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SID 5 Research Project Final Report

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Project identification

1. Defra Project code FD2319
2. Project title

Absolute Fixing of Tide Gauge Benchmarks and Land Levels

3. Contractor organisation(s)

Proudman Oceanographic Laboratory
Joseph Proudman Building
6 Brownlow Street
Liverpool

L3 5DA

4. Total Defra project costs (agreed fixed price) £ 579,375
5. Project: start date .... 01 October 2003

end date .... 31 December 2006

6. It is Defra's intention to publish this form.
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(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.

Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.

In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Since 1997, Defra and the Environment Agency (EA) have been funding research to measure long term changes in land and sea levels around the coast of Great Britain and in the 'Thames Region':

- to monitor current changes in land level due to land 'tilt' and regional/local geological effects;
- to improve estimates of climate driven changes in sea level based on tide gauges;
- to help in predicting future sea level rise;
- to carry out more refined regional studies to support planning for flood risk management for the Thames Estuary and River Thames.

The aims of these measurements are to obtain direct estimates of current changes in land level on the scale of millimetres per year, in a stable reference frame, both at tide gauges and at other specific locations, and to use these to obtain estimates of changes in sea level (decoupled from changes in land level) over the past few decades/past century. Such measurements represent a major challenge and the research carried out has essentially included three complementary monitoring techniques: the Global Positioning System (GPS); Absolute Gravimetry (AG); and Persistent Scatterer Interferometry (PSI).

From 2003 to 2006, the research work was carried out as a national study, funded by the Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme as FD2319, and a regional study, funded by the EA Thames Estuary 2100 project. The national study was carried out jointly by the Proudman Oceanographic Laboratory (POL) and the University of Nottingham's Institute of Engineering Surveying and Space Geodesy (IESSG). The regional study was led by IESSG and carried out jointly by IESSG, POL, Nigel Press Associates Ltd. (NPA) and the British Geological Survey (BGS). For the national study, continuous GPS (CGPS) stations have been established at ten tide gauges around the coast of Great Britain and AG measurements have been made at three of these. For the regional study, episodic GPS (EGPS) data from a network of stations in the Thames Region and PSI data for hundreds of thousands of persistent scatterer (PS) points in the Thames Region have been analysed and the changes in land level interpreted using various geoscience data sets.

A full, formal scientific report on the national and regional studies has been published as R&D Technical Report FD2319/TR and is available from Defra. This SID5 Research Project Final Report is focused on the national study; however, as the regional study was dependent on the national study, this report does make reference to the regional study, where appropriate.

The overall scientific objectives of the national study can be summarised as to:

- compute estimates of vertical station velocities for a national network of CGPS stations, through the processing of CGPS data and analysis of coordinate time series for the period from 1997 onwards;
- compute estimates of vertical station velocities for a national network of AG stations, through the processing of AG data and analysis of absolute gravity time series for the period from 1995 onwards;
- compute estimates of changes in land level at the national network of CGPS and AG stations, and estimates of changes in sea level (decoupled from changes in land level) at tide gauges around the coast of Great Britain;
- assess potential future changes in relative sea levels (i.e. referenced to the local land) around the coast of Great Britain.

The methods employed to meet these four scietific objectives are briefly described below.

During the period from 1997 to 2005, IESSG and POL established CGPS stations at ten of the 44 tide gauges which form the national tide gauge network. In chronological order, these were established at Sheerness, Newlyn, Aberdeen, Liverpool, Lowestoft, North Shields, Portsmouth, Lerwick, Stornoway and Dover tide gauges. All of these so-called ‘CGPS@TG stations’ were established such that the GPS receivers are housed in the same building as the tide gauge equipment and the GPS antennas are mounted on monuments, sited as close as possible to the tide gauge, i.e. within a few meters of the tide gauge itself; to fulfil the requirement to obtain site-specific, direct estimates of the changes in land level. For the national study, all archived daily observation data files for these CGPS@TG stations were collated along with similar data for International GNSS Service (IGS) stations on both a European and global scale to enable high accuracy positioning. Data from each day were processed separately in order to produce values for the station’s three-dimensional coordinates for each day, which were then used to form height time series from which an estimate of the vertical station velocity and uncertainty, were obtained.

For the AG research, POL began to make AG measurements near the tide gauges at Newlyn and Aberdeen in 1995 and at Lerwick in 1996. All of the measurements made to date have been obtained with the FG5-103 absolute gravimeter instrument owned by POL. The procedure adopted for the national study was to make near-annual, episodic AG measurements, with each set of measurements being carried out over at least three days, typically three to four days, and the absolute gravimeter instrument being carefully set up again at the start of each day. Data from each day were processed separately in order to produce one value of absolute gravity for each epoch, which were then used to form time series from which an estimate of the change of absolute gravity and its uncertainty, and the equivalent vertical station velocity and uncertainty, were obtained.

The vertical station velocities based on CGPS and AG measurements were then combined in order to obtain estimates of the changes in land level for eight of the 44 tide gauges which form the national tide gauge network. For each of these tide gauges, the changes in sea level based on monthly MSL data were obtained from the Permanent Service for Mean Sea Level (PSMSL) and combined with the changes in land level from the combination of CGPS and AG in order to compute estimates of the average change in sea level (decoupled from changes in land level) for the past few decades/past century around the coast of Great Britain.

The changes in land level, used to look at changes in sea level (decoupled from changes in land level) for the past few decades/past century, were also combined with future predictions of changes in global sea level to provide an assessment of future changes in relative sea levels (i.e. referenced to the local land). In this regard, the United Kingdom Climate Impacts Programme (UKCIP) has previously done this, using predictions of future changes in global sea level and changes in land level based on geological studies. For the national study, an alternative assessment was achieved by replacing the changes in land level based on geological studies by the changes in land level based on the combination of CGPS and AG.

The findings of the research are that the results for the national study demonstrate how:

- the combined CGPS and AG estimates of changes in land level correlate with long term geological and geophysical evidence for the ‘tilt’ of Great Britain, which have Scotland rising by 1 to 2mm/yr and the South of England subsiding by up to 1.2mm/yr.
- the combined CGPS and AG estimates of changes in land level are in general agreement with long term geological and geophysical evidence, in terms of whether there is subsidence or uplift at individual stations, although in some cases there are differences which are of the same order as the changes in land level themselves and are, therefore, significant in relation to any assumptions made regarding future changes in land level.
- when the combined CGPS and AG estimates of changes in land level are considered along with tide gauge data, two estimates for the average change in sea level (decoupled from changes in land level)

around the coast of Great Britain over the past few decades/past century can be obtained: the first, based on CGPS and AG data for the period up to the end of 2004, suggests that sea level has risen by 1.3mm/yr, and the second, based on CGPS data for the period up to the end of 2005 and AG data for the period up to September 2006, suggests that sea level has risen by 0.9 to 1.2mm/yr.

It has been clearly demonstrated, therefore, that the aims and objectives of the research work for the national study have been met as direct estimates of current changes in land level on the scale of millimetres per year, in a stable reference frame, both at tide gauges and at other specific locations, and estimates of changes in sea level (decoupled from changes in land level) over the past few decades/past century have been obtained through a novel method developed to best combine the information from CGPS and AG. However, as the estimates presented have formal uncertainties at about the 0.5 to 1.0mm/yr level, and potential systematic biases of the order of 0.5 to 1.0mm/yr, they can be used now, but do need to be treated with some caution.

Options for new work would include improving the confidence we can place on the current results and further actions relating to long term monitoring. In terms of further actions relating to long term monitoring it is recommended that on a national scale:

- the CGPS and AG measurements, and their processing and analysis, are continued at thirteen tide gauges around the coast of Great Britain.
- the AG measurements, and their processing and analysis, are extended to three other CGPS stations in Great Britain, selected based on geological setting.
- the tide gauge measurements are subjected to a refined analysis, in order to obtain revised estimates of changes in sea level at the thirteen tide gauges which have CGPS stations, considered over specific time periods rather than just taken from PSMSL.
- the use of PSI measurements, and their processing and analysis, is extended, following the success of their application in the regional study, to tide gauge sites around the coast of Great Britain which have CGPS stations.

