Using continuous GPS and absolute gravity to separate vertical land movements and changes in sea-level at tide-gauges in the UK

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Researchers investigating climate change have used historical tide-gauge measurements from all over the world to investigate the changes in sea-level that have occurred over the last century or so. However, such estimates are a combination of any true sea-level variations and any vertical movements of the land at the specific tide-gauge. For a tide-gauge record to be used to determine the climate related component of changes in sea-level, it is therefore necessary to correct for the vertical land movement component of the observed change in sea-level.

In 1990, the Institute of Engineering Surveying and Space Geodesy and Proudman Oceanographic Laboratory started developing techniques based on the Global Positioning System (GPS) for measuring vertical land movements (VLM) at tide-gauges in the UK. This paper provides brief details of these early developments and shows how they led to the establishment of continuous GPS (CGPS) stations at a number of tide-gauges. The paper then goes on to discuss the use of absolute gravity (AG), as an independent technique for measuring VLM at tide-gauges. The most recent results, from CGPS time-series dating back to 1997 and AG time-series dating back to 1995/1996, are then used to demonstrate the complementarity of these two techniques and their potential for providing site-specific estimates of VLM at tide-gauges in the UK.

Keywords: continuous global positioning system; absolute gravity; tide gauge; vertical land movements; changes in sea-level

1. Introduction

In 1990, 1995 and 2001, the Intergovernmental Panel on Climate Change (IPCC) reviewed the published evidence on the influence of global warming on sea-levels (IPCC 1990, 1995, 2001). They found that global sea-level had risen by 10–20 cm over the past century, with predictions indicating further rises of the order of up to a metre by 2100. The evidence for the past century came from mean sea-level (MSL) measurements obtained at tide-gauges, which measure MSL with respect to

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to a local tide-gauge bench mark (TGBM). It is generally accepted that a high quality tide-gauge record can enable the secular change of MSL to be estimated with an acceptable level of uncertainty if 50 years or more of data are used. However, to measure the climate related component of changes in sea-level using a tide-gauge, the rate of any vertical land movements (VLM) at the specific tide-gauge must be determined.

In some parts of the world it is possible to make this correction based on models of glacial isostatic adjustment (GIA). However, GIA does not account for all of the VLM occurring at all of the tide-gauges in the world. The GPS came into operation in the 1980s. Although this system was primarily designed for use in navigation, the potential to determine and monitor the heights of TGBMs at a workshop held at the Woods Hole Oceanographic Institute, USA (Carter et al. 1989). The ‘IAPSO Committee’ recommended that TGBMs should be connected to the International Terrestrial Reference Frame (ITRF) and monitored through episodic GPS campaigns, with simultaneous measurements made at tide-gauges and fundamental ITRF stations (Baker 1993). This meeting ‘spawned’ the first demonstrations of using GPS at tide-gauges, through national projects such as UKGAUGE (Ashkenazi et al. 1993), which included the first GPS measurements at tide-gauges in the UK, and regional projects such as EUROGAUGE (Ashkenazi et al. 1994) and SELF I (Zerbini et al. 1996).

In the years that followed the ‘Woods Hole meeting’ there were significant advances in GPS technology, with cheaper and more reliable GPS receivers available, the completion of the GPS satellite constellation and the establishment of the International GPS Service (IGS) (Zumberge et al. 1997). Hence, at a second workshop held at the Institute of Oceanographic Sciences, UK in 1993, the ‘IAPSO Committee’ recommended that continuous GPS (CGPS) stations should be installed at about 100 tide-gauges worldwide. The objective was to form a core network of a ‘global absolute sea-level monitoring system’, with regional densification of this core network carried out, through episodic GPS campaigns or the use of CGPS (Carter 1994). Although this core network was never realized, through the IGS, GPS was firmly established as a technique to sit alongside Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) in the realization of the International Terrestrial Reference System (ITRS). This could clearly be seen from the number of CGPS stations that contributed to successive realizations of the ITRS, which increased from about 50 in ITRF93 to over 200 in ITRF97 (Boucher et al. 1994, 1999). Nowadays, in the most recent realization of the ITRS, the ITRF2000 (Boucher et al. 2004), CGPS plays an important role in the definition of the global velocity field, with over 350 stations.

