Monitoring the Vertical Land Movement Component of Changes in Mean Sea Level Using GPS: Results from Tide Gauges in the UK

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Abstract

Long term changes in mean sea level recorded by a tide gauge are corrupted by changes in ground level at the tide gauge site, which can be of a similar order of magnitude. Hence, to properly monitor long term changes in sea level, the rate of any vertical land movement at a tide gauge must be determined. The application of the Global Positioning System (GPS) to this problem has been on-going in the UK since 1990. Initial measurements were based on the use of episodic GPS (EGPS) campaigns. Following these campaigns, there was a phased establishment of permanent, continuous GPS (CGPS) stations at five tide gauges in the UK. These have enabled the development of a monitoring strategy that combines CGPS and EGPS and the testing of a dual-CGPS station concept. The results obtained over the last ten years are presented and the current approaches to monitoring are reviewed.

1 Introduction

Global sea level has risen by 10 to 20 cm over the past century, with predictions indicating further rises of the order of 40 to 60 cm by 2100 (IPCC, 1990; 1995; 2000). Much of the evidence for the rise in global sea level over the past century came from mean sea level (MSL) measurements obtained at tide gauges, which measure ‘relative MSL’ with respect to a local tide gauge bench mark (TGBM). A high quality tide gauge record enables the secular change of relative MSL to be determined with an uncertainty of ±0.5mm/yr, if 30 years of data are used (Woodworth et al, 1999). However, using tide gauge data alone, it is impossible to distinguish between any ‘true’ sea level variations and any changes in ground level at a tide gauge site. GPS monitoring can be used to decouple vertical land movements from changes in relative MSL, so that tide gauges can provide estimates of changes in ‘absolute MSL’.

Following the recommendations of Carter et al (1989), the Institute of Engineering Surveying and Space Geodesy (IESSG) and the Proudman Oceanographic Laboratory (POL) started to use GPS for monitoring vertical land movements at tide gauges in the UK. From 1991 to 1996, a total of nine episodic GPS (EGPS) campaigns were carried out, with up to eight epochal measurements at a total of sixteen tide gauges. In these campaigns, a large number of receivers were deployed for a few days each year in order to determine station heights on an annual basis. This research showed that, with appropriate processing software and the modelling of systematic error sources, it was possible to determine station heights in a global geodetic reference frame to a precision of about 10 mm (Ashkenazi et al, 1993; 1998).

Significant advances in GPS technology were made in the early 1990’s, including cheaper and more reliable GPS receivers, improved data processing software and computer hardware, the completion of the GPS satellite constellation, and the establishment of the International GPS Service (IGS). In sympathy with the advances in GPS technology, Carter (1994) and Neilan et al (1997) recommended the establishment of CGPS stations at tide gauges.

During the period from March 1997 to February 1999, the IESSG and POL established CGPS stations at five tide gauges in the UK. At the same time, four other CGPS stations were established in the UK. Based on these CGPS stations, recent research has focused on reducing the length of the monitoring period required in order to obtain reliable estimates of vertical station velocities and assessing the validity of any vertical station velocities for correcting long term relative MSL trends or predicting future vertical land movements.

This paper starts by reviewing the magnitudes of long term changes in ground level in the UK in Section 2. The results obtained from the EGPS campaigns, carried out from 1991 to 1996, are then presented in Section 3 before the more recent results based on the use of CGPS stations are presented and discussed. On their own, CGPS stations have the potential to provide information on vertical land movements at a specific site, such as a tide gauge, over a much shorter monitoring period. Section 4 discusses this statement in light of the coordinate time series obtained for the CGPS stations. Section 5 details the development of the 'combined CGPS/EGPS monitoring strategy', and presents results to suggest that a dense network of CGPS stations can be used to improve height determination when using EGPS measurements. Section 6 describes a 'dual-CGPS station concept', where one CGPS station is established at a tide gauge and a second CGPS station is established on 'stable rock', within a few kilometres of the tide gauge. Results are presented for two dual-CGPS station scenarios in the UK with a discussion on how this approach could lead to improvements in the assessment of vertical land movements.

2 Long Term Changes in Ground Level in the UK

Observed trends in relative MSL for a selection of tide gauges in the UK, with more than 15 complete years of MSL and TGBM information in the Permanent Service for Mean Sea Level data set, were presented by Woodworth et al (1999) and are re-presented in Table 1. Taking the IPCC's estimate that global sea level has risen by 10 to 20 cm (or 1.5mm/yr on average) over the last century, Table 1 gives simple estimates for the magnitude of vertical land movements at individual tide gauges computed from the relative MSL trends.