All of these will lead to improved estimates for the changes in sea level (decoupled from changes in land level) around the coast of Great Britain over the past few decades/past century but, perhaps more importantly, will establish the selected tide gauges as devices with increasingly concurrent sea level and land level data from where estimates for any accelerations in changes sea level can be obtained. This will enable the validation of climate change model predictions of sea level rise around Great Britain, particularly as we move into the period of increasing variance between the different IPCC scenario predictions, which will lead to a better assessment of risk and more informed decisions on planning and managing flood risk at the coast and in our estuaries. The recommendations for long term monitoring on a national scale are particularly important in the context of policy needs from the sciences over the next 10 years which were set out in Defra (2004) and include the need for key long-term evidence relating to climate change and the specific requirements for monitoring, reliable regional predictions and a comprehensive understanding of the range of climate change impacts, including sea level rise.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

Introduction

Since 1997, Defra and the Environment Agency (EA) have been funding research to measure long term changes in land and sea levels around the coast of Great Britain and in the 'Thames Region':

- to monitor current changes in land level due to land 'tilt' and regional/local geological effects;
- to improve estimates of climate driven changes in sea level based on tide gauges;
- to help in predicting future sea level rise;
- to carry out more refined regional studies to support planning for flood risk management for the Thames Estuary and River Thames.

The aims of these measurements is to obtain direct estimates of current changes in land level on the scale of millimetres per year, in a stable reference frame, both at tide gauges and at other specific locations, and to use these to obtain estimates of changes in sea level (decoupled from changes in land level) over the past few decades/past century. Such measurements represent a major challenge and the research carried out has essentially included three complementary monitoring techniques: the Global Positioning System (GPS); Absolute Gravimetry (AG); and Persistent Scatterer Interferometry (PSI).

From 2003 to 2006, the research work was carried out as a national study, funded by the Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme as FD2319, and a regional study, funded by the EA Thames Estuary 2100 project. The national study was carried out jointly by the Proudman Oceanographic Laboratory (POL) and the University of Nottingham's Institute of Engineering Surveying and Space Geodesy (IESSG). The regional study was led by IESSG and carried out jointly by IESSG, POL, Nigel Press Associates Ltd. (NPA) and the British Geological Survey (BGS). For the national study, continuous GPS (CGPS) stations have been established at ten tide gauges around the coast of Great Britain and AG measurements have been made at three of these. For the regional study, CGPS and episodic GPS (EGPS) data from a network of stations in the Thames Region and PSI data for hundreds of thousands of persistent scatterer (PS) points in the Thames Region have been analysed and the changes in land level interpreted using various geoscience data sets.

A full, formal scientific report on the national and regional studies has been published as R&D Technical Report FD2319/TR (Bingley et. al., 2007) and is available from Defra. This SID5 Research Project Final Report is focused on the national study; however, as the regional study was dependent on the national study, this report does make reference to the regional study, where appropriate.

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NOTE: The application to Defra (CSG7) was prepared as a combined project, comprising of a national study and a regional study. As stated previously, the national study was funded by the Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme as FD2319 and the regional study was funded by the EA Thames Estuary 2100 project. This SID 5, and the accompanying SID 5A, are a report on the national study. Items that are shown as *underlined and italics* are those from the CSG7 that relate to the regional study.

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The abstract of research given in the CSG7 application to Defra stated:

"The project will use tide gauge, GPS and absolute gravity data observed on a national scale, *complemented by tide gauge, GPS and InSAR data observed on a regional scale (ie along the Thames Estuary)*:
(i) to provide accurate information on current changes in absolute ground/land level (i.e. referenced to the centre of the Earth) in Britain and compare these with longer-term geological estimates.
(ii) to provide accurate information on past changes in absolute sea level (i.e. referenced to the centre of the Earth), both around the coast of Britain *and along the Thames Estuary*, and compare these with estimates of past changes in global sea level.
(iii) to provide an assessment of potential future changes in relative sea level (i.e. referenced to the local land), *both* around the coast of Britain *and along the Thames Estuary*."

With regard to dissemination, the preliminary results of the national study were published in the Philosophical Transactions of the Royal Society (Teferle et. al., 2006), presented at and published in the proceedings of the 41st Defra Flood and Coastal Management conference, York, UK, July 2006 (Bingley et.al. 2006), and the final results from the national and regional study were presented at an end-of-project seminar held at the Thames Barrier Information Centre on Monday, 27 November 2006. The latter was attended by about 40 persons from Defra, the EA, commercial organisations/consultancies, councils, the media and universities.

Finally, as stated previously, in addition to this SID5 a full, formal scientific report on the national and regional study has been published as R&D Technical Report FD2319/TR (Bingley, et. al., 2007).

Scientific objectives

The scientific objectives as set out in the contract were as follows:

01 Compute estimates of vertical station velocities for a national network of 3 AG stations, through the analysis of AG time series for the period from 1995 onwards. [Responsible contractor: POL].
02 Compute estimates of vertical station velocities for a national network of 27 CGPS, 2 QCGPS and 2 EGPS stations, through the analysis of GPS coordinate time series for the period from 1997 onwards. [Responsible contractors: POL and IESSG].
03 Compute estimates of changes in absolute ground/land level at the national network of 3 AG stations and 31 GPS stations, and estimates of changes in absolute sea level at 17 tide gauges around the coast of Britain. [Responsible contractors: POL and IESSG].
04 Compute estimates of changes in relative sea level and changes in relative ground/land level for 9 tide gauges along the Thames Estuary, using all available and useful historical tide gauge records. [Responsible contractor: POL].
05 Compute estimates of vertical station velocities for a regional network of 13 EGPS stations along the Thames Estuary, through the analysis of GPS coordinate time series for the period from 1997 onwards. [Responsible contractor: IESSG].
06 Compute estimates of changes in relative ground/land level for a regional network of a few thousand PS points along the Thames Estuary, through the analysis of PSI height time series for the period from 1997 onwards. [Responsible contractor: NPA].
07 Compute estimates of changes in absolute ground/land level at the regional network of 13 EGPS stations and a few thousand PSI points along the Thames Estuary, and estimates of changes in absolute sea level at 6 tide gauges along the Thames Estuary. [Responsible contractors: POL, IESSG and NPA].
08 Assess potential future changes in relative sea levels (i.e. referenced to the local land), *both* around the coast of Britain *and along the Thames Estuary*. [Responsible contractors: POL, IESSG *and BGS*].
09 Report, submit deliverables and make recommendations to Defra *and the Environment Agency*. [Responsible contractors: POL, IESSG, *BGS and NPA*].

Extent to which the objectives were met

The aims and objectives of the research work have been met as direct estimates of current changes in land level on the scale of millimetres per year, in a stable reference frame, both at tide gauges and at other specific locations, and estimates of changes in sea level (decoupled from changes in land level) over the past few decades/past century have been obtained through novel methods developed to best combine the information from the three complementary monitoring techniques: CGPS and AG for the national study and CGPS/EGPS, AG and PSI for the regional study (Bingley et. al. 2007).

The results obtained, however, also highlight that the formal uncertainties in any of the estimates are at about the 0.5 to 1.0mm/yr level, with a further 0.5 to 1.0 mm/yr of potential systematic bias being apparent in many instances, e.g. the change in the CGPS vertical station velocities when the time series were extended from approximately 7.5 to 8.5 years; the change in the AG vertical station velocities when the time series were extended from approximately 8 or 9 to 10 or 11 years; the agreement between the combined CGPS and AG vertical station velocities and other evidence for changes in land level on a national scale. With these in mind, the estimates presented can be used now, but do need to be treated with some caution.

In conclusion, therefore, the national and regional studies were extremely successful and have greatly improved our knowledge of changes in land and sea levels around the coast of Great Britain and along the Thames Estuary and River Thames well beyond what was known at the start of the studies in 2003. They have provided new estimates of changes in land level due to ‘land tilt' and regional/local geological effects, new estimates of climate driven changes in sea level based on tide gauges and a new assessment of future sea level rise. The results are, therefore, of direct relevance to the Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme Modelling and Risk (MAR) Theme, in providing information and knowledge to support decision making in terms of coastal flood risk management and climate change, as part of the cross cutting risk based knowledge and methods sub-theme. The results are also a direct input to the Environment Agency Thames Estuary 2100 project.

Details of methods used and results obtained

In this subsection, brief details of the technology behind the measurements made by tide gauges and the use of CGPS and AG for monitoring long term changes in land level are given.

Tide gauges

A tide gauge is a device for measuring sea level at the coast or on tidal estuaries. At their most basic level tide gauges can be used to facilitate navigation within coastal and estuarine environments but on a more advanced level they can also be used for oceanographic and hydraulic/hydrological applications ranging from real-time, such as storm tide or storm surge warning, to longer term studies of mean sea level (MSL) and other tidal parameters. In this research, we have focused on the use of tide gauges for longer term studies of MSL.

In the British Isles, there are 44 'Class A' tide gauges which form the national tide gauge network as part of the National Tidal and Sea Level Facility (NTSLF). The tide gauge sensors were originally float devices but have now been replaced by a particular type of pressure sensor, referred to as a 'bubbler gauge', with each tide gauge having a number of sensors for redundancy. Tide gauge data from the national tide gauge network are subject to quality control and validation by the British Oceanographic Data Centre (BODC), which is also responsible for the archival of the 'quality controlled tide gauge data'. In addition to this, the Permanent Service for Mean Sea Level (PSMSL) archives historical and current quality controlled tide gauge data made available for any high quality tide gauges around the world; which includes all data for the 44 tide gauges mentioned above.