Going back to 1997, the advantages of using CGPS instead of episodic GPS had been demonstrated on a global scale by the IGS (Zumberge et al. 1997) and on a regional scale, e.g. in Fennoscandia (BIFROST 1996). The specific use of CGPS at tide-gauges was discussed further at a third workshop held at the Jet Propulsion Laboratory in 1997, which was jointly organized by the IGS and the Permanent Service for Mean Sea-level (PSMSL) (Neilan et al. 1997). At this ‘IGS/PSMSL meeting’ the first experiences of using CGPS at tide-gauges were
reported; from Sheerness in the UK (Ashkenazi et al. 1997), Solomons Island in the Chesapeake Bay (Nerem et al. 1997) and Porto Corsini in the Mediterranean (Zerbini 1997).

Since 1997, the Institute of Engineering Surveying and Space Geodesy (IESSG) and Proudman Oceanographic Laboratory (POL) have been using CGPS to measure the VLM at or close to tide-gauges in the UK, with a current network of seven CGPS stations, about to expand to 13 over the next year. However, the use of GPS at tide-gauges has proven to be not as straightforward as perhaps first imagined back in 1988. There are many issues to be considered when trying to monitor VLM of millimetres per year, in order to decouple these from the true sea-level variations in tide-gauge records. All of these issues effectively relate to the accuracy and precision of the vertical station velocity estimates.

In terms of precision, it is essential that a realistic uncertainty is assigned to any estimate. Zhang et al. (1997) and Mao et al. (1999) and recently Williams et al. (2004) showed that CGPS coordinate time-series contain both white noise and coloured noise. The result being that station velocity uncertainties may be underestimated by an order of magnitude if correlations in the form of coloured noise are not accounted for. Maximum-likelihood estimation (MLE) allows precise stochastic models to fit CGPS coordinate time-series, while simultaneously estimating linear trend, periodic signals and coordinate offsets. Such techniques have been applied when analysing the coordinate time-series for the CGPS stations at or close to tide-gauges in the UK, as detailed in §2 of this paper.

In terms of accuracy, the role of absolute gravity (AG) is proving critical. Although mentioned in the report from the ‘Woods Hole meeting’ (Carter et al. 1989), the cost of instrumentation and the field effort required, when compared to GPS, meant that there was very little activity in terms of the use of AG at tide-gauges until the mid 1990s, i.e. about 5 or 6 years after the first use of episodic GPS and almost coincident with the introduction of CGPS. Fortunately, in the UK, AG measurements were started close to three tide-gauges in 1995 and 1996, as detailed in Williams et al. (2001). As this paper shows, this has enabled an assessment of the vertical station velocity estimates based purely on CGPS and a demonstration of how CGPS and AG may be combined to obtain better estimates of the desired VLM.

2. CGPS at or close to tide-gauges in the UK

In this section, details of the CGPS network, the CGPS processing strategy and the CGPS coordinate time-series analysis strategies are given.

(a) The CGPS network

During the period from 1997 to 1999, the IESSG and POL established CGPS stations at five tide-gauges in the UK, namely Sheerness, Newlyn, Aberdeen, Liverpool and Lowestoft. The CGPS stations were installed such that the GPS antennas were sited as close as possible to the tide-gauge, i.e. within a few metres of the tide-gauge itself. A further two CGPS stations were established at the tide-gauges of North Shields and Portsmouth in 2001. An earlier study (Sanli & Blewitt 2001) claimed to detect uplift of the tide-gauge in North Shields by analysing episodic and six months of continuous GPS data collected over a period.
of only 2.5 years. Teferle et al. (2003), however, showed that GPS data from this station are affected by severe radio frequency interference, and that a much longer observation period will be needed in order to form any conclusions on the vertical movements of that tide-gauge. Therefore, neither North Shields nor Portsmouth have been used in this study, which has focussed on those CGPS stations with the longest, good quality, continuous time-series.

