DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS

Research and Development

Final Project Report

(Not to be used for LINK projects)

Two hard copies of this form should be returned to:
Research Policy and International Division, Final Reports Unit
DEFRA, Area 301
Cromwell House, Dean Stanley Street, London, SW1P 3JH.
An electronic version should be e-mailed to resreports@defra.gsi.gov.uk

Project title	ABSOLUTE FIXING OF TIDE GAUGE BENCHMARKS-Phase 2.
DEFRA project code	**FD2301**
Contractor organisation and location	PROUDMAN OCEANOGRAPHIC LABORATORY BIDSTON OBSERVATORY BIRKENHEAD CH43 7RA
Total DEFRA project costs	£ 597,987
Project start date	01/07/00
Project end date	30/6/03

Executive summary (maximum 2 sides A4)

The sea level rise trends around the British Isles consist of 2 components: the climate related changes in mean sea levels and the vertical movements of the land. The tide gauges in the National Tide Gauge Network measure the sea level relative to a local tide gauge bench-mark (TGBM). Thus a measured rise in mean sea levels can be due to the effects of climate change or it can be due to subsidence of the land at the TGBM (due to very local or regional subsidence or larger scale processes). In practice, the climate related component and the land movement component are of a similar order of magnitude at most sites and therefore it is important to measure the vertical land movements, so that these effects can be separated. In this project the new advanced geodetic techniques of GPS and absolute gravity are used to measure the land movements at a number of UK tide gauges. The improved knowledge and understanding of the variability of sea level changes around the coasts will provide important guidance for flood defence design.

Permanent Continuous GPS (CGPS) stations were set up at the tide gauges at Sheerness (1997), Newlyn (1998), Aberdeen (1998), Lowestoft (1999) and Liverpool (1999). In the present project additional CGPS stations were installed at the tide gauges at North Shields (2001) and Portsmouth (2001). The data from these 7 tide gauge CGPS stations, together with data from 13 other UK CGPS stations were downloaded on a daily basis using the automated procedures developed as part of the previous project. The CGPS data from the UK stations and 4 European reference stations (Kootwijk, Onsala, Villafranca and Wettzell) were processed and analysed on a daily basis using the final precise satellite coordinates given by the International GPS Service (IGS). Coordinate time series for the UK CGPS stations were found in a consistent global reference frame (ITRF2000) by tightly constraining the coordinates and velocities of the 4 European reference stations to their ITRF2000 values.

The vertical station velocities for the tide gauge CGPS stations were found to be in the range from approximately –2mm/year to +2mm/year. However, taking into account the uncertainties, none of the individual vertical station velocities can be considered to be statistically significant yet. It was concluded that for high quality CGPS stations at least 6 years of data are required to reduce the 1-sigma statistical uncertainty to +/- 1mm/year. Using CGPS data from Newlyn and Camborne, which is on solid rock about 20km from the tide gauge, it was shown that the tide gauge is not experiencing any significant localised land movement that is different from the regional geophysical movement observed at Camborne. This dual-CGPS concept can be usefully applied at other tide gauges in order to check how representative the vertical land movements observed at a tide gauge are of the land movements over a wider area.

In the previous project, episodic GPS (EGPS) measurements were made for 3 to 5 days at 10 further tide gauges. These episodic GPS measurements were repeated in the present project using roving GPS receivers. At 4 of these tide gauges (Dover, Immingham, Holyhead and Stornoway) the GPS receiver was installed for 3 to 6 weeks. These, so called quasi-continuous GPS (QCGPS), measurements allow better estimates of the uncertainties than is possible with the EGPS measurements. It was concluded that the EGPS measurements are sufficient for calibrating satellite altimeters or determining mean sea surface topography but are not sufficient for measuring vertical land movements. CGPS is the preferred GPS technique for determining vertical land movements on a national scale.

The series of absolute gravity measurements at Newlyn, Aberdeen and Lerwick that began in the previous project have been continued. It was shown that the POL absolute gravimeter FG5-103 continues to operate with an accuracy at the highest international standards. The gravity measurements at Newlyn show a subsidence of 1.7mm/year with a 1-sigma statistical uncertainty of +/-0.8mm/year and the measurements at Lerwick show a subsidence of 1.1 +/-0.9mm/year.

It is recommended that the CGPS and absolute gravity measurements should be continued in order to increase the lengths of the time series and reduce the uncertainties. Where possible, EGPS stations should be replaced with QCGPS, or preferably, CGPS stations. The vertical velocities determined from the absolute gravity measurements will provide an important assessment of any systematic biases in the estimated vertical velocities from CGPS.

Scientific report (maximum 20 sides A4)

GPS MEASUREMENTS

1 Introduction

The scientific objective of the research project was to improve the monitoring of long term vertical land movements at sites of the UK National Tide Gauge Network using the Global Positioning System (GPS). The deliverables for the research project were to be an improved monitoring network, estimates of vertical land movements and recommendations on a strategy for long term monitoring.

This research project followed on from previous MAFF R&D projects (funded from 1990-2000 as FD0305: The Geodetic Fixing of Tide Gauge Bench Marks). In the earliest projects, from 1990-1996, episodic GPS campaigns were used for the geodetic fixing of tide gauge bench marks in the UK. These campaigns were observed by using a large number of GPS receivers, deployed simultaneously for 5 days. Through these projects, extensive research and development was carried out on the mitigation of systematic biases and errors for high precision GPS (Ashkenazi et al, 1994; Ashkenazi et al, 1997). In the last of these projects, from 1997 to 2000, continuous GPS (CGPS) stations were established at the 5 tide gauge sites of Sheerness, Newlyn, Aberdeen, Liverpool and Lowestoft in 1997 and 1998, and two sets of episodic GPS (EGPS) measurements were carried out at 12 other tide gauge sites in the UK in 1999, using a small number of 'roving GPS receivers'. Research was then concentrated on the development and testing of automated procedures for GPS data processing and analysis (Bingley et al, 2000).

In this research project, the scientific objectives were to be addressed through five work packages, which can be summarised as:
- Setting up of two new CGPS stations at tide gauge sites (ie CGPS@TG stations).
- Processing and analysis of data from the 5 existing and 2 new CGPS@TG stations.
- Time series analysis of CGPS data from the past and current projects.
- Investigation of the use of the dual-CGPS station concept.
- Further development of the roving GPS receiver concept to include quasi-continuous GPS (QCGPS) stations.

The scientific objective and deliverables have been met in full, through a monitoring network of 30 GPS stations in the UK (see Figure 1). Details of the research and development carried out as part of the project are given in section 2 and a discussion of the results obtained is presented in section 3. The report is concluded in section 4, with the main implications of the findings, recommended actions resulting from the research and possible future work.

2 Research and Development

The research and development carried out as part of this research project can be broadly separated into the establishment of CGPS stations, GPS measurements, GPS data processing and analysis, and time series analysis.

2.1 Establishment of CGPS Stations

Shortly after the research project began in late 2000 and early 2001, there were a total of 18 CGPS stations in the UK that were contributing data to a scientific archive at the IESSG. This included the 5 CGPS@TG stations established in the previous research project, along with a further 13 non-TG CGPS stations established by the Environment Agency, the Met Office and other organisations. During 2001, this network was expanded to 20 CGPS stations through the establishment of CGPS@TG stations at North Shields and Portsmouth tide gauge sites.

For both of these tide gauge sites the necessary equipment was purchased, including an Ashtech GPS receiver with Dorne-Margolin T (choke ring) antenna, and a modem. Reconnaissances were then carried out in order to identify suitable locations for the GPS antenna and the GPS receiver. Following the same principles as applied at the other 5 CGPS@TG stations, the GPS antenna was mounted as close as possible to the tide gauge itself.

At North Shields, the reconnaissance was simplified through the availability of an existing monument that had been installed by the University of Newcastle-upon-Tyne in 1998. Agreement was obtained from the University and the Harbour Master for the IESSG to use this monument, and a telephone line was installed at this site. The installation of the GPS equipment was then carried out in May 2001. Subsequently, some historic data for this CGPS station was provided for the scientific archive at the IESSG, effectively extending the potential time series back to 1998 with EGPS data observed from March to August 1998 and February to October 2000.

At Portsmouth, engineering developments had resulted in the tide gauge being moved to a new location in the year 2000. Following a reconnaissance, permission for the establishment of the CGPS station was requested from the organisation responsible for the land and buildings on which the tide gauge is located. Once the relevant permission was obtained, a survey monument was designed and manufactured for this site, a telephone line was installed and the installation of the monument and GPS equipment was carried out in September 2001.