Following quality control and validation, the quality-controlled tide gauge data can then be used to calculate tidal parameters such as MSL, typically as either monthly or annual means which can be used to form time series. Using the monthly or annual tidal parameter time series it is then possible to carry out analysis in order to obtain estimates of changes in sea level. Much of the evidence for changes in sea level for the past few decades/past century came from measurements obtained at tide gauges, which measure MSL with respect to a TGBM. For Great Britain, a set of estimates of changes in sea level for a number of tide gauges in the British Isles for the period up to 1996 was published as Woodworth et. al. (1999). The changes in sea level obtained for a selection of the tide gauges analysed by Woodworth et. al. (1999) is given in Table 1 along with updated estimates of changes in sea level from the PSMSL, for the period up to 2004 (PSMSL 2005).

Table 1 Estimates of changes in sea level for selected British tide gauges for the period up to 1996 (Woodworth et. al. 1999) and for the period up to 2004 (PSMSL 2005)

Tide gauge	**Woodworth et. al. (1999)**			**PSMSL (2005)**		
	Period of RLR data used	**Number of complete years of RLR data used**	**Change in annual MSL and uncertainty (mm/yr)**	**Period of RLR data used**	**Number of complete years of RLR data used**	**Change in annual MSL and uncertainty (mm/yr)**
Lerwick	1957-1996	35	-1.09 ± 0.40	1957-2004	37	-0.79 ± 0.36
Aberdeen	1932-1996	48	+0.67 ± 0.20	1932-2004	55	+0.86 ± 0.15
North Shields	1901-1996	77	+1.86 ± 0.15	1897-2004	86	+1.85 ± 0.12
Liverpool	1959-1983	19	+2.58 ± 0.88	1858-1983	77	+1.03 ± 0.15
Lowestoft	1956-1995	36	+1.81 ± 0.48	1956-2004	42	+2.49 ± 0.37
Sheerness	1901-1996	51	+2.14 ± 0.15	1834-2004	75	+1.64 ± 0.09
Portsmouth	1962-1996	28	+1.45 ± 0.60	1962-2003	33	+1.82 ± 0.45
Newlyn	1916-1996	80	+1.69 ± 0.12	1916-2004	87	+1.69 ± 0.11

In both cases, with the exception of Lerwick tide gauge on Shetland, the British tide gauges all show a rise in sea level over the past few decades/past century, with the later estimates showing a range of values from 0.86mm/yr at Aberdeen tide gauge in East Scotland to 2.49mm/yr at Lowestoft tide gauge on the East coast of England; Lerwick is exceptional as the tide gauge measurements suggest a fall in sea level, of 0.79mm/yr.

From Table 1, it is clear that the uncertainties associated with the estimates of changes in sea level for the eight tide gauges considered are consistent with the statement made in Woodworth et. al. (1999) that "one needs typically 30 years of data in order to determine a secular trend with a standard error of the order of 0.5mm/yr and 50 years for an error of 0.3mm/yr." However, the evidence presented in this subsection also highlights that estimates of changes in sea level can still vary by up to 0.7mm/yr as MSL time series are extended forward within the range of 30 to 50 complete years of RLR data; whereas there appears to be little effect when MSL time series are extended within the range of approximately 80 to 90 complete years of RLR data. Considering the MSL time series for Sheerness tide gauge, there is a clear decrease in the change in sea level when the historical RLR data is included (the same occurs at Liverpool tide gauge but this should be treated with caution as the original MSL time series only consisted of 19 complete years of RLR data) which clearly supports the idea of a rise in sea level during the 20th century which was not present during the 19th century.

CGPS

GPS, or 'the Global Positioning System', is the American Global Navigation Satellite System (GNSS) primarily designed to meet the metric and decimetric positioning accuracy requirements of military and transport applications. However, at its most advanced level it can be used for high accuracy positioning to millimetric accuracies and has revolutionised surveying and geodesy.

A GNSS comprises a space segment, a ground segment and a user segment. For GPS, the space segment consists of a constellation of (currently) 30 mid-Earth orbiting satellites organised in six orbital planes with each satellite at an approximate altitude of 20,200km. The basic design of the constellation is such that at least four satellites are visible in an open environment at all locations on the Earth for 24 hours a day. The ground segment consists of the infrastructure which monitors the GPS satellites and uploads information on the satellite positions and the state of their satellite clocks (as the broadcast ephemeris which is part of the navigation message) as well as information on their health (as another part of the navigation message). The user segment consists of an unlimited number of users equipped with a GPS antenna and GPS receiver; unlimited by the fact that GPS is a passive system whereby a user receives all of the information required to acccurately position themselves without the need to transmit any information. An example of a GPS antenna and monument is given as Figure 1.

Figure 1 Photograph of a GPS antenna and monument*: the photograph shows the equipment installed at the Dover tide gauge.*

For high accuracy positioning using GPS, a station is established with a user receiver programmed to observe GPS data (time-tagged, pseudo-ranges and carrier phase) for a certain period of time whilst a user receiver-antenna is maintained at a fixed height above a survey marker. The data recorded by the user receiver is then combined with concurrent data from a number of other receivers (at least one, but usually many more) and GPS products (information on satellite positions, satellite clocks and Earth orientation parameters) and post-processed using software which attempts to mitigate the various systematic errors, including the ‘Earth processes’ of solid Earth tides and ocean tides, that affect GPS positioning. The other aspect of GPS data processing is to compute the coordinates of stations in a particular terrestrial reference frame (TRF). In this respect, GPS is unlike any other survey technique as, with appropriate GPS data processing software, it is possible to compute coordinates in a global TRF. This is particularly important for the national study as it enables the computation of changes in sea level (decoupled from changes in land level) to be effectively referred to the origin of the TRF and have an absolute nature, rather than being relative to any benchmarks that are then assumed to be ‘stable’.

The development of GPS techniques for monitoring changes in land level at British tide gauges has been on-going at IESSG and POL since 1990, based on research funded by both Defra and EA. This research and development was initially based on the use of near-annual, episodic GPS (EGPS) campaigns, with measurements made over 5 days, and latterly what was termed quasi-continuous GPS (QCGPS), where measurements were made for one month per year, close to 17 of the 44 tide gauges which form the national tide gauge network as part of the NTSLF. Since 1996, the research and development has focused on the establishment of continuous GPS (CGPS) stations, which are capable of providing observations 365 days per year and, therefore, enable much more precise and accurate measurements of changes in land level. Through the latest research, and similar research carried out by other scientists on an international scale, the advantages of QCGPS over EGPS, but more so, the advantages of CGPS over both QCGPS and EGPS became more and more evident, so that it is now generally accepted that the precision and accuracy demands of trying to use GPS on a national or larger scale (to obtain site-specific, direct estimates of current changes in land level that will enable a tide gauge to be better used for studying the climate related component of changes in sea level) can only be met through the use of CGPS. As such, and contrary to what was stated in the CSG7 application, the research for the national study focused purely on the use of CGPS.

During the period from 1997 to 2005, IESSG and POL established CGPS stations at ten of the 44 tide gauges which form the national tide gauge network. In chronological order, these were established at Sheerness, Newlyn, Aberdeen, Liverpool, Lowestoft, North Shields, Portsmouth, Lerwick, Stornoway and Dover tide gauges. All of these so-called ‘CGPS@TG stations’ were established such that the GPS receivers (all dual frequency) are housed in the same building as the tide gauge equipment and the GPS antennas (all Dorne Margolin choke ring antennas) are mounted on monuments, sited as close as possible to the tide gauge, i.e. within a few meters of the tide gauge itself; to fulfil the requirement to obtain site-specific, direct estimates of changes in land level.

In terms of Scientific Objectives 02 and 03 set out in the CSG7 application, which referred to “27 CGPS, 2 QCGPS and 2 EGPS stations” and “17 tide gauges”, the research carried out actually focused on a network of 44

CGPS stations as shown in Figure 2: ten CGPS@TG stations in Great Britain, one CGPS@TG station in Northern France and 33 non-TG CGPS stations in Great Britain, which are part of the British Isles GPS archive Facility (BIGF), and 12 tide gauges.