Table 1 Observed relative MSL trends and estimates of vertical land movements for tide gauges in the UK

Tide Gauge	MSL Data Period	Relative MSL Trend (mm/yr)	Vertical Land Movement (mm/yr)
Newlyn	1916-96	+1.69 ± 0.12	-0.19
Portsmouth	1962-96	+1.45 ± 0.60	+0.05
Dover	1961-93	+1.94 ± 0.50	-0.44
Sheerness	1901-96	+2.14 ± 0.15	-0.64
Lowestoft	1956-95	+1.81 ± 0.48	-0.31
Holyhead	1938-96	+2.12 ± 0.45	-0.62
Liverpool	1959-83	+2.58 ± 0.88	-1.08
Immingham	1960-95	+1.11 ± 0.52	+0.39
Heysham	1962-96	+1.04 ± 0.62	+0.46
Portpatrick	1968-95	+0.91 ± 0.61	+0.59
North Shields	1901-96	+1.86 ± 0.15	-0.36
Aberdeen	1932-96	+0.67 ± 0.20	+0.83
Lerwick	1957-96	-1.09 ± 0.40	+2.59

The variations in the observed relative MSL trends at these tide gauges serve to demonstrate the effects of vertical land movements on relative MSL. Conversely, as most of these tide gauges are sited on 'stable' structures, such as piers or harbours with piled foundations, the variations in the estimates of vertical land movements suggest that the magnitudes of long term changes in ground level in the UK are of the order of 0 to 3 mm/yr. These magnitudes and the pattern of the movements are generally consistent with the theory that there has been uplift in Scotland and subsidence in the South of England, due to the effects of post-glacial rebound (Shennan, 1989; Lambeck, 1993).

3 Results from the Episodic GPS Campaigns, 1991 to 1996

Between 1991 and 1996, nine EGPS campaigns were carried out, each incorporating some of the sixteen tide gauges shown in Figure 1 and Nottingham.

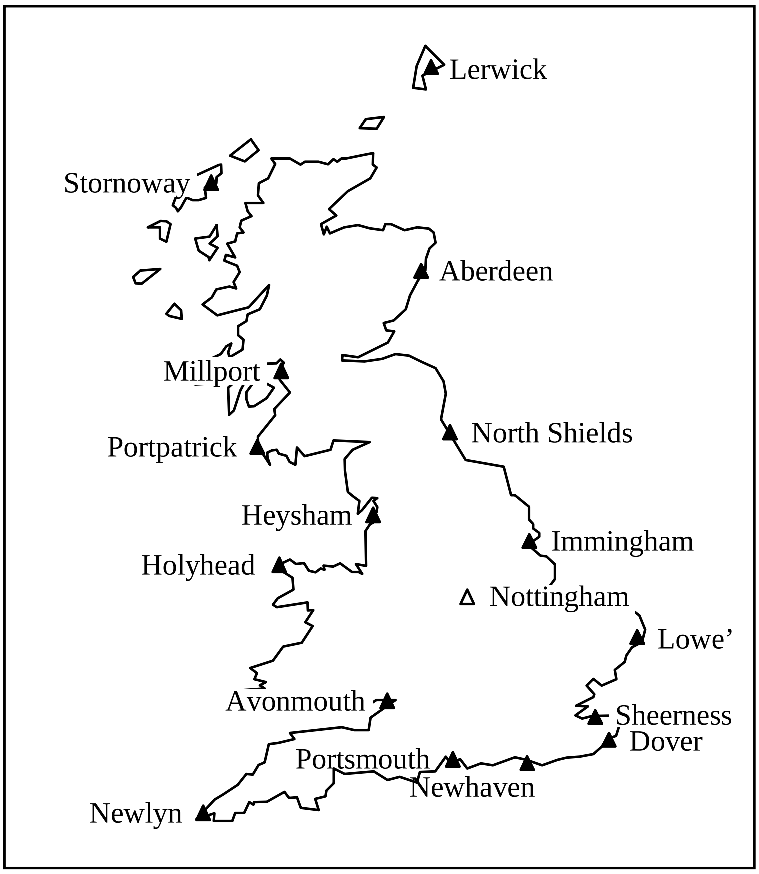

Figure 1 Stations included in the EGPS campaigns, 1991 to 1996

The availability of the GPS data from the nine EGPS campaigns is summarised in Table 2. The data from the nine EGPS campaigns were processed in combination with data from selected European IGS stations, using the IESSG's in-house developed GPS Analysis Software (Stewart et al, 1997).