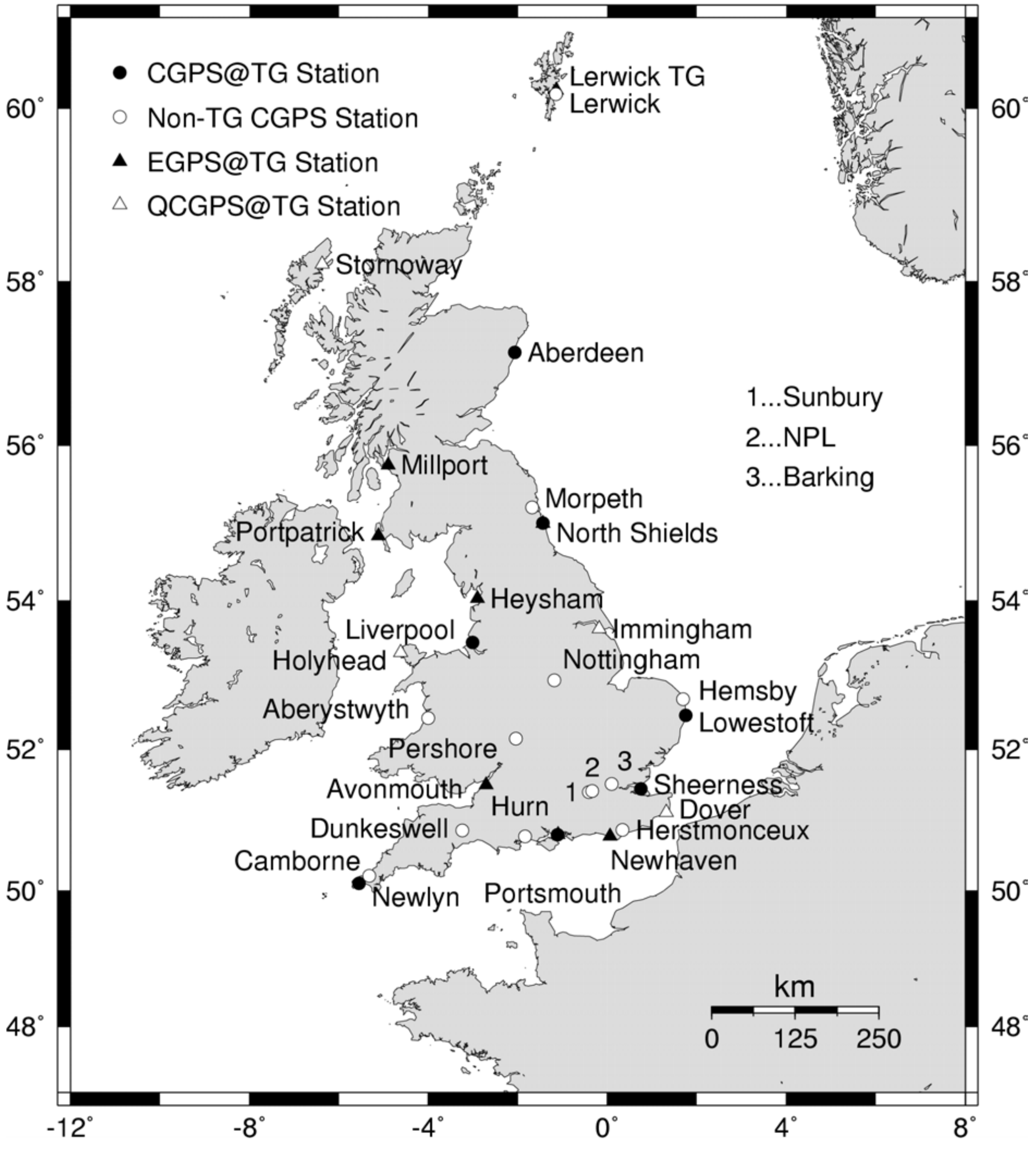


Figure 1 UK GPS stations included in the processing and analysis

2.2 GPS Measurements

Three different types of GPS station and associated GPS measurements were used in this research project; continuous, quasi-continuous and episodic.

For the 7 CGPS@TG stations, data were downloaded on a daily basis using the automated procedures developed as part of the previous research project. The automated procedures have continued to be extremely reliable, resulting in more than 99% of possible data being observed and downloaded. A summary of the data available from all 20 CGPS stations is given in Table 1, which considers data up to 11 March 2003 and is ordered in terms of length of time series. (Note: this date has been taken as the cut-off for this report and reflects the fact that up to the end of June, the data were processed and analysed on a daily basis, with a 110 day delay).

		START		END		
Station	**ID**	**Year**	**Day of Year**	**Year**	**Day of Year**	**Length (years)**
Morpeth	MORP	1997	085			6.0
Sheerness TG	SHEE	1997	085			6.0
Sunbury Yard	SUNB	1997	098			5.9
Barking Barrier	BARK	1997	115			5.9
Nottingham (IESSG)	IESG	1997	117			5.9
Herstmonceux	HERS	1997	119			5.9
Camborne	CAMB	1998	099			4.9
Aberystwyth	ABYW	1998	100			4.9
Hemsby	HEMS	1998	100	2001	026	2.8
Lerwick	LERW	1998	108			4.9
Aberdeen TG	ABER	1998	261			4.5
Newlyn TG	NEWL	1998	273			4.5
Liverpool TG	LIVE	1999	035			4.1
Lowestoft TG	LOWE	1999	044			4.1
Dunkeswell	DUNK	2000	036			3.1
Teddington (NPL)	NPLD	2000	229	2002	294	2.2
Hurn	HURN	2000	257			2.5
Pershore	PERS	2001	129			1.9
North Shields TG	NSTG	2001	135			1.8
Portsmouth TG	PMTG	2001	268			1.5

Table 1 Data availability for the CGPS stations included in the processing and analysis

In addition to the CGPS stations, the research project also included GPS measurements at 10 other tide gauge sites. Previously these measurements were made over 3 to 5 days, with observation periods of either 12 or 24 hours. In this research project, an investigation into the use of quasi-continuous GPS measurements with observation periods of 3 to 6 weeks was carried out at Dover, Holyhead, Immingham and Stornoway. A summary of the data available for these 4 QCGPS@TG stations is given in Table 2.

For the remaining 6 tide gauge sites, 'roving GPS receivers' were used to make episodic GPS measurements for 3 to 5 days at each site. The first set of measurements were carried out from July to October 2002 and the second set were carried out from February to May 2003. A summary of the data available for the 6 EGPS@TG stations is given in Table 3.

		EGPS Campaigns		EGPS	QCGPS	
Station	**ID**	**Number**	**First / Last Year**	**1999 (days x hours)**	**2002/3 (days x hours)**	**Approx Length (years)**
Dover TG	DOV2	6	1991 / 95	5 x 24 5 x 24	36 x 24 32 x 24	11.5
Holyhead TG	HOL1			5 x 24 5 x 24	28 x 24 28 x 24	4.0
Immingham TG	IMM1	1	1995 / 95	5 x 24 5 x 24	21 x 24 43 x 24	7.5
Stornoway TG	STO1	2	1993 / 94	5 x 24 5 x 24	18 x 24 38 x 24	9.5

Table 2 Data availability for the QCGPS@TG stations included in the processing and analysis

		EGPS Campaigns		EGPS		
Station	**ID**	**Number**	**First / Last Year**	**1999 (days x hours)**	**2002/3 (days x hours)**	**Approx Length (years)**
Newhaven TG	NWH1	3	1991 / 93	5 x 12 5 x 12	5 x 12 3 x 12	11.5
Avonmouth TG	AVO1	2	1995 / 96	5 x 12 5 x 12	5 x 12 3 x 12	7.5
Heysham TG	HEY1	2	1995 / 96	5 x 12 5 x 12	5 x 12 3 x 12	7.5
Portpatrick TG	PPA1	6	1991 / 96	5 x 12 5 x 12	5 x 12 3 x 12	11.5
Millport TG	MIL1	2	1995 / 96	5 x 12 5 x 12	5 x 12 3 x 12	7.5
Lerwick TG	LER2	4	1992 / 94	5 x 12 5 x 12	5 x 12 3 x 12	10.5

Table 3 Data availability for the EGPS@TG stations included in the processing and analysis

2.3 GPS Data Processing and Analysis

As reported in Bingley et al (2000; 2001a; 2001b), the move to using CGPS stations required a significant change in the way that GPS data were processed and analysed. As part of this project, the automated procedures for GPS data processing and analysis were modified to enable:

- CGPS data to be processed and analysed on a daily basis, with a 110 day delay.
- QCGPS and EGPS data to be processed for specific periods.
- Any historic GPS data to be re-processed and re-analysed, to take into account periodic improvements in the reference frame and improved strategies for the mitigation of systematic biases and errors.

Over the second half of this research project, the automated procedures for GPS data processing and analysis (version 3.2) were used to:

- Re-process all of the data that were first processed in the previous project, ie all of the CGPS and EGPS data that were observed between the beginning of 1997 and the end of 1999. The main reason for this re-processing was to remove systematic biases introduced through the over-constraining of IGS stations during the initial GPS data processing.
- Process all of the new data that were observed at the end of the previous project and throughout this project, ie all of the CGPS, QCGPS and EGPS data that were observed between the beginning of 2000 and March 2003.