For the national study, all archived data for these CGPS stations, for the period from the start of their operation to December 2005, were collated along with similar data for International GNSS Service (IGS) stations on both a European and global scale to enable high accuracy positioning. Data from each day were processed separately in order to produce values for the station's three-dimensional coordinates for each day. Two strategies were used when processing the daily CGPS data. In the first strategy, the IESSG's GPS Analysis Software version 2.4 (GAS2.4) (Stewart et. al. 2002) was used to produce a series of daily DD RNSs, i.e. 'Double Difference Regional Network Solutions', for the period from March 1997 to December 2005. In the second strategy, the IESSG's iGNSS processing tools (Orliac et. al. 2006) were used to run Bernese software version 5.0 (BSW5.0) (Hugentobler et. al. 2006) and produce a series of daily PPP GTSs, i.e. 'Precise Point Positioning Globally Transformed Solutions', for the period from January 2000 to December 2005 (Teferle et. al. 2007). In both cases, the daily coordinates of the British CGPS stations were estimated in the International Terrestrial Reference Frame 2000 (ITRF2000) at the mid-epoch of each day.

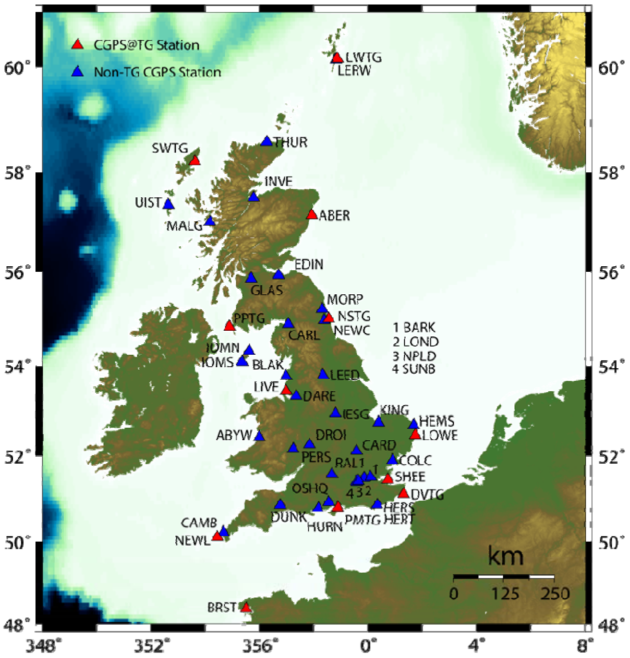

Figure 2 Map showing the CGPS stations in Great Britain and Northern France considered in the national study

The outputs from both CGPS data processing strategies were then used to form coordinate time series, based on the daily ITRF2000 coordinates (latitude, longitude and ellipsoidal height). For each of the 44 CGPS stations, up to five coordinate time series were produced. The first (Solution 1) are based on CGPS data for the period up to the end of 2004, as presented in Bingley et. al. (2006), and the other four (Solutions 2 and 3 being GAS2.4 DD RNS with and without spatial filtering; Solutions 4 and 5 being BSW5.0 PPP GTS with and without spatial filtering) are based on CGPS data for the period up to the end of 2005. In this SID5 report, the height time series from solution 2, for seven of the ten CGPS@TG stations in Great Britain and the non-TG CGPS station at LERW on Shetland, are presented as Figure 3. These CGPS height time series plots show the changes in height from day to day as green dots, any coordinate offsets accounted for as dashed vertical lines and the best fit linear plus periodic trend as a blue line. Statistics relating to the coordinate time series analysis are also given on the height time series plots in terms of the RMS difference between the individual height estimates and the best fit trend and the estimates of vertical station velocity with their corresponding uncertainty.

As we are primarily interested in the vertical station velocities and their uncertainties when considering changes in land level, the five height time series for each of the 44 CGPS stations were analysed using IESSG's CTSAna tools to run POL's CATS software (Williams 2003), which employs 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). The CGPS estimates of vertical station velocities and their uncertainties, from Solutions 2, 3, 4 and 5 for the seven CGPS@TG stations in Great Britain and the non-TG CGPS station at LERW, are summarised in Table 2.

At this stage it must be made clear that any estimates of vertical station velocity for the three most recently established CGPS@TG stations, DVTG at Dover tide gauge on the South-East coast of England, LWTG at Lerwick tide gauge on Shetland and SWTG at Stornoway tide gauge on the Western Isles, are nonsensical due to their extremely short time series of 0.1, 0.3 and 0.3 years respectively; however their RMS values are of use. Their height time series highlight that the RMS values of 4 to 5mm for DVTG, 5 to 6mm for LWTG and 5 to 8mm for SWTG are consistent with those obtained for the other CGPS@TG stations with longer time series and are an indication that the data quality from these three newly established CGPS@TG stations is of the required, high level. The discussions in the remainder of this subsection are, therefore, focused on the other seven CGPS@TG stations in Great Britain and the non-TG CGPS station at LERW, all of which have time series of at least 6 years in length, with the exception of PMTG at Portsmouth tide gauge on the South coast of England, but this still has a time series length of 4.3 years.

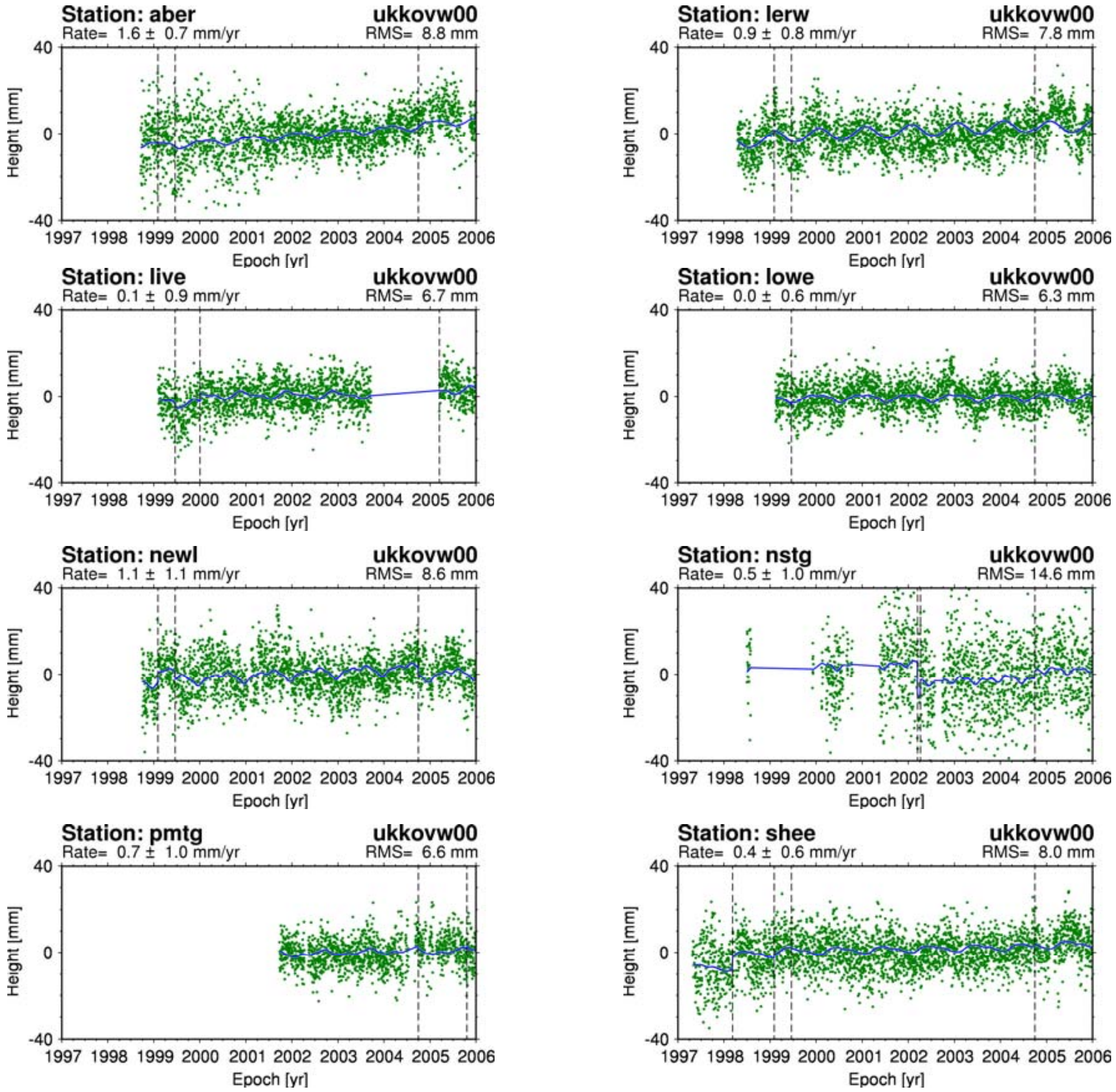

Figure 3 CGPS height time series from solution 2 for seven of the ten CGPS@TG stations in Great Britain and the non-TG CGPS station at LERW on Shetland