The GPS data from the first two campaigns in 1991 and 1992 were processed with regional orbit improvement carried out as part of a fiducial network adjustment. Meanwhile, the GPS data from the later campaigns were processed with the final IGS precise ephemerides fixed. For all of the campaigns, the GPS data were processed using the L1/L2 'ionospherically free' double difference observable and a common set of systematic error models, including corrections for solid Earth tides, antenna phase centre variations, tropospheric delay and ocean tide loading. Specifically, the tropospheric delay was mitigated by modelling the hydrostatic component using the Saastamoinen model and estimating the 'wet' component as a random walk process.

Table 2 Data availability for the EGPS campaigns, 1991 to 1996

EGPS Station	Campaign Date								
	09/91	08/92	08/93	11/93	03/94	04/95	09/95	11/95	09/96
Newlyn	•	•	•	•	•	•	•	•	
Portsmouth	•	•		•	•		•		
Newhaven	•	•	•					•	
Dover	•	•	•	•	•			•	
Sheerness	•	•	•				•		•
Avonmouth							•		•
Lowestoft	•	•	•					•	
Holyhead							•		•
Immingham								•	
Heysham							•		•
Portpatrick	•	•	•				•	•	•
North Shields							•	•	•
Millport							•		•
Aberdeen	•		•				•	•	•
Stornoway				•	•				
Lerwick		•	•	•	•				
Nottingham	•		•	•	•	•	•	•	•

For each campaign, the daily GPS solutions were combined to form an epochal solution, by constraining the IGS stations of Onsala, Wettzell and Madrid to their ITRF97 station coordinates, motioned to the observational epoch of the campaign using their ITRF97 station velocities (Boucher et al, 1999). The epochal solutions were then combined to form ITRF97 coordinate time series for all sixteen tide gauges.

Table 3 Height precisions for the EGPS campaigns, 1991 to 1996

EGPS Station	No of epochs	σ_{EPOCH} (mm)	EGPS Station	No of epochs	σ_{EPOCH} (mm)
Newlyn	8	7.7	Heysham	2	-
Portsmouth	5	1.9	Portpatrick	6	8.8
Newhaven	4	5.6	North Shields	3	5.6
Dover	6	4.7	Millport	2	-
Sheerness	5	9.7	Aberdeen	5	18.9
Avonmouth	2	-	Stornoway	2	-
Lowestoft	4	6.6	Lerwick	4	9.9
Holyhead	2	-	Nottingham	8	7.7
Immingham	1	-			

From such relatively short-term height time series, it is possible to compute a time-averaged mean height for each EGPS station. Based on this, the standard deviation (σ_{EPOCH}) of an epochal solution from the time-averaged mean can then be computed as an indication of the height precision attainable using EGPS campaigns. The standard deviations obtained for stations with three or more epochal solutions are given in Table 3.

Using the following equation given in Dixon (1991) an estimate of the length of monitoring period required in order to estimate vertical station velocities with an uncertainty (σ_{VEL}) can be obtained.

$$\sigma_{VEL} = \sigma_{EPOCH} \cdot \frac{1}{T} \cdot \sqrt{\frac{12\frac{T}{dt}}{(1+\frac{T}{dt})(2+\frac{T}{dt})}} \qquad (1)$$

where σ_{EPOCH} is the standard deviation of an epochal coordinate estimate in millimetres, T is the length of the monitoring period in years, and dt is the time interval between monitoring epochs in years.

Considering the information in Table 3, a value of 10 mm would appear to be typical for the standard deviation of an epochal height estimate. Using this value, and assuming annual EGPS campaigns, a monitoring period of about 20 years would be required in order to estimate vertical station velocities with an uncertainty of ±0.5mm/yr. Clearly, such a monitoring period is one limitation when using EGPS campaigns.

Based on Equation 1, the length of the monitoring period could be reduced by either reducing the time interval between monitoring epochs or improving the level of height precision. The former can be achieved by using CGPS stations, as detailed in Section 4. The latter has been attempted through the development of a combined CGPS/EGPS monitoring strategy, as detailed in Section 5.

4 Results from the CGPS Stations

During the period from March 1997 to February 1999, the IESSG and POL established CGPS stations at five tide gauges in the UK, namely Sheerness, Newlyn, Aberdeen, Liverpool and Lowestoft (see Figure 2). The CGPS receivers were installed such that the GPS antennas were sited as close as possible to the tide gauge, ie within a few metres of the tide gauge itself.

At the same time, four other CGPS stations were established in the UK, at Nottingham and at three Meteorological Office sites, namely Camborne, Hemsby and Lerwick (see Figure 2). The primary aim of the last three CGPS stations was the estimation of integrated precipitable water vapour for climatology and meteorology. However, the GPS antennas were mounted on survey monuments connected to concrete blocks founded on ‘stable rock’.