In all cases, the data from GPS stations in the UK were processed, using the IESSG's GPS Analysis Software (Stewart et al, 2003), along with data from IGS stations at Kootwijk, Onsala, Villafranca and Wettzell in order to produce a series of daily GPS 'free network' solutions. For each daily GPS free network solution, the GPS data were processed using the double difference observable with integer ambiguities not fixed, and the mitigation of systematic biases and errors was achieved through:

- The use of the final IGS precise ephemeris.
- The use of the L1/L2 'ionospherically free' observable.

- The estimation of total zenithal tropospheric delay after the effect of the hydrostatic component was modelled using the Saastamoinen model (Saastamoinen, 1973). For both the 'wet' and hydrostatic components the appropriate Niell mapping functions were used (Niell, 1996).
- The use of corrections for antenna phase centre variations based on the IGS_01.PCV relative values, which were first released in June 1996 and are updated periodically (IGSCB, 2003).
- The modelling of solid Earth tides according to the IERS 1992 standards (McCarthy, 1992).
- The modelling of ocean tide loading according to the IERS 1992 standards, with corrections to all three coordinate components for the M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_f, M_m and Ssa constituents based on the FES99 model (Le Provost et al, 1994).

In the daily GPS free network solutions, the only constraints applied were through the fixing of the satellite coordinates given in the final IGS precise ephemeris, which were computed in successive realisations of the International Terrestrial Reference System (ITRS) including ITRF94 (Boucher et al, 1996), ITRF96 (Boucher et al, 1998), ITRF97 (Boucher et al, 1999) and ITRF2000 (Altamimi et al, 2002).

Following the processing and analysis of GPS data for a certain period it is possible to form coordinate time series for a station. In order to form coordinate time series with no discontinuities, the vectors and associated variance-covariance information output from each daily GPS free network solution must be transformed to a common reference frame. For the final results for this project, this was achieved by tightly constraining Kootwijk, Onsala, Villafranca and Wettzell to their ITRF2000 coordinates, motioned to the observation epoch, so that the coordinate time series for the GPS stations in the UK are presented in ITRS2000.

2.4 Time Series Analysis

As stated in section 2.3, a major part of the research and development for the previous project was related to the development of automated procedures to enable continuous GPS data to be processed and analysed. In this project, a major part of the research and development has been focussed on the analysis of coordinate time series based on CGPS data from the past and current projects.

Through the analysis of coordinate time series it is possible to:
- Detect and eliminate any daily GPS free network solutions that are outliers in the coordinate time series.
- Detect and correct for any coordinate offsets caused by changes to equipment and/or environment at a site.
- Assess and mitigate any periodic variations, which may be related to un-mitigated loading effects, either site specific or introduced via the reference frame.
- Estimate linear station velocities
- Estimate realistic values for the uncertainty of any estimates of linear station velocities, taking into account the presence of both white and coloured noise.

Clearly, the success of such time series analysis has a significant bearing on any assessment of vertical land movements that are inferred from the estimates of linear station velocities.

During this research project a series of Perl scripts and Matlab M-files have been developed and tested, resulting in a set of 'coordinate time series analysis tools' (Teferle, 2003). The results obtained from these tools have also been compared to results obtained using the cats_MLE programs developed by Simon Williams at POL, which have been used for the detailed analysis of global and regional CGPS networks (Williams, 2003a; 2003b; Williams et al, 2003).

Other areas of research included an assessment of correlations between, and common mode biases within, the coordinate time series obtained for the 20 CGPS stations (Teferle, 2003), and a detailed investigation of the dual-CGPS station concept based on the coordinate time series for Newlyn TG and Camborne.

3 Final Results

Using the automated procedures for GPS data processing and analysis (version 3.2) and the coordinate time series analysis tools, it has been possible to generate a series of final results for the research project. These are presented in this section, in terms of the CGPS stations, the dual-CGPS station concept, and the QCGPS and EGPS stations.

3.1 Continuous GPS Stations

Figures 2, 3 and 4 show the ITRS2000 coordinate time series obtained for the CGPS stations. For each station and each coordinate component, the figures show the daily coordinate estimates in red, the location of any coordinate offsets that have been solved for in blue, and the periodic variations (modelled as an annual term) in black. On each figure there is also given the weighted RMS (WRMS) of a daily coordinate estimate from the time-averaged mean and, for those stations with more than 2.5 years of CGPS data, a linear station velocity estimate with a corresponding uncertainty (1-sigma), computed after the coordinate offsets and the periodic variations are taken into account.

The results obtained for all CGPS stations are summarised in Table 4, which is ordered in terms of length of time series.

The WRMS values can be used as an indication of the quality of the data being recorded at a particular site. As can be seen, the WRMS values range from 6 to 15 mm. Looking at the CGPS@TG stations, there is no indication that the data being recorded at tide gauge sites is generally worse than that being recorded at other sites. However, there are clear problems with the data observed at North Shields TG (NSTG), which are most likely to be a result of multipath from a number of buildings and structures close to the tide gauge (Teferle et al, 2002a; 2003). Interesting to note here is Aberdeen TG (ABER), where the data quality has improved significantly since a source of radio frequency interference was removed on 1 May 2001 (see Figure 2, where there is a visible reduction in the spread of the height time series after this date).

For the uncertainty values, these are effectively dependent on the length of the time series, the continuity of the time series and the amount of white noise (indicated by the WRMS) and coloured noise. Consider the CGPS stations Hurn (HURN) and Morpeth (MORP), the shortest and longest time series analysed. In this case, the WRMS values are about the same at approximately 9 mm and the uncertainty is clearly a function of the length of the time series, as it reduces from ± 5.54 mm/yr after only 2.5 years to ± 1.95 mm/yr after 6 years. Now consider the six CGPS stations with the longest time series available. In this case, the presence of coordinate offsets and gaps in the data for Morpeth (MORP) and Herstmonceux (HERS) have clearly contributed to a worsening of the uncertainty at these stations, whereas for Sheerness TG (SHEE), Sunbury Yard (SUNB), Barking Barrier (BARK) and Nottingham (IESG) it is clear that the uncertainty is now approaching ± 1 mm/yr. The uncertainties for Aberdeen TG (ABER), Liverpool TG (LIVE) and Lowestoft TG (LOWE) seem to have reached a level of about ± 1.7 mm/yr after 4 to 4.5 years and would be expected to approach ± 1 mm/yr with another 1 to 1.5 years of data. Clearly, this is not the case at Newlyn TG (NEWL), which has a larger than expected uncertainty after 4.5 years. Having identified this anomaly, it has now become apparent that there was a mis-application of the ocean tide loading corrections in GAS, which has introduced additional periodic variations and worsened the uncertainties at the sites most affected by ocean tide loading in the South-West of Britain, namely Camborne (CAMB), Aberystwyth (ABYW), Newlyn TG (NEWL) and Dunkeswell (DUNK). This problem has now been rectified and tests have shown that we can expect the uncertainties at these stations to be reduced significantly if the GPS data is re-processed.

The vertical station velocities range from approximately - 2 mm/yr to + 2 mm/yr. In terms of their order of magnitude, these are consistent with the geological estimates provided by Shennan (1989), Woodworth et al (1999) and Shennan and Horton (2002). It is clear, therefore, that there are no gross errors in any of the estimates of vertical station velocities. However, taking into account the uncertainties, none of the individual vertical station velocities can be considered to be statistically significant yet and none of them can be considered to be estimates of absolute vertical land movements at this stage. Nevertheless, it is interesting to note that an approximate computation of the relative vertical land movement between Aberdeen TG and Sheerness TG gives a value of + 1.24 mm/yr from GPS, which compares favourably with the value of + 1.43 mm/yr from Shennan and Horton (2002).