Table 2 CGPS estimates of vertical station velocities and uncertainties from Solutions 2, 3, 4 and 5 for a selection of eight CGPS stations in the national study

Station name	**4 char station ID**	**CGPS vertical station velocity and uncertainty**			
		GAS2.4 DD RNS		**BSW5.0 PPP GTS**	
		Solution 2 (mm/yr)	**Solution 3 (mm/yr)**	**Solution 4 (mm/yr)**	**Solution 5 (mm/yr)**
Lerwick	LERW	+0.89 ± 0.80	+0.77 ± 0.50	-0.10 ± 0.71	-0.09 ± 0.50
Aberdeen TG	ABER	+1.63 ± 0.65	+1.27 ± 0.32	-0.88 ± 1.00	-0.28 ± 0.44
N. Shields TG	NSTG	+0.55 ± 0.95	+0.07 ± 0.82	+0.11 ± 1.12	+0.30 ± 0.48
Liverpool TG	LIVE	+0.06 ± 0.89	+1.09 ± 0.31	+0.84 ± 1.07	+1.07 ± 0.37
Lowestoft TG	LOWE	+0.05 ± 0.61	-0.01 ± 0.50	-0.57 ± 0.70	-0.61 ± 0.33
Sheerness TG	SHEE	+0.43 ± 0.60	+0.53 ± 0.50	-0.22 ± 0.93	-0.21 ± 0.63
Portsmouth TG	PMTG	+0.67 ± 0.97	+0.48 ± 0.70	-0.56 ± 0.93	-0.59 ± 0.41
Newlyn TG	NEWL	+1.06 ± 1.11	+0.61 ± 0.91	+0.13 ± 0.83	+0.13 ± 0.66

Several points can be made regarding Table 2:

- The uncertainties in the CGPS estimates of vertical station velocity are at the level of 0.5 to 1.0mm/yr for these time series, which are between 6 and 8.7 years in length. These are consistent with an analysis of 99 global IGS stations based on BSW5.0 PPP GTS and two other solutions from international standard software/processing strategies (GAMIT/GLOBK GNS DD and GIPSY PPP GTS) presented by Teferle et. al. (2007), from where it can be inferred that a time series length of 10 to 13 years is typically required to obtain an uncertainty of 0.5mm/yr and 20 to 25 years for 0.3mm/yr.
- A comparison of Solutions 2 and 3 shows the effect of spatial filtering with the uncertainties for the vertical station velocity estimates for LERW, SHEE and NEWL reducing from 0.8 to 0.5, 0.6 to 0.5 and 1.1 to 0.9mm/yr respectively. A similar effect being apparent between Solutions 4 and 5 with the uncertainties for the vertical station velocity estimates reducing from 0.7 to 0.5, 0.9 to 0.6 and 0.8 to 0.7mm/yr respectively.

- A comparison of Solution 1 (Bingley et. al. 2006) and Solution 2 shows the effect of extending the CGPS height time series by 13 months, i.e. from 6.6 to 7.7 years for LERW, from 7.6 to 8.7 years for SHEE and from 6.2 to 7.3 years for NEWL. Here it can be seen that the estimates of vertical station velocity are changed systematically by approximately +0.9, +0.2 and +0.4mm/yr for LERW, SHEE and NEWL respectively.
- A comparison of Solutions 2 and 4 or 3 and 5, show a further systematic offset between the use of GAS2.4 DD RNS and BSW5.0 PPP GTS, with the estimates of vertical station velocity based on GAS2.4 DD RNS being more positive than the estimates based on BSW5.0 PPP GTS by about 0.5 to 1.0mm/yr.

From a further consideration of the results presented in Table 2 along with all of the height time series plots (not shown), it is clear that there are issues with three of the eight stations which are apparent through either a visual inspection of the CGPS height time series or the RMS values (not shown). Considering each of these in turn:

- In the case of ABER, a visual inspection of the time series shows that the data up to some point in 2001 was noisy, so much so that this data was not useable in Solutions 4 and 5, which are based on BSW5.0 PPP GTS. This noise was due to radio frequency interference at the site, as reported by Teferle et. al. (2003), and as a result of this, Solutions 4 and 5 for ABER (highlighted in grey in Table 2) are considered to be unreliable.
- In the case of NSTG, a visual inspection of the time series shows that Solutions 2 and 3, which are based on GAS2.4 DD RNS, are much noisier than Solutions 4 and 5, which are based on BSW5.0 PPP GTS. This is reflected in the RMS values which are 14.5 and 14.1mm for Solutions 2 and 3, and 7.5 and 6.1mm for Solutions 4 and 5; however, in this case, Solutions 2 and 3 are still considered to be reliable, but less reliable than Solutions 4 and 5.
- In the case of LIVE, the RMS values show that Solutions 2, 3, 4 and 5 are similar in terms of noise. The issue at this station relates to the gap in the time series from mid-2003 to early 2005, which was caused by rejecting data in order to avoid potentially erroneous results due to gradual, salt-water corrosion of the GPS antenna over this time period. In this case, the visual inspection reveals something different in that there is clearly more of a discontinuity over the gap in Solutions 2 and 3, which are based on GAS2.4 DD RNS, as oppose to Solutions 4 and 5, which are based on BSW5.0 PPP GTS. As a result of this, Solutions 2 and 3 for LIVE (highlighted in grey in Table 2) are considered to be unreliable.

Taking the reliable estimates given in Table 2, it is possible to compute differences between the CGPS estimates of vertical station velocities from GAS2.4 DD RNS and BSW5.0 PPP GTS and to compute the CGPS vertical station velocities in a relative sense. These are presented in Table 3.

Table 3 Comparison of the CGPS estimates of vertical station velocities from Solutions 2, 3, 4 and 5 for a selection of eight CGPS stations in the national study

Station name	**4 char station ID**	**CGPS vertical station velocity**			
		Differences between GAS2.4 DD RNS and BSW PPP GTS		**Relative to one CGPS station**	
		Solution 2 minus Solution 4 (mm/yr)	**Solution 3 minus Solution 5 (mm/yr)**	**Solution 3 relative to ABER (mm/yr)**	**Solution 3 relative to LOWE (mm/yr)**
Lerwick	LERW	+0.99	+0.86	-0.74	+0.77
Aberdeen TG	ABER			-	+1.28
N. Shields TG	NSTG	+0.43	-0.23	-1.20	+0.08
Liverpool TG	LIVE				
Lowestoft TG	LOWE	+0.62	+0.60	-1.58	-
Sheerness TG	SHEE	+0.65	+0.75	-1.20	+0.54
Portsmouth TG	PMTG	+1.23	+1.07	-0.97	+0.49
Newlyn TG	NEWL	+0.94	+0.49	-0.57	+0.62

Considering the results in Table 3, for the five longest, homogeneous time series (LERW, LOWE, SHEE, PMTG and NEWL), the mean offset (and corresponding standard deviation) between the CGPS estimates of vertical station velocity from the two software/processing strategies are 0.89 ± 0.25mm/yr between Solutions 2 and 4, and 0.75 ± 0.23mm/yr between Solutions 3 and 5. Expanding on the earlier discussion, the results in Table 3 confirm the systematic nature of the offset between the use of GAS2.4 DD RNS and BSW5.0 PPP GTS, with the estimates of vertical station velocity based on GAS2.4 RNS DD being more positive than the estimates based on BSW5.0 PPP GTS by 0.5 to 1.0mm/yr. In a relative sense, however, the results from GAS2.4 DD RNS do exhibit the expected patterns of subsidence at all stations with respect to the uplifting station at Aberdeen tide gauge, and patterns of uplift at all stations with respect to the subsiding station at Lowestoft tide gauge. This is also the case if such values are computed based on Solution 2. Furthermore, patterns of uplift at all stations with respect to the subsiding station at Lowestoft are also seen if such values are computed based on Solutions 4 or 5.

Based on the results presented in this subsection, therefore, it can be concluded that parallel processing with DD and PPP is essential in order to make the best use of stations that have data of varying quality, i.e. the ‘better’ solutions for ABER were 2 and 3 (GAS2.4 DD RNS) whereas the ‘better’ solutions for NSTG and LIVE were 4 and 5 (BSW5.0 PPP GTS). It can also be concluded that, at this demanding, high level of accuracy, an independent measure of vertical station velocities is essential, in order to assess the systematic offsets apparent between different software/processing strategies, hence the use of AG.

