MEASURING CHANGES IN GROUND LEVEL AT TIDE GAUGES, USING CONTINUOUS GPS AND ABSOLUTE GRAVIMETRY, TO IMPROVE ESTIMATES OF CHANGES IN SEA LEVEL AROUND BRITAIN

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Key Words: tide gauge, continuous GPS, absolute gravimetry, sea level, Britain

Abstract: Researchers studying 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 changes in ground level 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 necessary to correct for any changes in ground level. The development of geodetic techniques for monitoring changes in ground level at British tide gauges has been on-going at the IESSG and POL since 1990, based on research funded by both Defra and the Environment Agency. Since 1996, this research has focused on the establishment of continuous GPS (CGPS) stations and the use of absolute gravimetry (AG), as independent geodetic techniques for measuring changes in ground level. This paper details the results of Defra/EA R&D project FD2319, which is part of the Risk Evaluation and Understanding of Uncertainty Theme. The paper shows how CGPS and AG have been used on a national scale to monitor changes in ground level at tide gauges and obtain estimates of changes in sea level, decoupled from changes in ground level.

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, e.g. Church et. al. (2001). They found that global sea level had risen by 10 to 20cm over the past century, with predictions indicating further rises of the order of up to a metre by 2100. Recent studies of 20th century sea level from combined tide gauge and satellite altimetry measurements showed a global averaged rise in sea level of 1.7 to 1.8mm/yr (Church et. al. 2004; Holgate and Woodworth 2004; White et. al. 2005, Church and White 2006). Much of the evidence for the past century came from mean sea level (MSL) measurements obtained at tide gauges, which measure MSL with respect 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 30 to 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 changes in ground level at the specific tide gauge must be accounted for. In some parts of the world it is possible to make this correction based on models of glacial isostatic adjustment (GIA), e.g. Lambeck and Johnston (1995) and Peltier (2001). However, GIA does not account for all of the changes in ground level occurring at all of the tide gauges in the world.

In Britain, estimates of changes in ground level, due to GIA and compaction, were presented by Shennan (1989) and Shennan and Horton (2002) based on geological studies. Woodworth et. al. (1999) used the then latest estimates to show that for a small number of very long British Isles tide gauge records, the changes in sea level (decoupled from changes in ground level) were consistent with a 20th Century change in sea level of the order of 1mm/yr. More recently, the UK Climate Impact Programme (UKCIP) produced a table of net sea-level change using values of regional changes in ground level, based on Shennan and Horton (2002), and the global sea-level changes predicted by the IPCC (UKCIP 2005).

In all of these studies, evidence or models of changes in ground level that have occurred over the past 16,000 years are used to calculate estimates of current changes in ground level and it is then assumed that these represent the changes in ground level that have occurred at the tide gauges for the past few decades and will continue to occur at the tide gauges for the next few decades.

As an alternative to the use of GIA models and geological information, the IESSG and POL have developed geodetic techniques for using continuous GPS (CGPS) and absolute gravimetry (AG) at or close to tide gauges to obtain site-specific, direct estimates of current changes in ground level. These estimates of changes in ground level are an estimate of the total change, including GIA, natural and man-made compaction and any local, engineering movements of the structure that supports the tide gauge. The aim of using such techniques is to provide a direct measure of the current changes in ground level that will enable a tide gauge to be better used for studying the climate related component of changes in sea level.

When considering the changes in sea level that have occurred over the past few decades, the geodetic estimates of changes in ground level are treated in a similar way to the GIA models and geological information. In this way, the direct estimates of current changes in ground level are assumed to represent the changes in ground level that have occurred at the tide gauges for the past few decades. In the future, as more concurrent data is obtained for both the tide gauge records and the changes in ground level, together these should lead to a more direct indication of the climate related component of changes in sea level. This will be particularly important over the next few decades, when such estimates will be extremely useful for validating the various climate models that lead to the range of global sea-level changes predicted by the IPCC. Notable here is the fact that the recent studies of 20th century sea level from combined tide gauge and satellite altimetry also identified that sea level was not rising at the same rate everywhere, but was, e.g. slower in the East Atlantic and North Sea than in the West Atlantic (Church et. al. 2004; Holgate and Woodworth 2004).

At a previous Defra conference, Bingley et. al. (2001) reported on the establishment of the first five CGPS stations at tide gauges in Britain and showed the first vertical station velocity estimates for these. Williams et. al. (2001) discussed the establishment of three AG sites close to tide gauges in Britain and reported on their initial results. Since then, the IESSG and POL have set up six more CGPS stations at tide gauges in Britain and a detailed summary of the CGPS and AG results obtained up to the end of 2003 was given in Teferle et. al. (2006). This paper presents an update from Teferle et. al. (2006) and includes the latest estimates of changes in ground level and sea level from this research.

CGPS MEASUREMENTS AND ANALYSIS

During the period from 1997 to 2005, the IESSG and POL have established CGPS stations at ten tide gauges in Britain, namely Sheerness, Newlyn, Aberdeen, Liverpool, Lowestoft, North Shields, Portsmouth, Lerwick, Stornoway and Dover. All of these CGPS@TG stations were established such that the GPS antennas were sited as close as possible to the tide gauge, i.e. within a few meters of the tide gauge itself. As the CGPS@TG stations Lerwick, Stornoway and Dover were only established in late 2005, no results from these are presented here; however, at Lerwick, data from a CGPS station, established in 1998 on bedrock about 5km from the tide gauge, have been used. The processing of data for the eight CGPS stations considered was carried out using the IESSG's GPS Analysis Software (Stewart et. al. 2002). The results presented in this study are based on 24-hour, dual frequency GPS data for the period up to November 2004. The CGPS data from Britain were processed along with data from stations in Europe, which form part of the International GNSS Service (IGS) global network, to produce coordinate time series for each of the stations in the International Terrestrial Reference Frame 2000. These time series have then been analysed using POL's CATS software (Williams 2003) to obtain accurate vertical station velocity estimates and realistic uncertainties, using Maximum-Likelihood estimation (MLE) to compute a linear trend, periodic signals, coordinate offset magnitudes and stochastic noise parameters in a single process (Williams et. al. 2004). Further details of this processing and analysis can be found in Teferle et. al. (2006).

