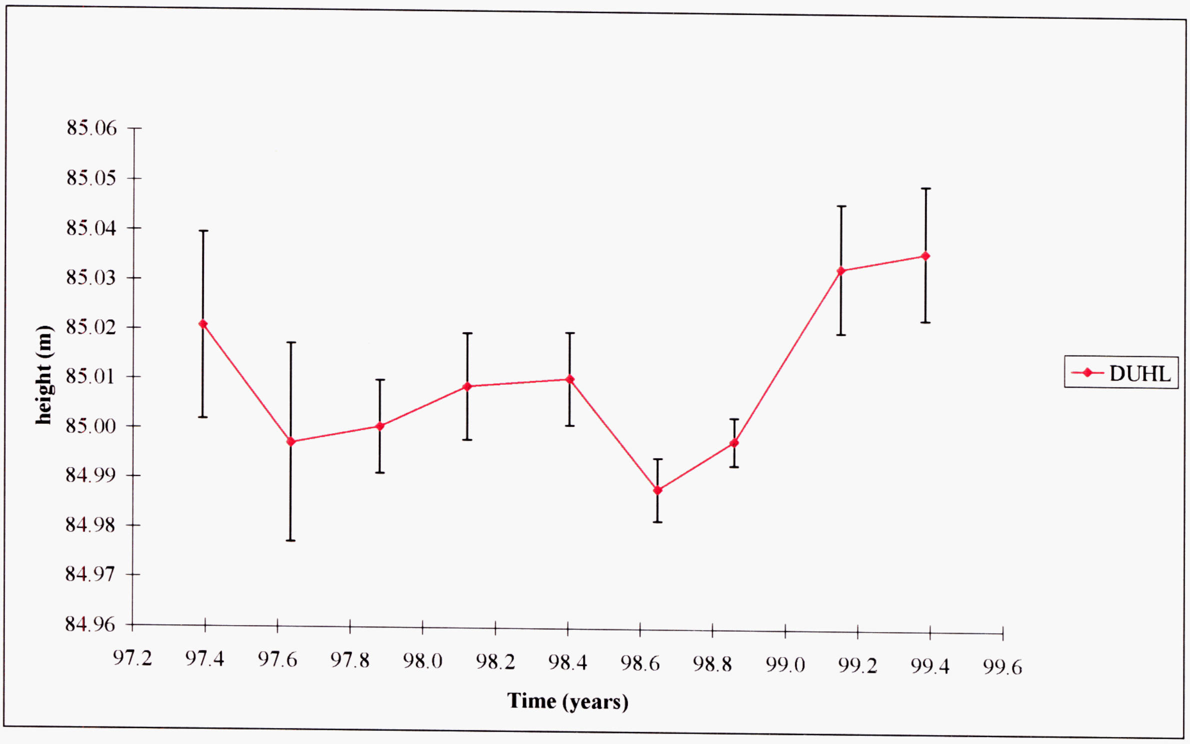


Figure D19 Dunton Hills monitoring station epochal height time series (with standard errors)