Absolute Gravimetry

Through recent advances in geometrical optics and interferometry, it has become possible to use ‘free fall methods’ to obtain measurements of absolute gravity to an unsurpassed level of precision and accuracy. In this context, AG, or ‘Absolute Gravimetry’, is the measurement of the acceleration due to gravity (“g”) from distance and time measurements. In this respect, an absolute gravimeter instrument must have a unique feature in that the quantities it measures (distance and time) must directly define gravity, so that the calibration of the instrument comes only through the metrological control of these measured quantities. Absolute gravity is measured in units of μgal, where 1μgal = $1 \times 10^{-8} m/s^2$. To put this into context, if two objects were allowed to fall with a 1μgal difference in gravity between them, one object would be ahead of the other by the thickness of a sheet of paper after traveling a distance of 248 km!

The FG5 absolute gravimeter instrument developed by the company, Micro-g Solutions Inc., USA uses the free fall method to determine absolute gravity with a precision and accuracy of the μgal level, through the use of three critical components: a dropping chamber, a laser interferometer and a superspring. A photograph of the FG5 absolute gravity instrument is given as Figure 4.

The dropping chamber is in fact a ‘drag free’ dropping chamber, which houses a free-falling corner cube reflector. It reduces drag due to residual gas molecules, follows the dropped corner cube, then gently arrests and lifts it, and shields the corner cube from external electrostatic forces. The laser interferometer carries out the distance measurement to the free-falling corner cube reflector, and the superspring provides an inertial reference frame. This enables the instrument to avoid any microseismic noise, which would otherwise reduce the precision of the instrument.

Figure 4 Photograph of the FG5 absolute gravity instrument*: the photograph shows the equipment in use at the AG station near the Newlyn tide gauge.*

Through inter-comparisons between FG5 absolute gravimeter instruments it is generally accepted that the instrument accuracy is about 2μgal and precision (based on a 10 second drop interval, at a quiet site) is about ±1μgal (over a 3.75 minutes observation period) or ±0.1μgal (over a 6.25 hour observation period). The FG5 can be used anywhere in the world, but requires an environment with a stable operating temperature in the range of 10 to 30°C. As with GPS, AG is also affected by ‘Earth processes’ including polar motion, solid Earth tides, ocean tides and changes in atmospheric pressure. In addition to these, the nature of AG means that there are also instrument-specific corrections that need to be applied, namely: comparator response correction, speed of light correction, gradient correction and reference height correction.

For the AG research, 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). Considering the nature of AG measurements, it was decided to focus on three tide gauges and these three were selected based on: their geographical distribution; their representation of the expected changes in land level due to glacial isostatic adjustment (GIA), i.e. subsidence at Newlyn tide gauge near to Land’s end in South-West England, uplift or no movement at Aberdeen in East Scotland and subsidence at Lerwick tide gauge on Shetland. Other things considered were: the fact that Newlyn and Lerwick tide gauges contribute to the Global Sea Level Observing System (GLOSS); and Newlyn and Aberdeen both having long, high quality MSL time series (Williams et. al. 2001).

Considering each of the three tide gauges, a detailed reconnaissance was carried out in order to identify potential sites for the establishment of an AG station suitable for monitoring long term changes in land level. In this respect, the principle was for the AG station to be housed inside a building (to have a stable environment with no winds), which would ideally remain in place and unchanged over a long period of time, and be founded on solid rock (for both stability and to be representative of the changes in land level for the surrounding area). Furthermore, the AG station could not be too close to the coast, and certainly not at the tide gauge as for the CGPS@TG stations, as it would be near-impossible to model the direct mass attraction effect of the ocean tides.

Following the reconnaissance suitable sites were identified for the AG stations and Figure 5 shows the location of the three AG stations and their relationship to the nearby tide gauge and CGPS stations. Lerwick AG station is located in the basement of a school, about 0.5km from the tide gauge and the CGPS@TG station LWTG and 5km from the non-TG CGPS station LERW; Aberdeen AG station is located in a church, about 3.2km from the tide gauge and the CGPS@TG station ABER; and Newlyn AG station is located in the church at Paul about 1.5km from the tide gauge and the CGPS@TG station NEWL.

All of the measurements made to date have been obtained with the FG5-103 absolute gravimeter instrument owned by POL. The procedure adopted for the national study was to make near-annual, episodic AG measurements, with each set of measurements being carried out over at least three days, typically three to four days, and the absolute gravimeter instrument being carefully set up again at the start of each day.

Data from each day were processed separately, with corrections made for solid-earth tides, ocean-loading effects, atmospheric pressure, polar motion and comparator response. From this it was possible to compute one mean value per day and then a weighted mean for the epoch, or just one mean value for the epoch. The uncertainty being the root sum square of the instrument uncertainty estimate (1 to 2 μgal) and the statistical error (based on the drop to drop standard deviation and the number of drops).

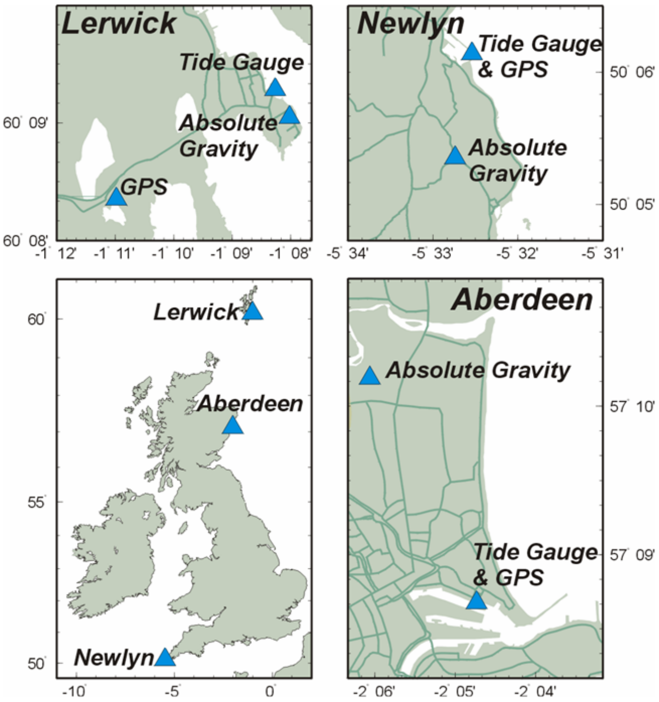

Figure 5 Map showing the AG stations in Great Britain considered in the national study

The absolute gravity values for each epoch were used to form time series for each AG station. A best fit linear trend was then used to obtain an estimate of the change of absolute gravity and its uncertainty, from which the equivalent vertical station velocity and uncertainty were inferred, through applying a conversion factor of -2μgal/cm or -5mm/μgal. For each of the three AG stations, two absolute gravity time series are considered in this subsection. The first (Solution A) are based on AG data for the period up to September 2004, as presented in Bingley et. al. (2006), and the others (Solution B) are based on AG data for the period up to September 2006. For both solutions, the AG data was processed using POL in-house developed software.

The absolute gravity time series from Solution B, for the three AG stations in Great Britain are presented as Figure 6, where the AG estimates of absolute gravity for a station are shown as red dots, at approximately annual intervals, and the plots also show the best fit linear trend in the absolute gravity estimates (as a blue line).

A visual inspection of Figure 6 shows that there appears to be a positive change in absolute gravity at both Lerwick and Newlyn AG stations, which would equate to a negative vertical station velocity, and a negative change in absolute gravity at Aberdeen AG station, which would equate to a positive vertical station velocity.

In the case of the AG station in Aberdeen, however, the absolute gravity time series is clearly, significantly different in character to the time series for the other two AG stations: it shows a change in absolute gravity which is six to nine times greater than that observed at the other two AG stations and the data for the period up to September 2004 appears to exhibit a bi-modal distribution, as illustrated by the red and green dots. At this stage, therefore, any estimate of a change in absolute gravity or vertical station velocity based on the current AG station in Aberdeen must be treated with extreme caution.

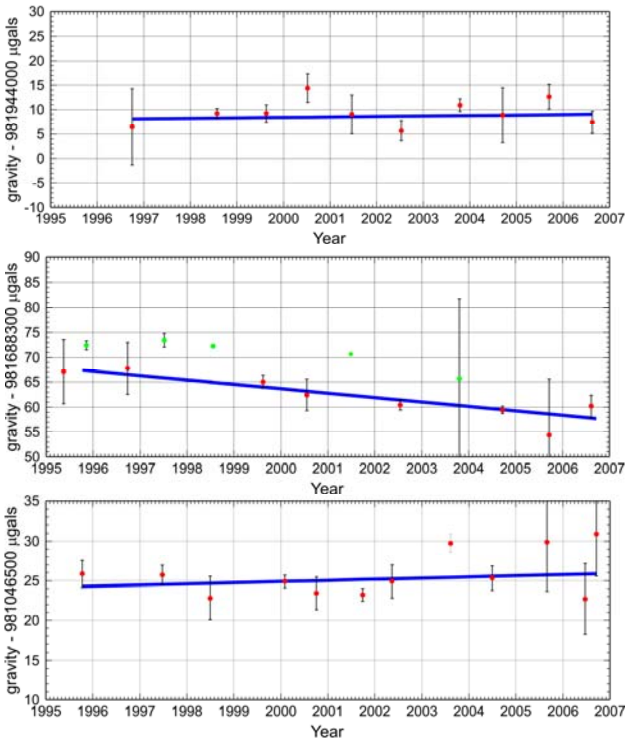

Figure 6 Absolute gravity time series for Solution B for Lerwick (top), Aberdeen (middle) and Newlyn (bottom) AG stations used in the national study

The estimates of vertical station velocities and their uncertainties, from both solutions for the two reliable AG stations in Great Britain are summarised in Table 4, which confirms that both stations have negative vertical station velocities and presents their magnitudes as being of the order of 0.5 to 1.1mm/yr.