The data from these nine CGPS stations are combined with data from selected European IGS stations and processed on a routine basis using the IESSG’s in-house developed GPS Analysis Software (Stewart et al, 1997) and a series of automated procedures based on UNIX Shell scripts (Bingley et al, 1999). The data are processed using the L1/L2 ‘ionospherically free’ double difference observable, with the final IGS precise ephemerides fixed and a common set of systematic error models, including corrections for solid Earth tides, antenna phase centre variations, tropospheric delay and ocean tide loading. Specifically, the tropospheric delay is mitigated by modelling the hydrostatic component using the Saastamoinen model and estimating the ‘wet’ component as a random walk process.

By constraining the IGS stations of Onsala, Wettzell and Madrid to their ITRF97 station coordinates, motioned to the observational epoch of the campaign using their ITRF97 station velocities (Boucher et al, 1999), daily GPS solutions are produced. The daily GPS solutions are then combined to form ITRF97 coordinate time series for all nine CGPS stations.

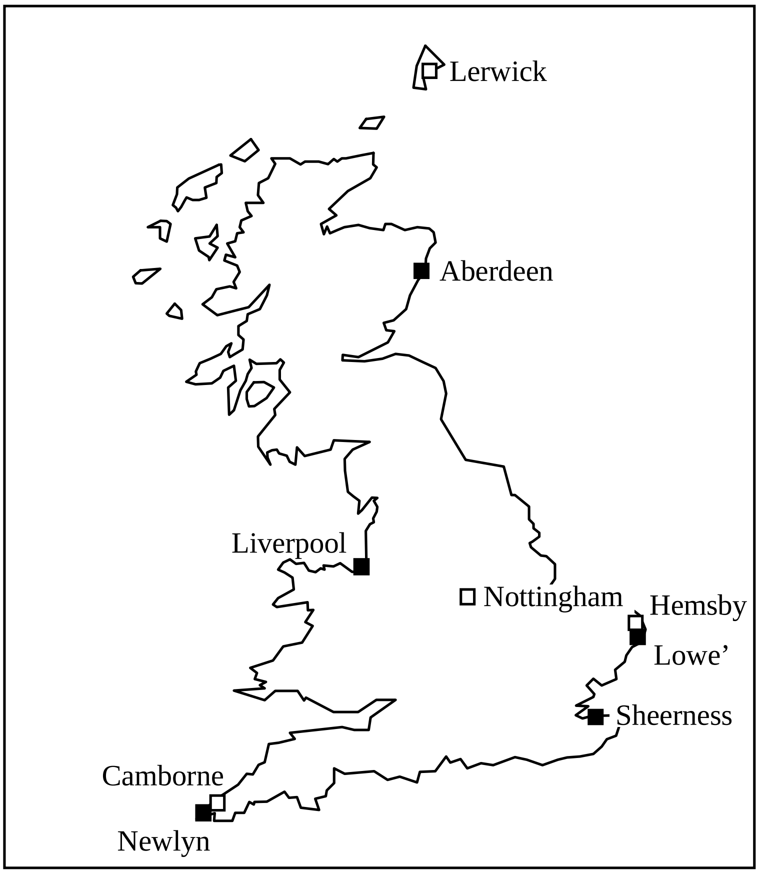

Figure 2 CGPS stations established between 1997 and 1999

Figure 3 shows the coordinate time series obtained for the nine CGPS stations, ordered in terms of the length of their monitoring period. These coordinate time series have been used to compute station velocities for the CGPS stations, using a linear regression. These are shown in Figure 3 as a rate with a corresponding uncertainty.

When computing the uncertainties for station velocities, Zhang et al (1997) and Mao et al (1999) demonstrated that CGPS coordinate time series contain both time-independent (white) noise and time-correlated (coloured) noise. Hence, if Equation 1 was used to compute the uncertainties, this would lead to an estimate that could be too optimistic by a factor of 5 to 11, depending on the magnitude of flicker and random walk (coloured) noise.

The values given in Figure 3 are based on the model presented by Mao et al (1999) for estimating the station velocity uncertainty (σ_{VEL}) for a CGPS coordinate time series in the presence of combined white and coloured noise.

$$\sigma^2_{VEL} = \frac{12\sigma^2_{WN}}{gT^3} + \frac{a\sigma^2_{FN}}{g^bT^2} + \frac{\sigma^2_{RWN}}{gT} \qquad (2)$$

where σ_{WN}, σ_{FN}, σ_{RWN} are the amplitudes of white, flicker and random walk noise, g is the number of observations in one year, T is the length of the monitoring period in years and a and b are empirical constants of 1.78 and 0.22 respectively. For this analysis, the amplitudes of white and flicker noise were derived from the WRMS of the coordinate time series as described by Dixon et al (2000). In addition, an amplitude of 3mm/√yr was used as a pessimistic value for an underlying random walk process.