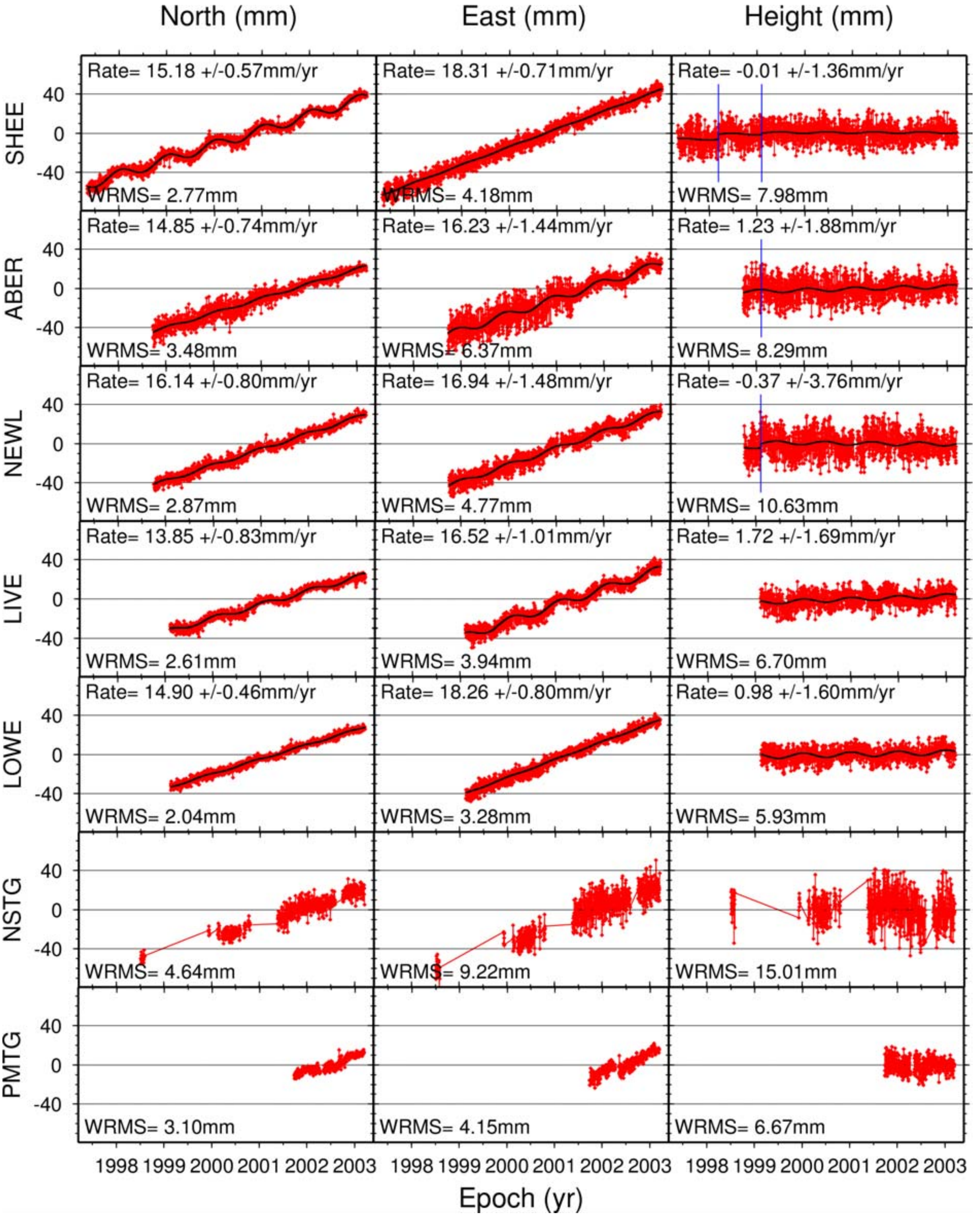


Figure 2 ITRS2000 coordinate time series (up to 11 March 2003) for the seven CGPS@TG stations

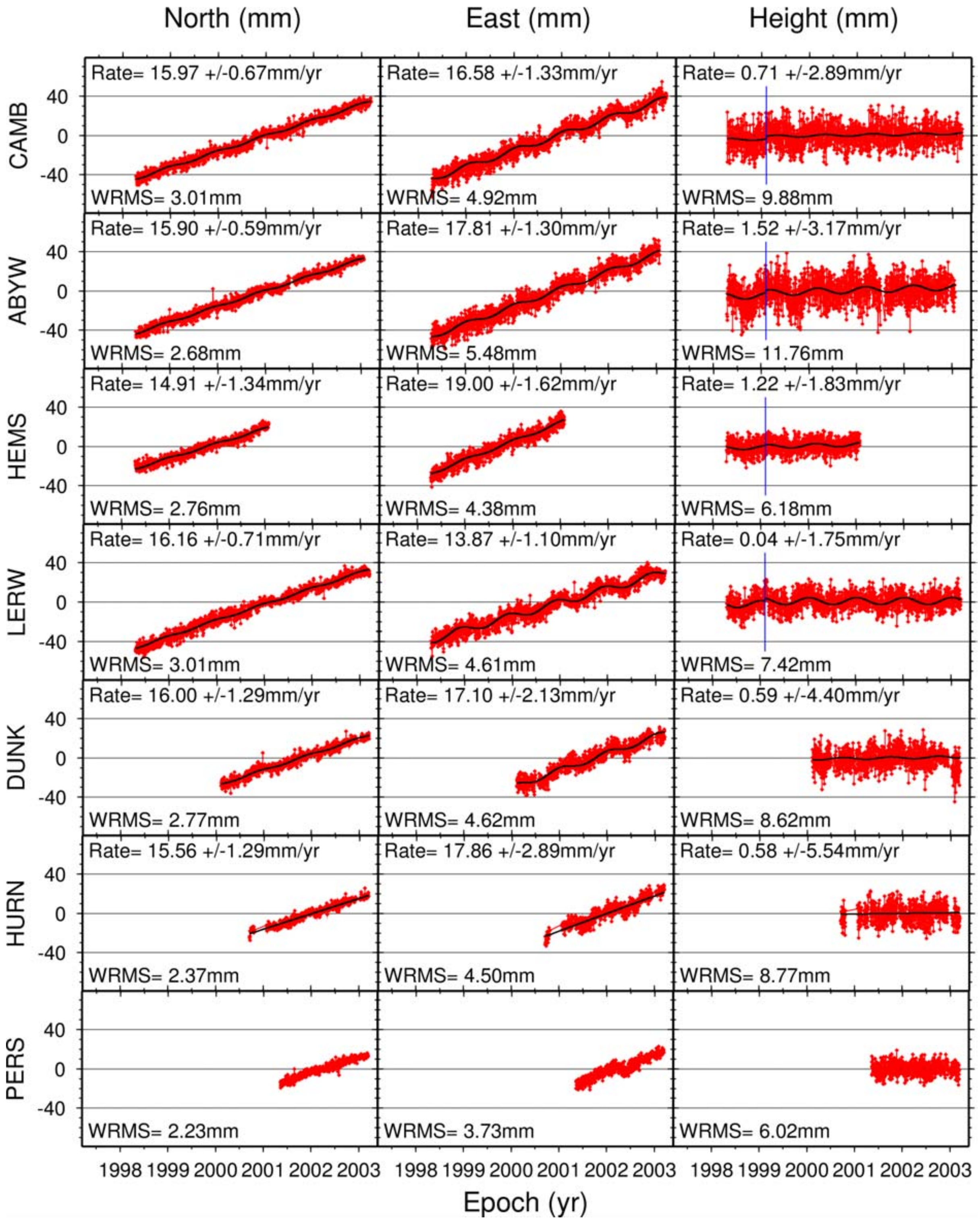


Figure 3 ITRS2000 coordinate time series (up to 11 March 2003) for the seven Met Office non-TG CGPS stations.