Table 4 Estimates of changes in absolute gravity and AG vertical station velocities, and their uncertainties, from Solutions A and B for two AG stations in the national study

Station name	AG change in absolute gravity and uncertainty		AG vertical station velocity and uncertainty	
	Solution A (μgal/yr)	Solution B (μgal/yr)	Solution A (mm/yr)	Solution B (mm/yr)
Lerwick	+0.2 ± 0.2	+0.10 ± 0.19	-1.1 ± 1.1	-0.49 ± 0.96
Newlyn	+0.1 ± 0.2	+0.14 ± 0.14	-0.5 ± 0.9	-0.74 ± 0.72

Considering Figure 6 along with Table 4, two points of interest can be made:

- The uncertainties in the AG estimates of vertical station velocity are at the level of 0.7 to 1.0mm/yr for the Solution B time series, which are between 9.9 and 10.9 years in length.
- A comparison of Solutions A and B shows the effect of extending the absolute gravity time series by approximately 2 years, i.e. from 8.0 to 9.9 years for Lerwick, from 8.8 to 10.9 years for Newlyn. Here it can be seen that the estimates of vertical station velocity are changed by approximately +0.6mm/yr for Lerwick and -0.2mm/yr for Newlyn respectively.

Discussion of the results and their reliability

In this subsection, we compare the CGPS and AG estimates of vertical station velocities with each other and with other independent evidence of changes in land level for Great Britain, and then present a strategy for combining the current CGPS and AG estimates of vertical station velocities to enable estimates for the changes in land and sea levels around the coast of Britain.

Comparison of CGPS and AG estimates of vertical station velocity

Based on AG Solution B, presented in Table 4, and CGPS Solutions 2, 3, 4 and 5, presented in Table 2, a comparison between the CGPS and AG vertical station velocities can be made for stations close to Lerwick tide gauge on Shetland and close to or at the Newlyn tide gauge near to Land's End in the South-West of England. The results of this comparison are given in Table 5.

Table 5 Comparison of CGPS and AG estimates of vertical station velocities from the national study

		GAS2.4 DD RNS		BSW5.0 PPP GTS	
		Solution 2 (mm/yr)	Solution 3 (mm/yr)	Solution 4 (mm/yr)	Solution 5 (mm/yr)
Lerwick	LERW	+1.38	+1.26	+0.39	+0.40
Newlyn TG	NEWL	+1.80	+1.35	+0.87	+0.87
Weighted Mean		+1.52	+1.27	+0.59	+0.56
Standard Deviation		±0.30	±0.07	±0.34	±0.33

As stated in the previous subsection, when considering the five longest, homogeneous CGPS height time series, the mean offset (and corresponding standard deviation) between the CGPS estimates of vertical station velocity from the two software/processing strategies were 0.89 ± 0.25mm/yr between Solutions 2 and 4, and 0.75 ± 0.23mm/yr between Solutions 3 and 5, with the estimates of vertical station velocity based on GAS2.4 RNS DD being more positive than the estimates based on BSW5.0 PPP GTS. When considering AG, the weighted mean offset (and corresponding standard deviation) suggest that all of the CGPS estimates of vertical station velocity are systematically offset from the estimates based on AG: those based on GAS2.4 RNS DD being more positive by 1.27 or 1.52mm/yr and those based on BSW5.0 PPP GTS being more positive by 0.56 or 0.59mm/yr.

At this stage of the discussions it is quite correct to ask the question of "which is the more correct: AG or CGPS?" Before attempting to answer this question, it is worth considering the uncertainties in the estimates of vertical station velocity presented thus far, which show that CGPS and AG are in agreement within the 1-sigma uncertainties given in Tables 2 and 4, e.g. in the worst case for Newlyn tide gauge, the CGPS estimate from Solution 2 is +1.06 ± 1.11mm/yr, or between -0.05 and +2.17mm/yr at the 1-sigma level, and the AG estimate from Solution B is -0.74 ± 0.72mm/yr, or between -1.46 and -0.02mm/yr at the 1-sigma level.

Before exploring this question further, we can consider other published evidence on CGPS estimates of vertical station velocity at this demanding, high level of accuracy. In this respect, several authors have reported systematic offsets when comparing CGPS estimates of vertical station velocity to independent evidence:

- Prawirodirdjo and Bock (2004) compared CGPS estimates of vertical station velocity, based on another international standard software/processing strategies (GAMIT/GLOBK GNS DD), with estimates from a GIA model and reported an offset of +1.1mm/yr for sites in North America and +1.7mm/yr for sites in Northern Europe, with the CGPS estimates being more positive than the GIA model.

- MacMillan (2004) compared CGPS and Very Long Baseline Interferometry (VLBI) which forms a critical component of the ITRF, and found that CGPS estimates of vertical station velocity were 1.5mm/yr more positive than VLBI estimates at 22 co-located global sites.
- As part of the European Sea Level Service – Research Infrastructure project, CGPS and AG estimates of vertical station velocity at Newlyn were also compared, based on two other international standard software/processing strategies (GAMIT/GLOBK GNS DD and GIPSY-OASIS II GTS PPP) with offsets of +0.6 and +1.7 to +2.5mm/yr found, i.e. the CGPS estimates were more positive than the AG estimates.

At the moment, therefore, the general consensus in the international community is that there is a systematic bias in all 'current' CGPS estimates of vertical station velocity at this demanding, high level of accuracy, which is due to a combination of: the use of models for relative antenna phase centre variations, i.e. inadequate modelling of satellite and receiver antenna phase centres in a changing satellite constellation (Ge et. al. 2005); the use of ITRF2000; and, in the case of GAS2.4 DD RNS, limitations in using a regional network solution (rather than a globally transformed solution), for which we have already shown a systematic offset of 0.75 or 0.89mm/yr. At this point it should be noted that the use of models for relative antenna phase centre variations and the use of ITRF2000 is inherent in all of the CGPS estimates of vertical station velocity computed for the national study, as these models and reference frame are what were adopted and used by the IGS to produce the IGS products and in our own processing, which was made to be consistent with the IGS processing strategy as it was during the period of the national study. In this respect, since 26 November 2006, the IGS have changed their processing strategy to include models for absolute antenna phase centre variations and the use of ITRF2005. This revised processing strategy is now being used by the IGS in the computation of new IGS products, and will be used by the IGS in a re-processing and re-analysis effort planned for the next three years or so, to produce revised and improved IGS products that go back in time, which will then enable re-processing and re-analysis efforts to be made on CGPS data sets such as the one used in the national study.

In terms of our results, we can also: consider the stability, in a local and regional context, of the AG and CGPS@TG stations for Newlyn tide gauge; compare the AG and CGPS estimates of vertical station velocity with the published changes in the land level of Great Britain; compare the CGPS estimates of vertical station velocity for the IGS station HERS with the ITRF2000 published vertical station velocity for Herstmonceux, on the South Coast of England, which is based on a combination of CGPS and SLR as part of the realisation of ITRF2000.

From the first test, considering evidence from precise levelling carried out between 1952 and 1990 and evidence from the non-TG CGPS station CAMB at Camborne, about 20km from Newlyn and founded on solid rock, it was concluded that the apparent systematic offsets between the CGPS and AG estimates of vertical station velocity for Newlyn are not due to relative movements between the CGPS@TG station NEWL founded on the pier adjacent to Newlyn tide gauge and the AG station founded on solid rock in the church at Paul, some 1.5km away. From the third test, it was found that the CGPS estimates of vertical station velocity for HERS from Solutions 2, 3, 4 and 5 were also systematically offset from the ITRF2000 published value, with the CGPS estimates of vertical station velocity being 'too positive'. Full details of these two tests are given in Bingley et. al. (2007). This SID5 report concentrates on the results of the second test, which involved a comparison with the published evidence for changes in land in level in Great Britain.