During 1998, several other CGPS stations were established by the IESSG and the Met Office, for the purpose of estimating integrated precipitable water vapour. One of these was on the Shetland Islands, located about 5 km from the tide-gauge at Lerwick. This means that it is not monitoring the vertical movements of the land at that specific tide-gauge, but with the GPS antenna mounted on a survey monument connected to ‘solid rock’, it should be monitoring any underlying geophysical movements in that area. To complement the five CGPS stations listed above, the CGPS station at Lerwick and the CGPS station at the Brest tide-gauge in northern France have also been used in this study, making a total of seven CGPS stations at or close to tide-gauges (see figure 1).

(b) CGPS processing and coordinate time-series

The processing for all of the CGPS stations shown in figure 1 has been carried out using the GPS analysis software (Stewart et al. 2002), which was developed at the IESSG and uses the double-difference observable. The results presented in this study are based on 24 h, dual frequency GPS data for the period up to
December 2003. All CGPS data were processed along with data from IGS stations at Kootwijk, Onsala, Villafranca and Wettzell. As a result, a series of loosely constrained daily solutions was obtained, with no stations fixed. These daily solutions used the IGS final ephemeris, the ionospherically free observable, no integer fixing of phase ambiguities, the estimation of tropospheric zenith delay parameters at 15 min intervals, the IGS antenna phase centre variation models

Figure 2. CGPS common-mode filtered ITRF2000 height time-series and vertical station velocity estimates based on a maximum-likelihood estimation (MLE) using a white plus power-law noise model. In this figure, $T$ is time-period, SHEE is Sheerness, LERW is Lerwick, NEWL is Newlyn, ABER is Aberdeen, LIVE is Liverpool, LOWE is Lowestoft and BRST is Brest. The vertical dashed lines represent times at which coordinate offsets were estimated.

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and corrections for both solid Earth tides and ocean tide loading according to International Earth Rotation Service standards (McCarthy 1996). In order to form consistent coordinate time-series for each of the CGPS stations, each loosely constrained daily solution was then constrained at the observation epoch, based on the ITRF2000 coordinates and velocities of the above IGS stations.

(c) CGPS coordinate time-series analysis

For the CGPS coordinate time-series, residual systematic effects due to unmitigated tropospheric delay, antenna phase centre variations or loading processes, can remain in the daily height estimates. Furthermore, biases in the realization of the ITRF and in the satellite orbits can also propagate into these height solutions, and these may depend on the selection of the IGS stations that are constrained. Not only do these effects increase and change the stochastic properties of the noise level (Zhang et al. 1997; Mao et al. 1999; Williams et al. 2004), but they may also introduce artificial signals at the several millimetre-level in the height time-series (Herring 2001; Altamimi et al. 2002; Dong et al. 2002).

Taking these facts into account, in order to obtain vertical station velocity estimates and realistic uncertainties from the CGPS results, the following multi-step coordinate time-series analysis strategy has been carried out (Teferle 2003):

(i) Computation of residual geocentric coordinate time-series by removal of a linear trend from the outlier-cleaned, daily ITRF2000 geocentric coordinate time-series.

(ii) Computation of the common mode bias using weighted stacking of the daily geocentric coordinate residuals.

(iii) Filtering of the daily ITRF2000 geocentric coordinate time-series by removal of the daily common mode bias, which has a periodic signal over annual and semi-annual time periods.

(iv) Transformation of the filtered geocentric coordinate time-series to filtered topocentric coordinate time-series.

(v) A MLE of the filtered, daily ITRF2000 height time-series to simultaneously obtain estimates for a linear trend, annual signals, coordinate offsets and noise parameters.

The method of weighted stacking is essentially equivalent to a similarity transformation using only the three translation parameters. By filtering the height time-series, periodic spatial correlations in the regional CGPS network solutions are removed, improving the signal-to-noise ratio, which is especially important for the height component (Wdowinski et al. 1997; Nikolaidis 2002; Wdowinski et al. 2004; Williams et al. 2004). Furthermore, for the estimation of realistic uncertainties it is important to understand the time-correlated (coloured) noise content of height time-series, as the often quoted statistical uncertainties, assuming time-uncorrelated (white) noise, can lead to largely optimistic error bounds (Zhang 1997; Langbein & Johnson 1997; Mao 1999). By using MLE, precise stochastic models have been fitted to the time-series and the noise parameters have been estimated based on a white plus power-law noise model (Williams 2003; Williams et al. 2004).