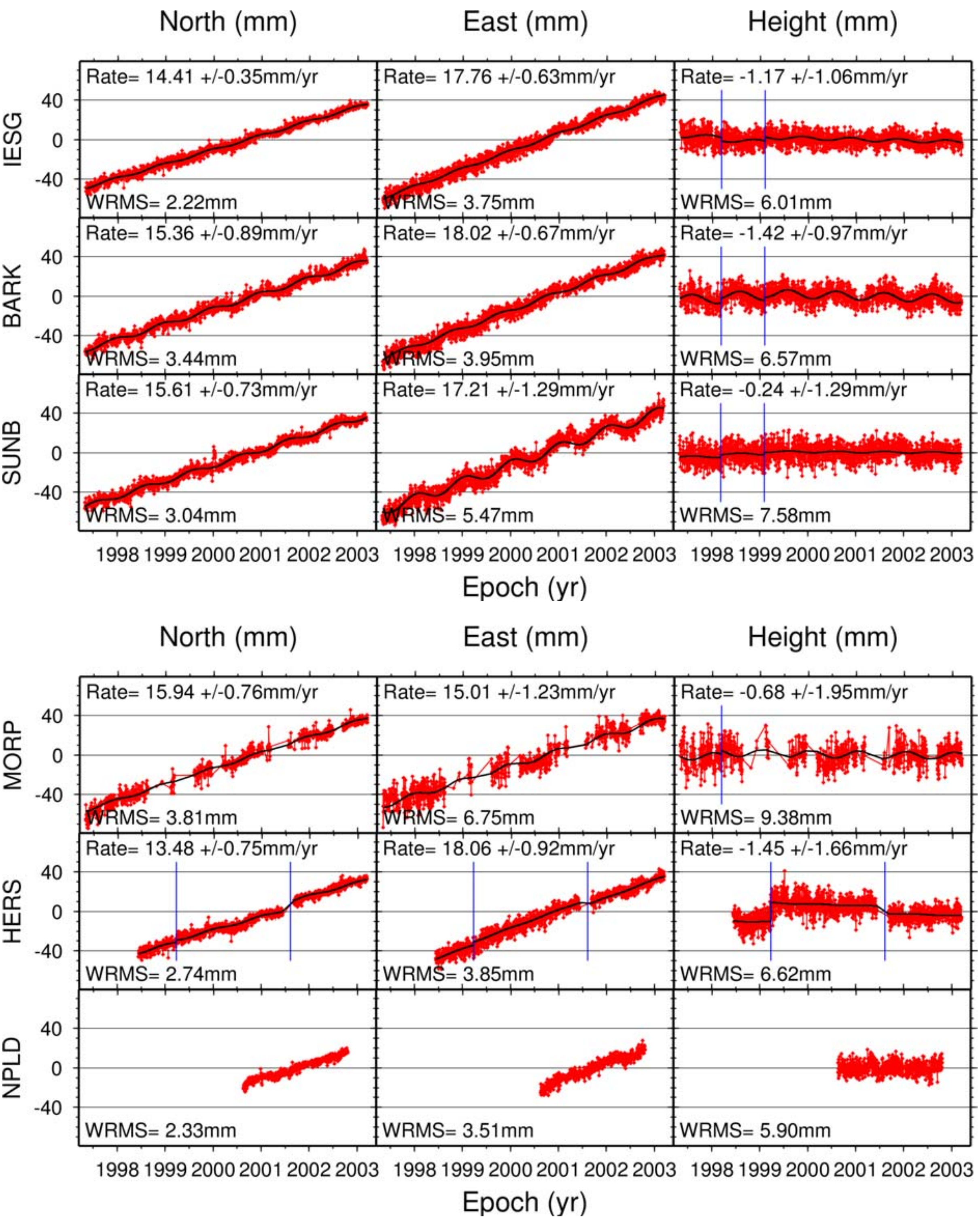


Figure 4 ITRS2000 coordinate time series (up to 11 March 2003) for the six other non-TG CGPS stations.

Station	ID	Length (years)	No. of Offsets Solved	WRMS (mm)	Vertical Velocity (mm/yr)	Uncert'y +/- (mm/yr)
Morpeth	MORP	6.0	1	9.38	- 0.68	1.95
Sheerness TG	SHEE	6.0	2	7.98	+ 0.01	1.36
Sunbury Yard	SUNB	5.9	2	7.58	- 0.24	1.29
Barking Barrier	BARK	5.9	2	6.57	- 1.42	0.97
Nottingham (IESSG)	IESG	5.9	2	6.01	- 1.17	1.06
Herstmonceux	HERS	5.9	2	6.62	- 1.45	1.66
Camborne	CAMB	4.9	1	9.88	+ 0.71	2.89
Aberystwyth	ABYW	4.9	1	11.76	+ 1.52	3.17
Hemsby	HEMS	2.8	1	6.18	+ 1.22	1.83
Lerwick	LERW	4.9	1	7.42	+ 0.04	1.75
Aberdeen TG	ABER	4.5	1	8.29	+ 1.23	1.88
Newlyn TG	NEWL	4.5	1	10.63	- 0.37	3.76
Liverpool TG	LIVE	4.1	0	6.70	+ 1.72	1.69
Lowestoft TG	LOWE	4.1	0	5.93	+ 0.98	1.60
Dunkeswell	DUNK	3.1	0	8.62	+ 0.59	4.40
Teddington (NPL)	NPLD	2.2	0	5.90		
Hurn	HURN	2.5	0	8.77	+ 0.58	5.54
Pershore	PERS	1.9	0	6.02		
North Shields TG	NSTG	1.8	0	15.01		
Portsmouth TG	PMTG	1.5	0	6.67		

Table 4 CGPS station results summary

3.2 The Dual-CGPS Station Concept

The dual-CGPS station concept was investigated in order to establish whether it is possible to carry out a more rigorous assessment of relative vertical land movements between CGPS stations that are relatively close together. For this investigation, a dual-CGPS station pair was formed from the CGPS@TG station at Newlyn TG (NEWL) and the non-TG CGPS station at Camborne (CAMB), which is founded on solid rock and located about 20 km from the tide gauge site.

The dual-CGPS station analysis is relatively straightforward in that the daily coordinate estimates that form two coordinate time series are simply differenced from each other to produce a coordinate difference time series, from which estimates of relative station velocities and corresponding uncertainties can be computed (Teferle et al, 2001; 2002b).

The results of the analysis are presented in Figure 5. Unlike the results shown in Figures 2 and 3, the dual-CGPS station analysis considered a 3.7 year period of common data from October 1998 to May 2002. Furthermore, periodic variations are not modelled but are considered to be spatially correlated and mitigated by differencing. Therefore, the estimates of absolute station velocities shown in Figure 5 should not be considered, as they are biased by the presence of the periodic variations. Instead, what is important is the fact that the coordinate difference time series have a lower WRMS than the coordinate time series of the individual stations, which shows that common systematic features are removed when differencing is carried out. This is further reflected in the uncertainties of the estimates of relative station velocities, which are about half of the magnitude of the uncertainties of the estimates of station velocities. Further tests on simulated data, confirmed that relative vertical station velocities quickly approach reliable values, even if the coordinate time series are affected by periodic variations.

Although not statistically significant, the relative vertical station velocities shown in Figure 5 suggest that the CGPS@TG station NEWL is well founded and is not experiencing any localised land movements in addition to the underlying geophysical crustal motion experienced by both Newlyn TG and Camborne. To be able to make such a conclusion is very important, if estimates of vertical land movements for the last few years are going to be combined with estimates of changes in relative sea level for the past few decades.

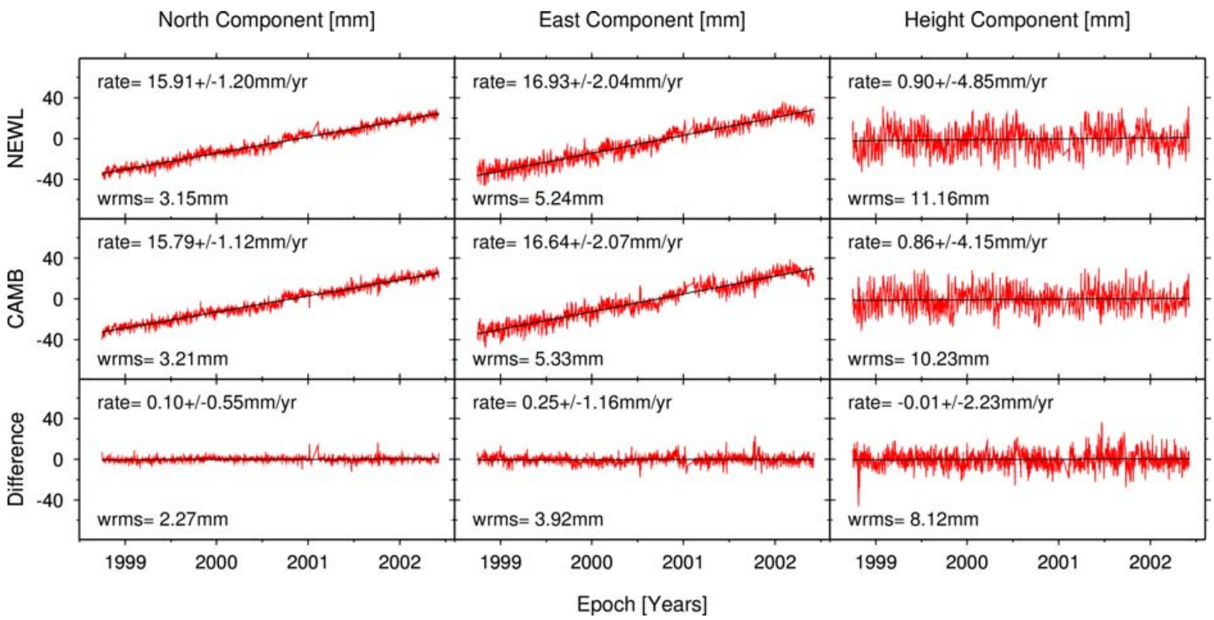


Figure 5 ITRS2000 coordinate time series (up to 31 May 2002) for the dual-CGPS station pair NEWL and CAMB.

3.3 Quasi-Continuous and Episodic GPS Stations

Figure 6 shows the ITRS2000 height time series obtained for the 6 EGPS@TG stations and for the 4 EGPS@TG stations that have been upgraded to QCGPS@TG stations, ordered in terms of their latitude and represented on an arbitrary scale for height. For an EGPS@TG station the daily coordinate estimates for each specific five day period of episodic GPS data were combined in order to produce an epochal height estimate for each campaign or set of measurements. For the QCGPS@TG stations, the daily height estimates are shown.

Immediately visible in Figure 6 is the amount of additional information provided when a station is upgraded from EGPS to QCGPS. The spread of the QCGPS@TG station daily height estimates also highlights the fact that epochal height estimates, based on only 5 days of data, could be biased and their uncertainties too optimistic. With this in mind then, from these results, it is only really possible to say that there have been no significant, sudden land movements at any of these tide gauge sites over the last few years.

Considering the results further, it must now be said that the use of EGPS stations is sufficient for the absolute fixing of tide gauge bench marks, which has enabled studies on gravimetric geoids (Bingley et al, 2002), satellite altimetry (Dong et al, 2002) and mean sea surface topography (Hipkin et al, 2003), but is not sufficient for the monitoring of vertical land movements at tide gauges on a national scale. Realistically, this is best achieved through the establishment of CGPS@TG stations, and may be possible through the use of QCGPS@TG stations.