From Figure 3, it can clearly be seen that the uncertainty in the velocity estimates are a function of both the length of the monitoring period and the level of noise at a particular CGPS station, which is indicated by the WRMS value.

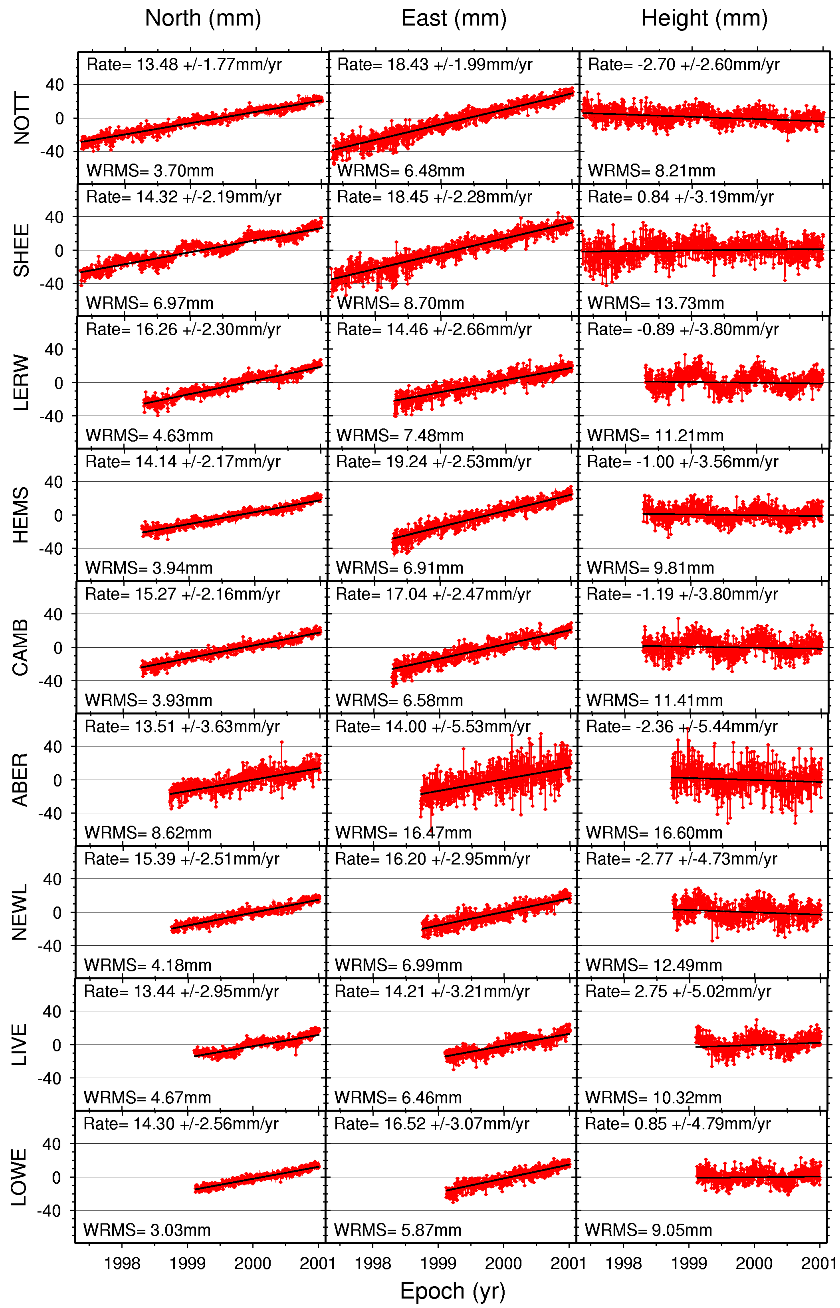

Figure 3 CGPS station coordinate time series and preliminary station velocity estimates

As these coordinate time series are formed in a ‘dynamic’, global geodetic reference frame the North and East time plots show a pattern of horizontal movement that is driven by plate motion. As such, all of the stations have similar horizontal movements of about 22 mm/yr in a North-East direction, which is representative of the motion of the Eurasian plate on which the UK is found. As for the height time series, these provide the first real indication of the magnitudes of changes in ground level on a national scale based on geodetic observations. As suggested by the evidence from the long term relative MSL observations, these range from 0 to 3 mm/yr.