The resulting coordinate time-series are shown in figure 2.
Comparison of vertical station velocity estimates

In Figure 2, and throughout the paper, all uncertainty values quoted are $1 - \sigma$. As can be seen from Figure 2, all of the CGPS vertical station velocities are positive or zero and their uncertainties are in the range from $\pm 0.2$ to $\pm 0.7$ mm yr$^{-1}$. A comparison of the CGPS vertical station velocities to values previously published is possible for Brest. For Brest, Sella et al. (2002) and Boucher et al. (2004) reported values of $-4.2 \pm 3.4$ and $-3.4 \pm 2.3$ mm yr$^{-1}$, respectively. In both cases the large uncertainties are indicative of a much shorter observation time span compared to this analysis and the magnitude of subsidence is clearly not supported by the MSL trend for Brest, which is $1.0 \pm 0.1$ mm yr$^{-1}$ (PSMSL 2001).

3. Absolute gravity close to tide-gauges in the UK

Proudman Oceanographic Laboratory began to make AG measurements near the tide-gauges at Newlyn and Aberdeen in 1995 and at Lerwick in 1996 (Williams et al. 2001). These measurements are being made with the POL absolute gravimeter FG5-103, manufactured by Micro-g Solutions, Inc., USA. A value of gravity is obtained every 10 s by dropping a test mass in a vacuum and using an iodine stabilized He–Ne laser interferometer and rubidium atomic clock to obtain distance–time pairs and solve the equations of motion (Niebauer et al. 1995). Absolute gravity measurements are taken for typically 3–4 days every year at each site. The sites were chosen to be on bedrock and FG5-103 is regularly intercompared with other instruments in Europe and the USA to ensure that it gives consistent results at the 1–2 $\mu$gal level (Williams et al. 2001).

The time-series of AG values at Newlyn and Lerwick are of particularly high quality and are used in the present work (see Figure 3). The uncertainties in the linear trends have been determined by combining an instrumental set-up error with a Gauss–Markov model for the coloured noise (Van Camp et al. 2004).

4. Vertical land movements comparison

For the British Isles, a number of alternative, high quality and independent evidence of VLM have been published. These data include estimates based on: geological information (Shennan & Horton 2002), styled as GEOL; the negative of the difference between the MSL trend measured by the tide-gauge at each site (Woodworth et al. 1999; PSMSL 2001) and an assumed global sea-level rise of $1.5$ mm yr$^{-1}$, styled as $-(\text{MSL–GSL})$; glacial isostatic adjustment models, e.g. Lambeck & Johnston (1995) and Peltier (2001), styled as GIA L and GIA P, respectively. Table 1 and Figure 4 show the independent estimates along with the values obtained from CGPS and AG.

From Table 1, it is clear that there is generally good agreement between the estimates of VLM based on geology, tide-gauges and GIA models, at all sites except Brest and Lerwick. Taking the estimates based on AG into account, these would seem to suggest that the anomaly at Lerwick is in the tide-gauge measurements, which only began in the 1960s and show a fall of MSL from the 1960s to 1990s.

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From figure 4, however, it is also clear that the CGPS estimates of VLM are systematically offset from the AG estimates of VLM and from the estimates of VLM from the other independent evidence. It would appear that the AG estimates of VLM are closely aligned to the estimates of VLM from geology and GIA models. Whereas, the CGPS estimates are in the range of 0.3–1.7 mm yr\(^{-1}\).

Table 1. Vertical land movements comparison. All figures shown are in mm yr\(^{-1}\).