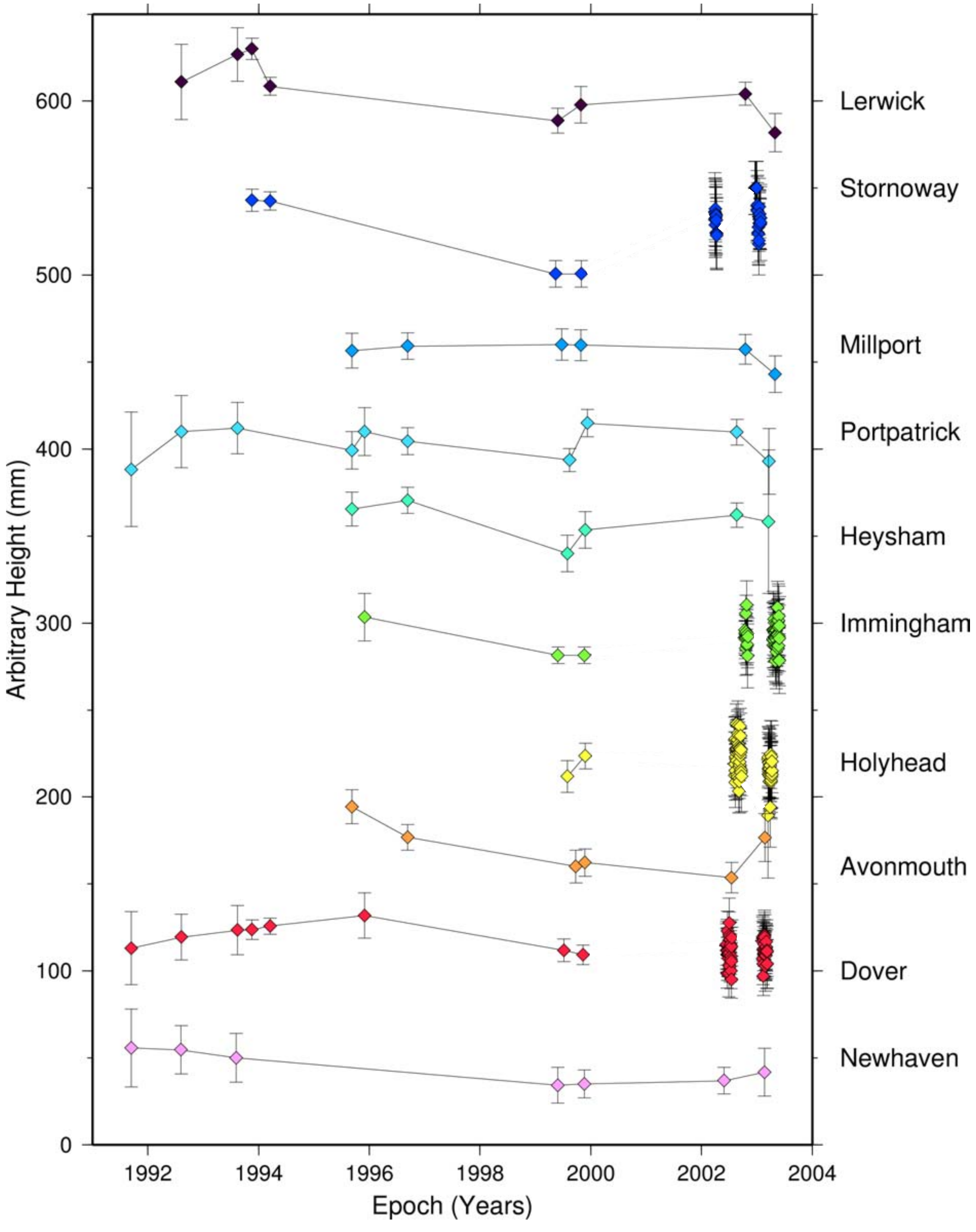


Figure 6 ITRS2000 coordinate time series (up to 31 May 2003) for the six EGPS stations and the four QCGPS stations.

4 Conclusions and Recommendations

The main implications of the findings of the research project are that:

- Through the establishment of CGPS stations in the UK it is possible to obtain vertical station velocities with uncertainties approaching ± 1 mm/yr, if the data is of a high quality and the time series is at least 6 years in length.
- Using the dual-CGPS station concept it is possible to separate localised land movements at tide gauge sites from the underlying geophysical crustal motion.

- By converting four of the EGPS stations to QCGPS stations it has been possible to demonstrate that the use of EGPS stations is sufficient for the absolute fixing of tide gauge bench marks, but is not sufficicent for the monitoring of vertical land movements at tide gauge sites on a national scale.

In terms of the monitoring network, the recommended action resulting from the research is:
- To continue to operate the 7 CGPS@TG stations in order to extend the coordinate time series beyond their current maximum of 6 years.
- To establish CGPS stations at other tide gauge sites wherever possible. If it is not possible to establish a CGPS station at a tide gauge site, then a QCGPS station should be employed in preference to an EGPS station. These QCGPS stations do not necessarily have to be co-located with the EGPS station, but could be established in a way that would enable them to be upgraded to CGPS stations in the future.
- The dual-CGPS station concept should be used wherever possible, through the incorporation of existing non-TG CGPS stations into the monitoring network. Using data that is already part of the scientific archive at the IESSG, it should be possible to pair Sheerness TG with Barking Barrier, Aberdeen TG with Girdle Ness, Liverpool TG with Daresbury, North Shields TG with Morpeth and Portsmouth TG with Southampton. However, the long-term stability of the Ordnance Survey active stations at Girdle Ness, Daresbury and Southampton would need to be assessed.

In terms of the monitoring of long term vertical land movements, possible future work should include:
- Expansion of the processing and analysis of data from the monitoring network so that it is carried out using both the IESSG GPS Analysis Software (GAS) and the widely used Bernese software, to provide a comparative check on the daily coordinate estimates.
- Inclusion of some of the CGPS@TG stations in parallel European and International activities, to provide an external check on the daily coordinate estimates. Over the next three years this could be achieved by contributing data from some of the CGPS@TG stations to the European Sea Level Service Research Infrastructure (ESEAS-RI) project and the International GPS Service Tide Gauge Pilot Project (IGS TIGA-PP).
- Expansion of the time series analysis so that it is carried out using both the tools developed for this project and the cats_MLE programs developed by Simon Williams at POL, to provide a comparative check on the estimates of vertical station velocities and their uncertainties.
- Focus on the closer integration of the CGPS and absolute gravity results, so that the estimates of vertical station velocities from absolute gravity can be used to assess any systematic biases in the estimates of vertical station velocities from GPS.

Through these recommended actions, it should be possible to make the first proper assessment of the contribution of absolute vertical land movements to changes in relative sea level at the tide gauge sites of Sheerness, Aberdeen, Newlyn, Liverpool and Lowestoft, within the next three years. This assessment would be based on time series that are **un-biased**, through the alignment with absolute gravity, **reliable**, through the internal and external checks to be introduced, **and statistically significant**, with reduced uncertainty values based on the extended monitoring period, and improvements in the time series analysis strategy.

ABSOLUTE GRAVITY MEASUREMENTS

1 Scientific objectives

The overall objective of the absolute gravity work is to formulate a procedure that can be used for measuring vertical land movements at UK tide gauges, in order to be able to separate the climate related changes in mean sea levels from the component due to land movements. The research work involved the continuation of the absolute gravity measurements made under the previous project near the core UK tide gauges at Newlyn, Aberdeen and Lerwick. Newlyn and Lerwick are UK tide gauges contributing to the Intergovernmental Oceanographic Commission's Global Sea Level Observing System (GLOSS). Aberdeen is the UK tide gauge with the longest record (140 years). Since absolute gravimeters are at the forefront of technology (see section 2) an important part of the programme of work was to inter-compare the POL gravimeter (FG5-103) with other absolute gravimeters at fundamental gravity sites. This ensured that FG5-103 continues to measure gravity with an accuracy equivalent to the highest international standards. The scientific objectives have been achieved and the work is described in the following sections.

2 The absolute gravimeter

The FG5 absolute gravimeter is the latest in a series of technical developments made over many years by the USA National Institute of Standards and Technology and the University of Colorado (Niebauer et al., 1995). It is now produced commercially by Micro-g Solutions Inc., Colorado, USA. The principal of the absolute gravimeter is straightforward in that it measures the acceleration of a mass in free fall in a vacuum. However, in order to achieve an accuracy of 2 parts in a billion of gravity (i.e. 20 nm/sec^2 or 2 microgals) several technical advances have been made so that various possible sources of systematic errors are reduced to well below this level. The falling mass is a corner-cube retroreflector and its position is measured using a laser interferometer. The light path to the corner-cube forms one arm of the interferometer and a corner-cube mounted on an active long period seismometer (superspring), so as to act as an inertial reference mass, forms the other arm of the interferometer. The interference fringes between the 2 light beams are counted and timed and the distance-time pairs collected during the 20cm drop are used in the equation of motion to solve for the acceleration due to gravity 'g'. The whole system is automatically controlled by computer and typically 200 drops i.e. 200 independent determinations of 'g', are made per hour. The key to the accuracy of the FG5 absolute gravimeter is that the measurements are directly related to international standards of length and time. The instrument uses a newly developed iodine-stabilised laser, which is the international length standard. A rubidium frequency reference is used for timing and this can be calibrated against a caesium standard. For further details of the instrument and the technical developments see Niebauer et al. (1995).