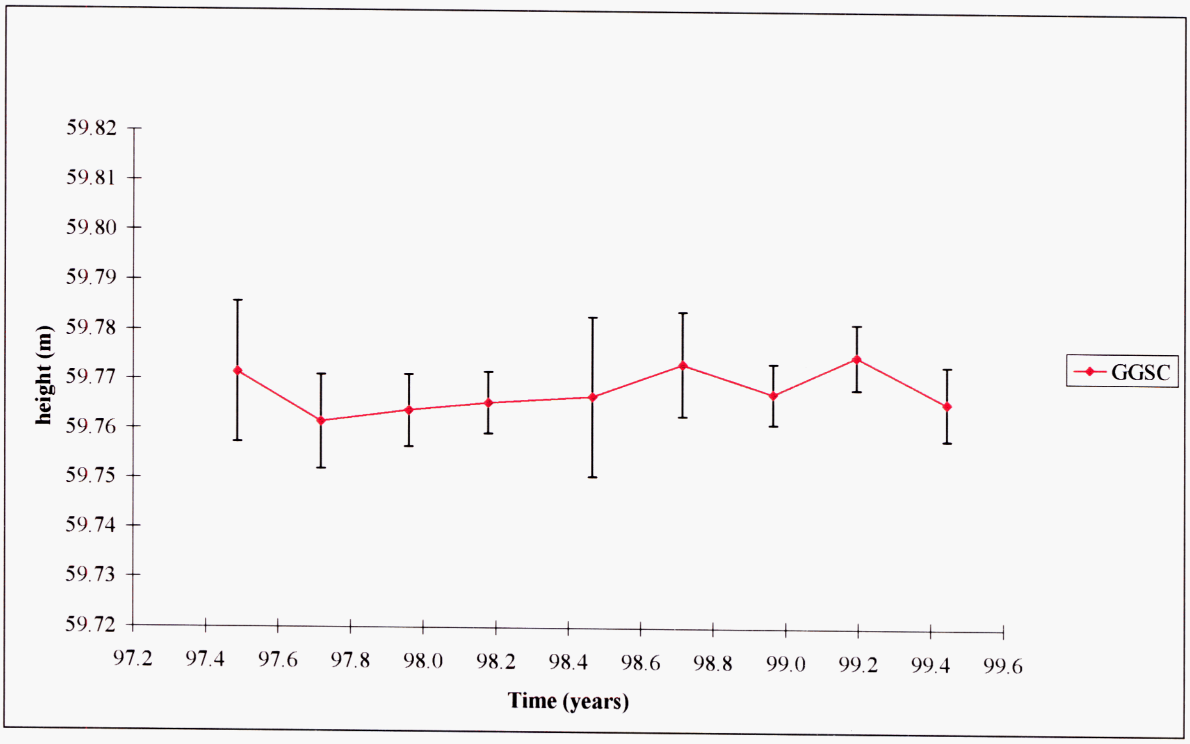


Figure D20 Gravesend Grammar School monitoring station epochal height time series (with standard errors)