<table>
<thead>
<tr>
<th>Station</th>
<th>CGPS</th>
<th>AG</th>
<th>GEOL</th>
<th>(-(\text{MSL–GSL}))</th>
<th>GIA L</th>
<th>GIA P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheerness</td>
<td>0.2±0.3</td>
<td>—</td>
<td>−0.7</td>
<td>−0.6</td>
<td>−0.5</td>
<td>−0.2</td>
</tr>
<tr>
<td>Newlyn</td>
<td>0.0±0.5</td>
<td>−0.5±0.9</td>
<td>−1.1</td>
<td>−0.2</td>
<td>−1.0</td>
<td>−0.3</td>
</tr>
<tr>
<td>Aberdeen</td>
<td>1.0±0.2</td>
<td>—</td>
<td>0.7</td>
<td>0.8</td>
<td>0.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Lerwick</td>
<td>0.5±0.7</td>
<td>−1.1±1.1</td>
<td>—</td>
<td>2.5</td>
<td>−1.8</td>
<td>−0.5</td>
</tr>
<tr>
<td>Liverpool</td>
<td>1.5±0.4</td>
<td>—</td>
<td>−0.2</td>
<td>0.1</td>
<td>−0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Lowestoft</td>
<td>1.0±0.4</td>
<td>—</td>
<td>−0.6</td>
<td>−0.5</td>
<td>−0.5</td>
<td>−0.4</td>
</tr>
<tr>
<td>Brest</td>
<td>0.6±0.3</td>
<td>—</td>
<td>—</td>
<td>0.5</td>
<td>−0.9</td>
<td>−0.3</td>
</tr>
</tbody>
</table>

From figure 4, however, it is also clear that the CGPS estimates of VLM are systematically offset from the AG estimates of VLM and from the estimates of VLM from the other independent evidence. It would appear that the AG estimates of VLM are closely aligned to the estimates of VLM from geology and GIA models. Whereas, the CGPS estimates are in the range of 0.3–1.7 mm yr\(^{-1}\).

Figure 4. Vertical land/crustal movement estimates for seven continuous Global Positioning System stations close to or at tide-gauge sites in the UK and northern France compared to alternative evidence for vertical land movements. 1–σ uncertainties are shown where available.
greater than the geology estimates, 0.7–2.3 mm yr\(^{-1}\) greater than the GIA L estimates and 0.3–1.4 mm yr\(^{-1}\) greater than the GIA P estimates.

Similar offsets of CGPS estimates of VLM from independent evidence have also recently been reported by Prawirodirdjo & Bock (2004) and MacMillan (2004). From the analysis of a global CGPS network, Prawirodirdjo & Bock (2004) showed average offsets between CGPS and GIA P of 1.1 mm yr\(^{-1}\) for stations in North America and 1.7 mm yr\(^{-1}\) for stations in northern Europe. Separately, in a comparison of VLBI and CGPS, MacMillan (2004) showed the CGPS estimates to be on average 1.5 mm yr\(^{-1}\) greater than the VLBI estimates.

In considering the nature of the offsets apparent in our CGPS estimates, it is worth noting that the various sources of independent evidence have their own ‘reference frames’, e.g. the GIA L and GIA P estimates are based on GIA models for the last 10 000 years, and are referred to a ‘Centre of mass of the Solid Earth’ reference frame, and the geology estimates are based on changes in sea-level for the last 10 000 years, assuming no net global melting for the last 3000 to 4000 years.

The ITRF2000 reference frame, to which our CGPS solutions are aligned, has an origin that is defined as the ‘Centre of Mass of the Earth System’, based on SLR. However, the CGPS estimates given in this paper are effectively referenced to their own realization of the ITRF2000 reference frame and, hence, their own definition of centre of mass (CM), which depends mostly on the sub-set of IGS stations constrained in ITRF2000, partly on the fact that the IGS final orbit is in its own reference frame that is not exactly in ITRF2000 and partly due to subtle changes caused by the common-mode filtering carried out as part of the CGPS coordinate time-series analysis (Wdowinski et al. 2004). Hence, the CGPS estimates of VLM could be offset from the ‘truth’ because the reference frame of the regional network solutions is not identical to ITRF2000, and because the origin of ITRF2000 varies with respect to the true CM (Dong et al. 2003). Recent presentations made within the IGS community have also suggested that a scale rate bias is present in CGPS estimates of VLM due to the current use of relative, and not absolute, phase centre variation corrections for both satellites and receivers.