3 Absolute gravity measurements at fundamental gravity sites

Although an absolute gravimeter measures gravity using a laser length standard and an atomic clock, utmost care is required to ensure that all the components of the system are working correctly and not giving unexpected off-sets in gravity values. Every 4 years many of the absolute gravimeters from around the world are inter-compared at the fundamental gravity station at the Bureau International des Poids et Mesures (BIPM) near Paris. As well as an inter-comparison of the gravity measurements for instruments operating side by side, this also provides a valuable opportunity to compare experimental procedures between the different groups. The POL absolute gravimeter FG5-103 was taken to BIPM for the inter-comparison experiments in 1997 and 2001.

Since the aim of our work is to determine vertical land at tide gauges to better than +/- 1 mm/year, we require the highest possible accuracy for our gravimeter. Therefore it was decided to make more inter-comparisons at fundamental gravity stations, in order to provide a more frequent check than is provided by the 4-yearly BIPM measurements. During the regular servicing of the instrument at Micro-g in Colorado, the opportunity has been taken to make measurements at the USA fundamental gravity station at Table Mountain in Colorado. Other inter-comparison experiments have been made at the German fundamental station at Bad Homburg and at POL. The results of these inter-comparisons are given in Figure 7, where the differences are shown between the results from the other FG5 absolute gravimeters and the gravity value from FG5-103. It can be seen that the USA fundamental site at the Table Mountain Gravity Observatory (TMGO) is quieter than the BIPM site in Paris. Altogether inter-comparisons with 17 other FG5 gravimeters are included in Fig. 7. The measurements over this 6 year period provide a confirmation that FG5-103 continues to give results that are consistent with the specified accuracy (20nm/sec^2 or 2 microgals).

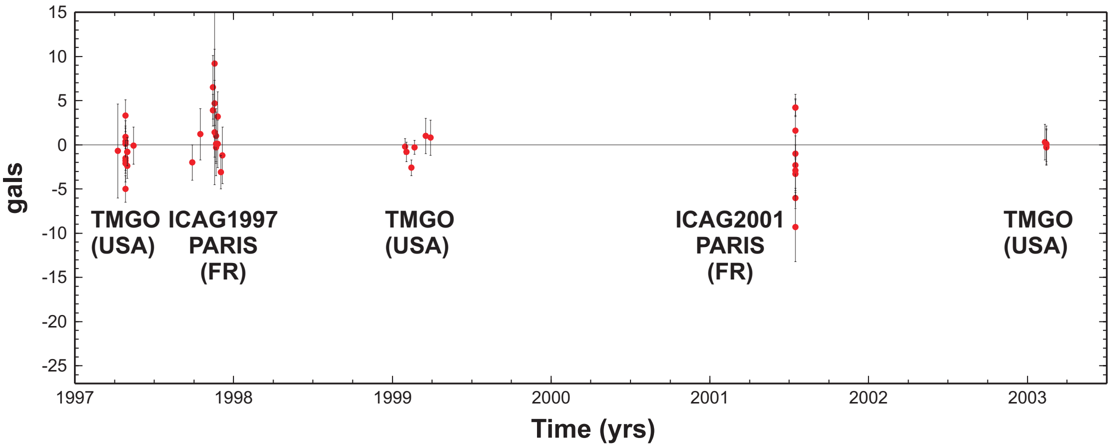


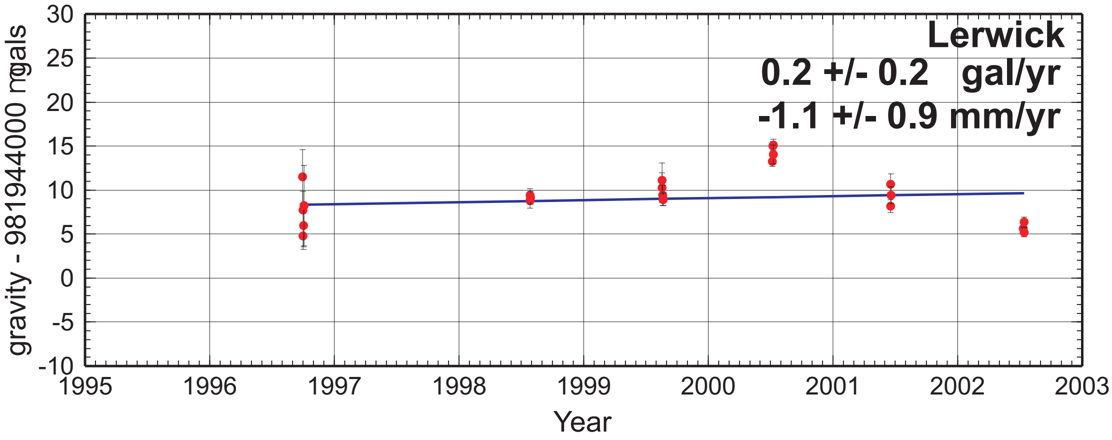
Figure 7. Inter-comparison experiments showing the differences in microgals between other FG5 absolute gravimeters and FG5-103.

4 Methodology and Results

Since the absolute gravimeter produces typically 200 values of gravity per hour, it is common practice to measure gravity at a site by measuring for 1 day or even just for a few hours. For the present work, in order to achieve the best possible results, it was decided to make measurements for at least 3 days, with the gravimeter being carefully set-up again at the start of each day. This not only produced significantly more data for a given field trip, but also allowed a comparison of the standard deviations of the hourly means each day with the variablity from day to day. This enabled the assessment of the noise in the measurements at a particular site and epoch. One of the main sources of noise in the absolute gravity measurements is due to microseisms, which typically have periods from 5 to 7 seconds. These are generated by ocean waves and are therefore important at coastal sites. The superspring has a period of about 60 seconds, in order to reduce the effects of high frequency noise. However, on very windy days the energy in the microseismic band increases significantly and oscillations of the reference mass give an increase in the noise of the gravity measurements. The extended visits to each site are therefore also valuable, since this allowed the possibility of avoiding days with very high microseisms.

The absolute gravity sites were established in buildings on solid bedrock, which is important for both stability and for being representative of the vertical crustal movements of the area. Nearby ‘witness’ gravity stations are available, which were set-up and measured relative to the absolute gravity station by the University of Edinburgh using LaCoste and Romberg relative spring gravimeters. Newlyn and Aberdeen are also part of the British Precise Gravity Network (BPGN), which consists of 65 gravity sites covering most of Britain, that have been measured by the University of Edinburgh using the relative spring gravimeters (Charles and Hipkin, 1995). Measurements with the POL absolute gravimeter at Wick, Aberdeen, Edinburgh, POL, Herstmonceux, Taunton and Newlyn have been used to fix the datum and scale of this relative network.

The absolute gravity measurements began in Newlyn and Aberdeen in 1995 and in Lerwick in 1996 (Williams et. al, 2001). Figure 8 shows the observed gravity values at Lerwick and Newlyn and the associated error bars on each observation. At both sites there is a small increase in gravity, which corresponds to a subsidence at each site. A subsidence of the Earth’s surface by 1mm gives an increase in gravity of 0.2 microgals. The least squares linear trends are shown in Fig. 8 and Table 5. Newlyn is subsiding by 1.7mm/year and the 1-sigma uncertainty of the trend is +/- 0.8mm/year. Lerwick is subsiding by 1.1mm/year +/- 0.9mm/year. At Aberdeen the gravity results give an uplift of 1.8mm/year but with an uncertainty of +/- 1.9mm/year. Geophysical models of post-glacial rebound, which are based on the response of the Earth’s viscous mantle to the changing ice load on the Earth’s surface during the last ice age, predict subsidence at Newlyn and Lerwick and uplift at Aberdeen. Although longer time series of absolute gravity measurements are required in order to reduce the uncertainties, the present results are very encouraging.