At this stage, the values for the station velocities must be taken as preliminary. A comparison of the velocity with its respective uncertainty confirms that the estimates are not statistically significant over such short monitoring periods. Furthermore, there are obvious periodic signals in the height time series. It is not clear whether these signals are an artefact of the GPS data processing or whether they are ‘true’ indications of annual changes in ground level, or a combination of both. However, such periodic variations will bias the vertical station velocity estimates by varying amounts, depending on the length of the monitoring period.

What is clear at this stage is the improvements in the uncertainties from Lowestoft (LOWE) with the shortest monitoring period to Sheerness (SHEE) with the longest monitoring period. Such improvements mean that by extending the monitoring period for a CGPS station to beyond 6 years, it should be possible to obtain an estimate of vertical station velocity which is unbiased and has an uncertainty of less than ±1mm/yr. At this stage, it should then be possible to combine the estimates for vertical land movement with the estimates for changes in relative MSL in order to obtain estimates for the changes in absolute MSL at these five tide gauges.

5 Results from the Combined Monitoring Strategy

Although GPS receivers have become cheaper and more reliable, it may still not be economically feasible to establish entire networks of CGPS stations, particularly at regional scales. With this in mind, a monitoring strategy has been developed which uses a combination of CGPS stations and EGPS measurements.

The combined monitoring strategy is carried out in two stages. In the first stage, the continuous GPS data from the CGPS stations is processed along with data from selected European IGS stations in order to determine station velocities for the CGPS stations, as described in the previous section. The second stage involves carrying out episodic GPS measurements using a small number of 'roving' GPS receivers, which visit the EGPS stations at periodic intervals. The episodic GPS data from the EGPS stations is then processed along with data observed simultaneously at the CGPS stations. In this way, the coordinates for the EGPS stations are computed, with respect to the CGPS stations, for the specific epoch of the observations. Over time, such epochal coordinate estimates can then be used to form ITRF97 coordinate time series for the EGPS stations, from which station velocities can be estimated.

In mid-1999, the twelve tide gauges shown in Figure 1 that were not equipped with CGPS stations (see Figure 2) were visited by a roving GPS receiver, with each EGPS station being observed for five consecutive days. Depending on the site conditions at the tide gauge, observation session lengths of 24 hours or 12 hours were used. The EGPS stations were then re-observed for a further five days, about three months later.

The data from each EGPS station were processed along with data from the CGPS stations at Sheerness, Nottingham, Camborne and Lerwick, and the European IGS stations at Onsala, Kootwijk, Wettzell and Villafranca. This GPS data processing resulted in a series of ten daily GPS solutions for each EGPS station. To test the combined monitoring strategy, two approaches were taken when computing the coordinates of the EGPS stations. In the first approach, the coordinates of the IGS stations were fixed, in a similar way to an EGPS campaign. In the second approach, the EGPS station coordinates were obtained by fixing Sheerness, Nottingham, Camborne and Lerwick to their ITRF97 coordinates, motioned to the observation epoch using the station velocities computed from the processing and analysis of the CGPS data.

Improvements in height determination were assessed by computing the agreement between the five-day mean heights obtained for the first and second sets of EGPS measurements. The results are shown in Table 4.

From Table 4, it can be seen that the height agreements were significantly improved when the four UK CGPS stations were constrained. This suggests that height determination based on EGPS measurements can be improved over a network of about 500x1000km in extent, by using the combined monitoring strategy as opposed to EGPS campaigns.

The epochal height estimates determined using the combined monitoring strategy have been used in conjunction with the height estimates from the earlier episodic GPS campaigns in order to form height time series dating back to 1991. Figure 4 shows the results.

Table 4 Height agreements for the EGPS stations, with either European IGS stations or UK CGPS stations fixed

EGPS Station	IGS (mm)	CGPS (mm)	EGPS Station	IGS (mm)	CGPS (mm)
Portsmouth	+13	+7	Heysham	+7	+7
Newhaven	+11	+6	Portpatrick	+27	+5
Dover	+5	0	North Shields	+23	+9
Avonmouth	+5	+9	Millport	+12	+11
Holyhead	+4	+8	Stornoway	-5	-5
Immingham	+19	+9	Lerwick	+12	+8