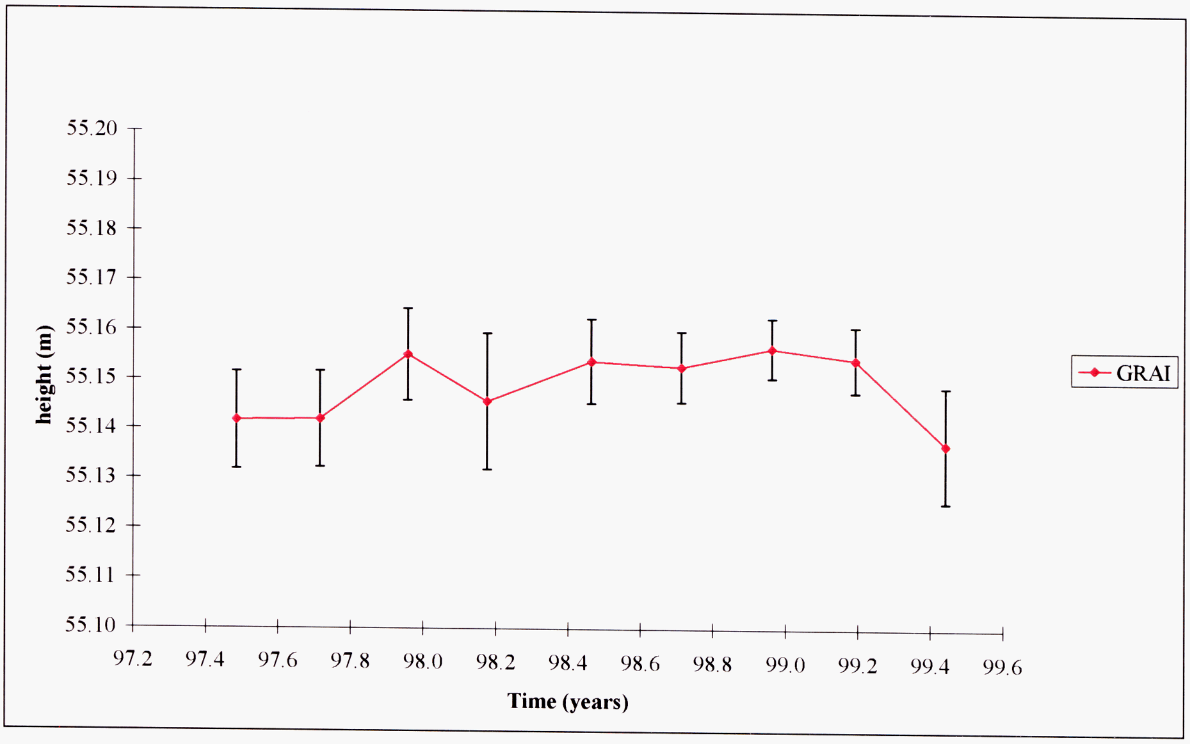


Figure D21 Grain monitoring station epochal height time series (with standard errors)

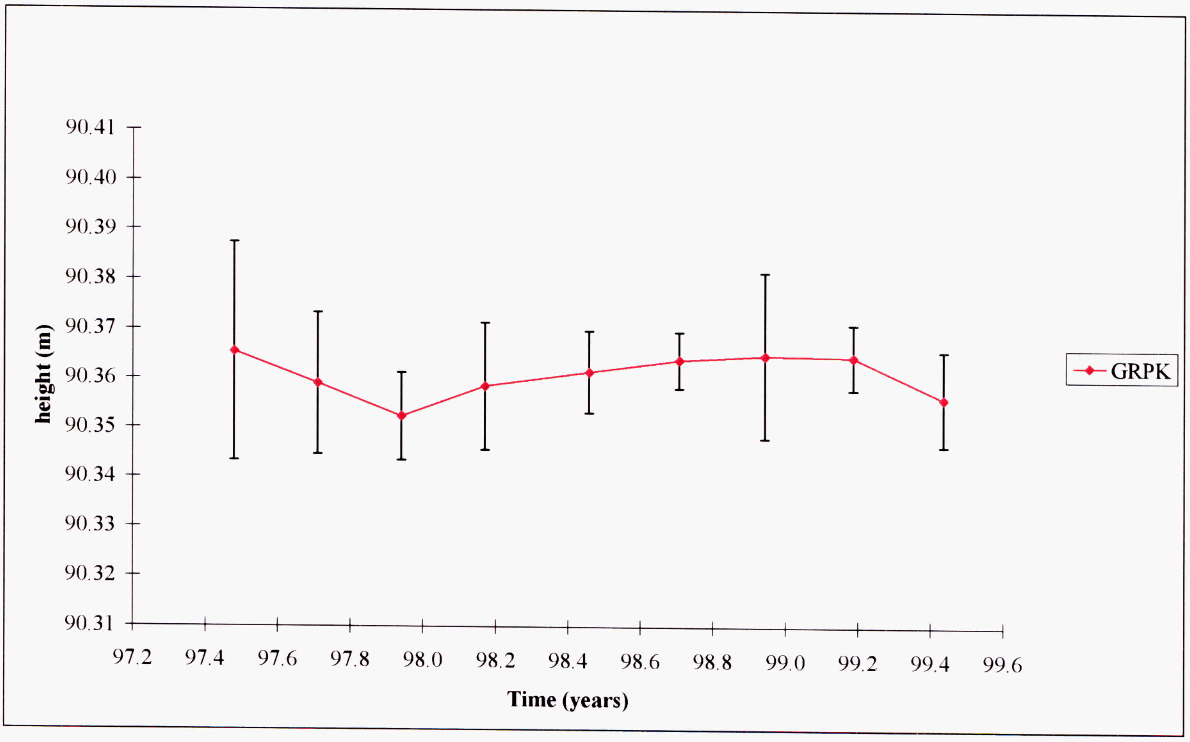


Figure D22 Greenwich Park monitoring station epochal height time series (with standard errors)