AG MEASUREMENTS AND ANALYSIS

POL 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 10s 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. AG measurements are taken for typically 3 to 4 days every year at each site. The sites were chosen to be on bedrock and FG5-103 is regularly inter-compared with other instruments in Europe and the USA to ensure that it gives consistent results at the 1 to 2 μgal level (Williams et. al. 2001). The time series of AG values at Newlyn and Lerwick are of particularly high quality and 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).

ESTIMATES OF CHANGES IN GROUND LEVEL AND SEA LEVEL

For Britain, a variety of high quality, independent evidence of changes in ground level have been published. These data include estimates based on: geological information (Shennan and Horton, 2002), denoted as GEOL; the negative of the difference between the MSL trend measured by the tide gauge at each site (PSMSL 2005) and the average sea level rise for Northern Europe of 1.5mm/yr (Holgate and Woodworth 2004), denoted as -(MSL-GSL); and the GIA models of Lambeck and Johnston (1995) and Peltier (2001), denoted as GIA L and GIA P respectively. Table 1 presents these independent estimates along with the values obtained from a combination of CGPS and AG, in which the CGPS estimates have been 'aligned' to the AG estimates in order to account for a systematic bias that is currently present in the vertical station velocity estimates from CGPS at this demanding, high level of accuracy.

Station	Station ID	CGPS&AG	GEOL	-(MSL-GSL)	GIA L	GIA P
Sheerness	SHEE	-1.0 ± 0.4	-0.7	-0.1	-0.5	-0.2
Lerwick	LERW	-1.1 ± 0.7		+2.3	-1.8	-0.5
Newlyn	NEWL	-0.5 ± 0.7	-1.1	-0.2	-1.0	-0.3
Aberdeen	ABER	+0.2 ± 0.7	+0.7	+0.6	0.0	+0.6
Liverpool	LIVE	0.0 ± 0.7	-0.2	+0.1	-0.3	+0.4
Lowestoft	LOWE	-1.1 ± 0.6	-0.6	-1.0	-0.5	-0.4
N. Shields	NSTG	0.0 ± 0.7	+0.2	-0.4	0.0	+0.4
Portsmouth	PMTG	-0.7 ± 0.5	-0.6	-0.3	-0.5	-0.1

Table 1: Comparison of estimates of changes in ground level for eight tide gauges. All figures shown are in mm/yr and the uncertainty values quoted are 1σ.

From Table 1, it is clear that there is generally good agreement between the estimates of changes in ground level based on geodetic measurements, geology, tide gauges and GIA models, at all sites except Lerwick.

Figure 1 shows the MSL trends from the tide gauge records and the negative of the emergence/submergence rates based on the geodetic measurements. In Figure 1, data points on the dashed line would imply a sea level rise (decoupled from changes in ground level) of 1.0mm/yr.

In both the Table and the Figure, the results would seem to suggest that the Lerwick tide gauge measurements, which only began in the 1960s and show a fall of mean sea level, are an anomaly specific to this tide gauge; this is currently under further investigation. Considering Sheerness, Newlyn, Aberdeen, Liverpool, Lowestoft, North Shields and Portsmouth, a sea level rise (decoupled from changes in ground level) of 1.3 ± 0.3mm/yr is obtained.

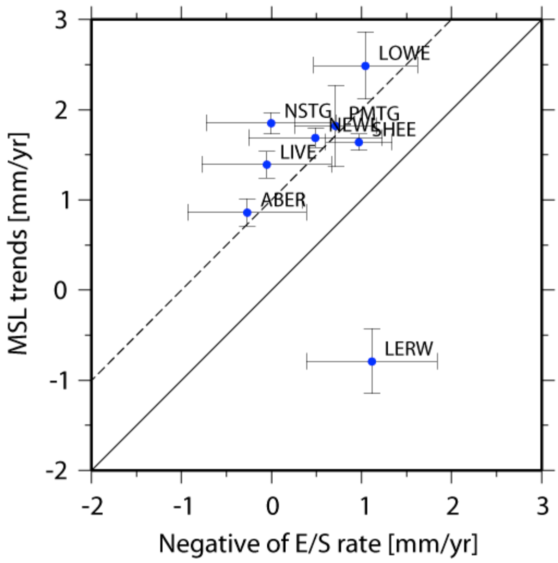

Figure 1: MSL trends for eight tide gauges compared with the negative of the emergence/submergence (E/S) rates based on CGPS and AG.

CONCLUSIONS

Results, from CGPS time series dating back to 1997 and AG time series dating back to 1995/6, have been used to compute geodetic estimates of current changes in ground level for eight tide gauges. An initial comparison between these estimates of changes in ground level and changes in MSL observed by the tide gauges, suggests a sea level rise (de-coupled from changes in ground level) for the past few decades of 1.3mm/yr around Britain. 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 will reduce if the time series are extended into the future, enabling the geodetic estimates to play a vital role in validating the various climate models that lead to the full range of global sea-level changes predicted by the IPCC.

ACKNOWLEDGEMENTS

This research was funded by Defra/EA R&D Project FD2319. The CGPS data were taken from BIGF - British Isles GPS archive Facility (www.bigf.ac.uk) funded by the Natural Environment Research Council (NERC).

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