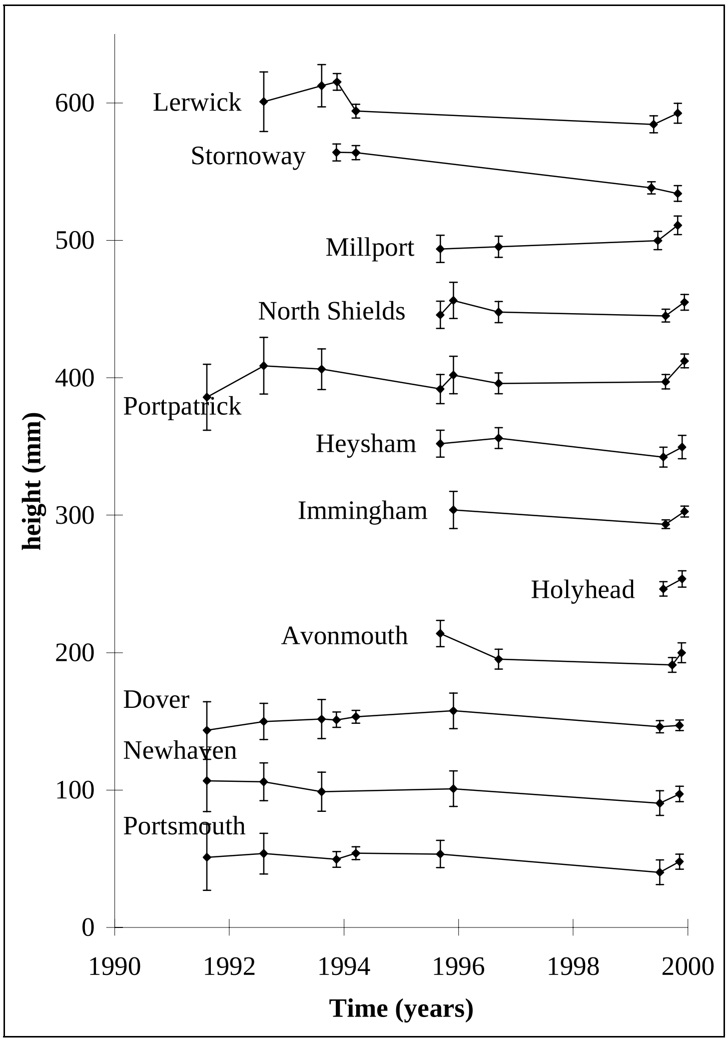

Figure 4 EGPS station height time series based on EGPS campaigns from 1991 to 1996 and the combined monitoring strategy in 1999 (heights presented on an arbitrary scale)

On visual inspection of Figure 4, the trends would seem to support the post-glacial rebound theory of subsidence in the South of England, stability in the North of England and uplift in mainland Scotland. Furthermore, the apparent subsidence at Lerwick is also consistent with post-glacial rebound theory, which suggests uplift in mainland Scotland and Scandinavia but not in the

Shetland Isles. Instead, Lambeck and Johnston (1995) give a model estimate of 2mm/yr subsidence, which is similar to the trend in the height time series for Lerwick.

Once again, these height time series must be taken as preliminary. For such annual height estimates it will be necessary to extend the monitoring period in order to obtain reliable estimates of vertical station velocities. However, the length of monitoring period may not have to go far beyond the present, if the combined monitoring strategy is used and the vertical station velocities for the CGPS stations in the UK are continually improved.

6 The Dual-CGPS Station Concept for Tide Gauges

The previous sections presented coordinate time series and vertical station velocities that, through the establishment of CGPS stations in the UK, will enable the decoupling of vertical land movements and relative MSL at tide gauges. However, it is important to realise that the use of GPS at tide gauges has been carried out with this specific aim in mind. Hence, the CGPS or EGPS stations have been sited as close as possible to the tide gauge, ie within a few metres of the tide gauge itself. In practice, this means that GPS is being used to measure the changes in ground level that are currently affecting the structure that supports the tide gauge, which may be due to a combination of geophysical, geological and engineering processes operating over different time scales.

Most of the tide gauges in this study have relative MSL data for more than 20 years, with many having data for much longer periods. These data provide an indication of the changes in relative MSL over certain periods. However, GPS monitoring has only been carried out for the last 10 years. In order to assess whether the vertical station velocities determined using GPS can be used to correct relative MSL over a much longer monitoring period, it is necessary to establish whether the vertical land movements measured by GPS are of a long term nature.

Through the discussions of working group 1 of the European Commission COST Action EOSS, the concept of a dual-CGPS station approach to monitoring changes in ground level at tide gauge sites was proposed (Plag et al, 2000). In this concept, one CGPS station is established at the tide gauge and a second CGPS station is established on ‘stable rock’, within a few kilometres of the tide gauge, with the aim of quantifying both the underlying geophysical movements and the local movements at the tide gauge.

Initial tests on the dual-CGPS station concept have been carried out in the UK, through the establishment of the CGPS stations at Camborne and Hemsby, which are approximately 20 km from the tide gauges of Newlyn and Lowestoft respectively. Considering the height time series presented in Figure 3, there are clear similarities in the periodically repeating signals observed at these dual-CGPS stations. Assuming these signals to be common in the two height time series they should be removed by forming a height difference time series, as shown for Camborne and Newlyn in Figure 5.