5. Combining CGPS and AG for tide-gauges in the UK

Using weighted least-squares and data for Newlyn and Lerwick it is possible to compute an offset of 1.0 ± 0.8 mm yr\(^{-1}\) between the VLM estimates based on CGPS and those based on AG. The uncertainty in the offset from this limited data set is quite large, due mainly to the large uncertainties in the AG measurements. Therefore, the systematic nature of the offset cannot be confirmed at this stage, although it is still worth noting that the separate values of 0.5 and 1.6 mm yr\(^{-1}\) are both positive.

This positive offset is consistent with that found in the comparisons between CGPS and the other independent evidence, both in this paper and, e.g. Prawirodirdjo & Bock (2004) and MacMillan (2004). At this stage, therefore, the combination of CGPS and AG for tide-gauges in the UK has been effected by ‘aligning’ the CGPS estimates of VLM to the AG estimates.

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Computing a sea-level rise

The relative MSL trends and the ‘AG-aligned CGPS estimates of VLM’ have been used to compute an estimate of sea-level rise for the British Isles. Figure 5 shows the relative MSL trends compared to the negative of the AG-aligned CGPS estimates of VLM.

The Lerwick tide-gauge measurements only began in the 1960s and show a fall of MSL, which appears to be an anomaly specific to this tide-gauge. Considering Sheerness, Newlyn, Aberdeen, Liverpool, Lowestoft and Brest, a sea-level rise of 1.1 ± 0.7 mm yr\(^{-1}\) is obtained. However, only using data for Sheerness, Newlyn, Aberdeen and Brest gives a sea-level rise of 0.6 ± 0.2 mm yr\(^{-1}\), and only using data from Liverpool and Lowestoft gives a sea-level rise of 1.9 ± 0.1 mm yr\(^{-1}\).

(a) Computing a sea-level rise

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6. The UK contribution to European and global initiatives

In Europe, Baker et al. (1997) first proposed a European network for sea and coastal land level monitoring. At about the same time, the ‘IGS/PSMSL meeting’ took place (Neilan et al. 1997) and working group 1 of the European Commission COST action 40: European sea-level observing system started to address the issues that relate to the use of CGPS at tide-gauges (Plag et al. 2000). Ultimately, these have led to two definitive actions: on a European scale, ESEAS—the European Sea-level Service (www.eseas.org); and on a global scale, IGS TIGA—the IGS GPS Tide Gauge Benchmark Monitoring Pilot Project (op. gfz-potsdam.de/tiga/). Of the CGPS@TG stations in Britain that are detailed in this paper, all have contributed data from 1 January 2000 onwards to ESEAS and three (namely Newlyn, Sheerness and Aberdeen) have contributed all of their data to IGS TIGA.
This paper provides details of the research that is on-going in relation to the use of CGPS and AG for measuring VLM at tide-gauges in the UK. The most recent results, from CGPS time-series dating back to 1997 and AG time-series dating back to 1995/6, have been used to demonstrate the complementarity of these two techniques, and a series of AG-aligned CGPS estimates of VLM have been computed for seven tide-gauges. An initial comparison between these estimates of VLM and changes in relative MSL observed by the tide-gauges, suggests a sea-level rise around the British Isles of between 0.6 and 1.9 mm yr\(^{-1}\). Clearly, the statistical significance of such results cannot be assured as yet, due to the level of the uncertainties in the CGPS and AG time-series. However, these should reduce as the time-series are extended into the future.

It has recently been argued that studies of VLM and sea-level changes at tide-gauges are best performed on regional scales and more importantly only in a relative sense \textit{(Caccamise \textit{et al.} 2005)}, due to the reference frame issues discussed above. However, the alignment procedure demonstrated in this paper has been shown to have the potential for determining site-specific VLM at tide-gauges, by using a combination of CGPS and AG. Furthermore, the procedure enables multiple CGPS stations to be deployed without the need for simultaneous AG measurements at each site.

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