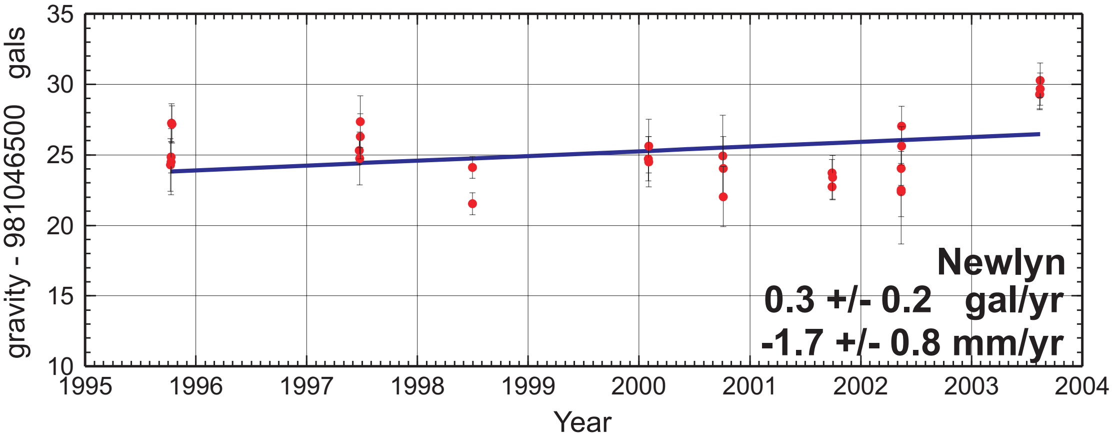


Figure 8. Absolute gravity observations at Lerwick and Newlyn.

Gravity Station	Start	Vertical Velocity (mm/yr)	Uncertainty +/- (mm/yr)
Newlyn	1995	-1.7	0.8
Aberdeen	1995	+1.8	1.9
Lerwick	1996	-1.1	0.9

Table 5. Absolute gravity station results summary.

5 Conclusions and Recommendations

It has been shown that the procedures developed for making absolute gravity measurements to the highest international standards have successfully been used to determine vertical land movements at the 3 core UK tide gauges. Within the error estimates, the vertical velocities are in agreement with models of large scale land movements due to post-glacial rebound and subsidence.

It is recommended that the absolute gravity measurements should be continued in order to obtain longer time series, so that the error bars in the vertical velocities can be reduced to a few tenths of mm per year. The absolute gravity results will play an important role in the assessment of any systematic biases in the vertical velocities determined from GPS.

References

Altamimi, Z, and Sillard, P, and Boucher, C, 2002. ITRF2000: A new release of the International Terrestrial Reference Frame for Earth science applications. *Journal of Geophysical Research,* 107 (B10), 2214, doi:10.1029/2001JB000561.

Ashkenazi, V, Beamson, G A, Bingley, R M, Dodson, A H, and Baker, T F, 1994. The determination of tide gauge heights using GPS. *POL Internal Document No 75,* August 1994.

Ashkenazi, V, Bingley, R M, Dodson, A H, Penna, N T, and Baker, T F, 1997. The determination of tide gauge heights using GPS (Second Report). *POL Internal Document No 125,* August 1994.

Bingley, R M, Dodson, A H, Penna, N T, and Teferle, F N, 2000. The determination of tide gauge heights using GPS (Third Report). *Report to the Proudman Oceanographic Laboratory and the University of Nottingham's contribution to the Final Report for MAFF R&D Project FD0305*, May 2000.

Bingley, R M, Dodson, A H, Teferle, F N, Penna, N T, and Baker, T F, 2001a. GPS monitoring of changes in ground level for flood and coastal defence. *Proceedings of the 36th DEFRA (MAFF) Conference of River and Coastal Engineers,* Keele, UK, June 2001, 12 pp.

Bingley, R M, Dodson, A H, Teferle, F N, Penna, N T, and Baker, T F, 2001b. Monitoring the vertical land movement component of changes in mean sea level using GPS: Results from tide gauges in the UK. *Journal of Geospatial Engineering, Vol* 3, Number 1, June 2001, ISSN 1563-3772, pp 9-20.

Bingley, R M, Dodson, A H, Penna, N T, and Baker, T F, 2002. Using a 'GPS/MSL geoid' to test geoid models in the UK. Vertical Reference Systems, Edited by Drewes, *International Association of Geodesy Symposia*, Vol 124, Springer-Verlag, August 2002, ISBN 3-540-43011-3, pp 197-202.

Boucher, C, Altamimi, Z, Feissel, M, and Sillard, P, 1996. Results and analysis of the ITRF94. *International Earth Rotation Service (IERS) Technical Note 20,* Observatoire de Paris.

Boucher, C, Altamimi, Z, and Sillard, P, 1998. Results and analysis of the ITRF96. *International Earth Rotation Service (IERS) Technical Note 24,* Observatoire de Paris.

Boucher, C, Altamimi, Z, and Sillard, P, 1999. Results and analysis of the ITRF97. *International Earth Rotation Service (IERS),* Observatoire de Paris.

Charles, K, and Hipkin, R G, 1995. British Precise Gravity Network 1993. Gravity and Geoid, Edited by Sunkel and Marson, *International Association of Geodesy Symposia*, Vol 113, Springer-Verlag, pp 39-45.

Dong, X, Woodworth, P L, Moore, P and Bingley, R M, 2002. Absolute calibration of the TOPEX/POSEIDON altimeters using UK tide gauges, GPS and precise, local geoid differences. *Marine Geodesy*, 25(3), pp 189-204.

Hipkin, R G, Haines, K, Beggan, C, Bingley, R M, Hernandez, F, Holt, J, and Baker, T F, 2003. The geoid EDIN2000 and mean sea surface topography around the British Isles. *Geophysical Journal International* (in press).

IGSCB, 2003. IGSCB ftp archive [online]. ftp://igscb.jpl.nasa.gov/igscb/station/general/igs_01.pcv [Last accessed on 14 March 2003].

Le Provost, C, Genco, M L, Lyard, F, Vincent, P, and Canceil, P, 1994. Spectroscopy of the world ocean tides from a finite element hydrodynamic model. *Journal of Geophysical Research,* 99, C12, pp 24,777-24,797.

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

Niebauer, T M, Sasegawa, G S, Faller, J E, Hilt, R, and Klopping, F, 1995. A new generation of absolute gravimeters, *Metrologia,* 32, 159-180.

Niell, A E, 1996. Global mapping functions for the atmospheric delay at radio wavelengths. *Journal of Geophysical Research,* Vol 101, No B2, pp 3227-3246.

Saastamoinen, S, 1973. Contributions to the theory of atmospheric refraction. *Bulletin Geodesique,* in three parts; 105 pp 279-298, 106 pp 383-397, 107 pp 13-34.

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

Shennan, I, and Horton, B, 2002. Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science,* 17 (5-6), pp 511-526.

Stewart, M P, Ffoulkes-Jones, G H, Chen, W, Ochieng, W Y, Shardlow, P J, Penna, N T, and Bingley, R M, 2003. GPS Analysis Software (GAS) Version 2.4 User Manual. *IESSG Publication,* University of Nottingham.

Teferle, F N, 2003. Strategies for the long-term monitoring of tide gauges using GPS. PhD Thesis, University of Nottingham.

Teferle, F N, Bingley, R M, Dodson, A H, Apostilidis, P, and Staton, G, 2003. RF interference and multipath effects at continuous GPS installations for long-term monitoring of tide gauges in UK harbours. *Proceedings of ION-GNSS 2003,* the 16th International Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, USA, September 2003.

Teferle, F N, Bingley, R M, Dodson, A H, and Baker, T F, 2002b. Application of the dual-CGPS concept to monitoring vertical land movements at tide gauges. *Physics and Chemistry of the Earth,* Vol 27, Issue 32-34, pp 1401-1406.

Teferle, F N, Bingley, R M, Dodson, A H, Baker, T F, and Williams, S D P, 2001. Evaluation of the dual-CGPS concept to monitoring vertical land movements at tide gauges. *Book of Extended Abstracts of the Final Workshop of European COST Action 40, European Sea Level Observing System (EOSS),* Sea Level in Europe: Observation, Interpretation and Exploitation, Dubrovnik, Croatia, September 2001, pp 40-43.

Teferle, F N, Bingley, R M, Dodson, A H, Penna, N T, and Baker, T F, 2002a. Using GPS to separate crustal movements and sea level changes at tide gauges in the UK.. Vertical Reference Systems, Edited by Drewes, *International Association of Geodesy Symposia,* Vol 124, Springer-Verlag, August 2002, ISBN 3-540-43011-3, pp 264-269.

Willams, S D P, Baker, T F, and Jeffries, G, 2001. Absolute gravity measurements at UK tide gauges. *Geophysical Research Letters,* 28, pp 2317-2320.

Williams, S D P, 2003a. The effect of coloured noise on the uncertainties of rates estimated from geodetic time series. *Journal of Geodesy,* 76 (9-10), pp 483-494, doi:10.1007/s00190-002-0283-4.

Williams, S D P, 2003b. Offsets in Global Positioning System time series. *Journal of Geophsyical Research,* Vol 108 B6, 2310, doi: 10.1029/2002JB002156.

Williams, S D P, Nikolaidis, R M, Bock, Y, Fang, P, Miller, M, and Johnson, D, 2003. MLE error analysis of global and regional continuous GPS time series. *Journal of Geophsyical Research (in press).*

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, pp 651-670.