Comparing the individual height time series with the height difference time series it is clear that the periodic signal has been removed. In the case of Newlyn - Camborne, the WRMS values of about 10 mm are reduced to 8 mm for the height difference time series. Similarly, in the case of Lowestoft - Hemsby, WRMS values of about 7 mm are reduced to 5 mm for the height difference time series. More importantly, in both cases, the relative vertical station velocity is unbiased and the uncertainty is improved by a factor of about 1.2 to 1.4 when compared to the individual vertical station velocities.

These preliminary results, based on only 2.3 and 1.9 years of common data, are the first indication that the dual-CGPS station concept may enable a better assessment of the nature of the vertical land movement at a tide gauge. This in turn, should enable a better assessment of the validity of any vertical station velocity estimates for correcting long term relative MSL trends or predicting future vertical land movements.

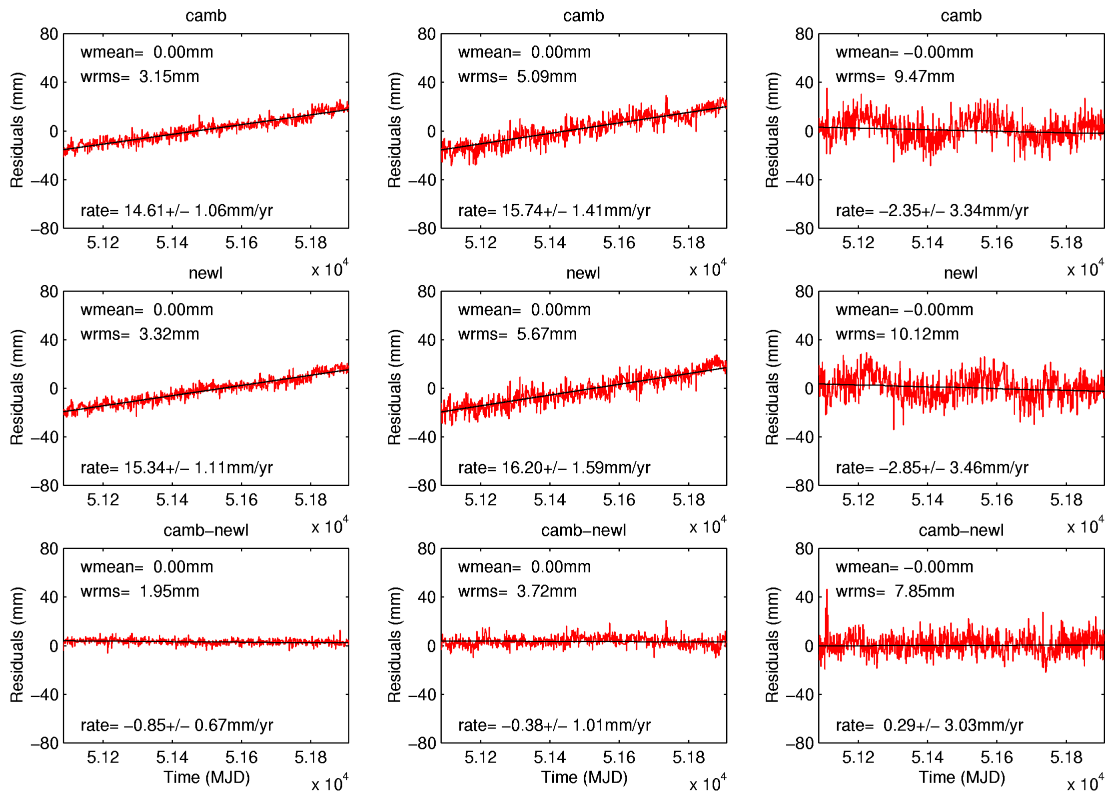

Figure 5 Dual-CGPS station height time series for Camborne and Newlyn

7 Conclusions

A combination of continuous and episodic GPS data are currently being used to monitor vertical land movements at tide gauges in the UK. Over the next three years, the height time series for the CGPS stations and the EGPS stations will be extended and research will continue on the use of CGPS stations, the combined monitoring strategy and the dual-CGPS station concept.

With extended monitoring periods, reliable estimates for vertical station velocities will be obtained in the near future. These will enable estimates of changes in absolute MSL at tide gauges around the UK, which will be useful for flood and coastal defence on both a national and regional scale. In the longer term, monitoring of vertical land movements at tide gauges coincident with changes in relative MSL should enable spatial and temporal variations in absolute MSL to be measured and compared to the predicted global sea level rise.

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