In this respect, when considering AG, the vertical station velocities for Newlyn and Lerwick for Solution B were presented in Table 4 as -0.49 ± 0.96mm/yr and -0.74 ± 0.72mm/yr respectively. A comparison of these with the published changes in the land level of Great Britain shows that the AG estimate of vertical station velocity for Lerwick is in agreement with the value of -0.5mm/yr from the GIA model of Peltier (2001), and the AG estimate of vertical station velocity for Newlyn is somewhere in between the values from the GIA model of Peltier (2001) at -0.3mm/yr and the values from the GIA model of Lambeck and Johnston (1995) of -1.0mm/yr and the geological studies of Shennan and Horton (2002) of -1.1mm/yr.

Considering CGPS, the comparisons are presented as Figures 7 and 8 for Solutions 2 and 3, and Solutions 4 and 5 respectively. Each figure consists of a series of four plots, which show the vertical land movement (VLM) estimates, i.e. estimates of changes in land level, from the CGPS estimates of vertical station velocity (shown in red on all four plots) in comparison with estimates from: geological studies, shown in blue on the top plots; and models of GIA, shown in green and blue on the bottom plots.

A visual inspection of Figure 7 clearly shows that, in most cases, the CGPS estimates of vertical station velocity from GAS2.4 DD RNS are more positive than the published evidence for changes in land level. A visual inspection of Figure 8 shows that with the systematic offset between the GAS2.4 DD RNS and BSW5.0 PPP GTS effectively removed, the GPS estimates of vertical station velocity are more in sympathy with the published changes in land level. To assess whether there are any systematic offsets between the different CGPS solutions and the published changes in land level, a statistical comparison between the reliable (as discussed in the previous subsection) CGPS vertical station velocities for stations in Great Britain and the published changes in land level was made. The results of this are summarised in Table 6.

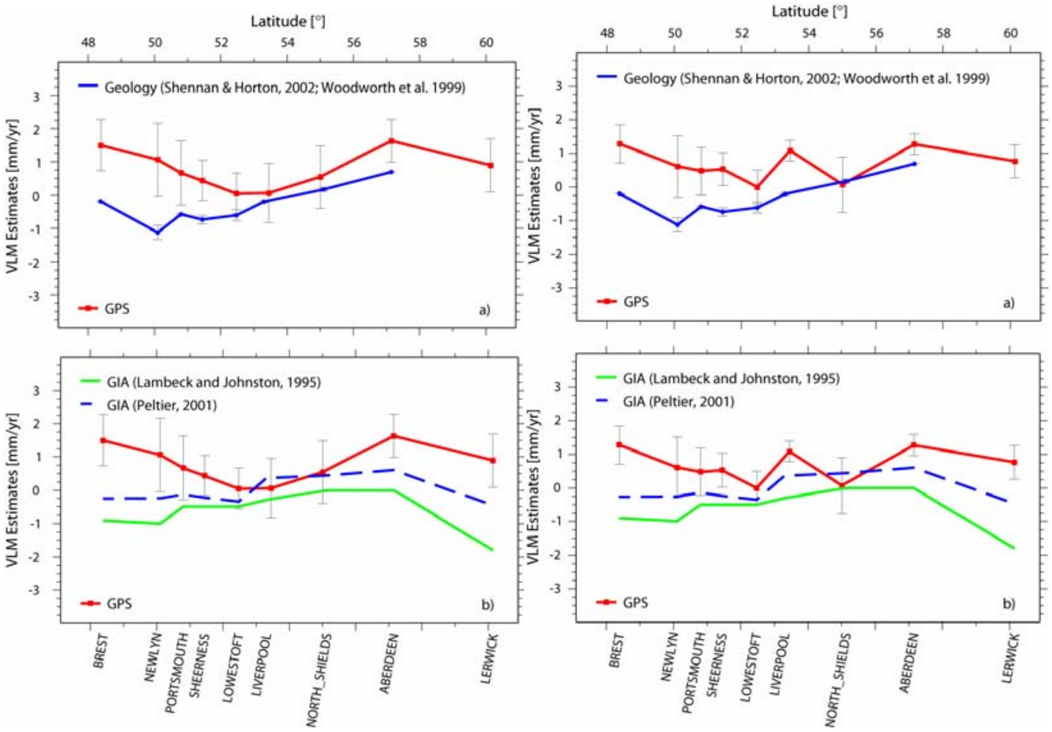

Figure 7 CGPS estimates of vertical station velocities from Solutions 2 (left) and 3 (right) compared to published evidence for changes in the land level of Great Britain

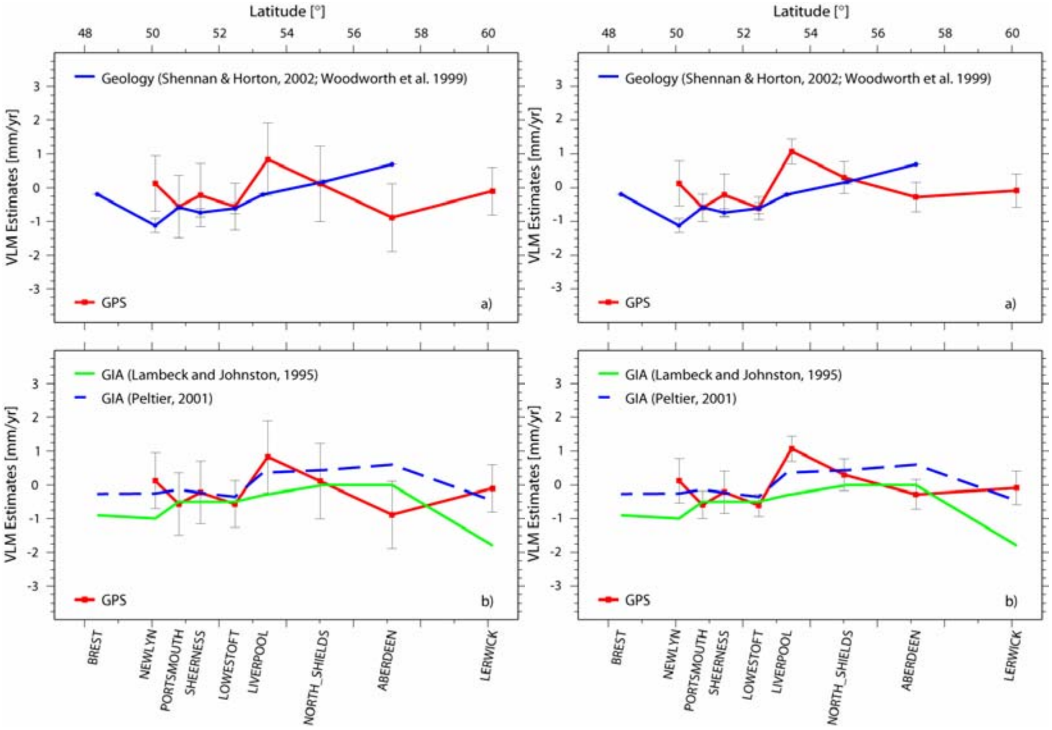

Figure 8 CGPS estimates of vertical station velocities from Solutions 4 (left) and 5 (right) compared to published evidence for changes in the land level of Great Britain

Table 6 Comparison of CGPS estimates of vertical station velocities from the national study and published changes in land level based on the GIA model of Lambeck and Johnston (1995), the GIA model of Peltier (2001) and the geological studies of Shennan and Horton (2002)

Published evidence from GIA/GEOL	Stat.	CGPS minus GIA/GEOL difference in vertical station velocity			
		GAS2.4 DD RNS		BSW5.0 PPP GTS	
		Solution 2 (mm/yr)	Solution 3 (mm/yr)	Solution 4 (mm/yr)	Solution 5 (mm/yr)
Lambeck and Johnston (1995)	Mean	+1.37	+1.15	+0.60	+0.66
	SD	±0.80	±0.80	±0.71	±0.74
Peltier (2001)	Mean	+0.83	+0.60	+0.05	+0.10
	SD	±0.47	±0.49	±0.37	±0.41
Shennan and Horton (2002)	Mean	+1.08	+0.84	+0.45	+0.52
	SD	±0.63	±0.64	±0.56	±0.60

Before considering these results any further, it is worth considering that six of the 12 mean differences could be considered as zero, within the 1-sigma uncertainties given in Table 6, and all could be considered zero at the 2-sigma level. Furthermore, it is clear that CGPS Solutions 4 and 5 are in good agreement with the GIA model of Peltier (2001). Apart from this one GIA model, though, the other mean offsets are of the same sign and of a similar magnitude to the systematic offset between the CGPS and AG estimates of vertical station velocity: those based on GAS2.4 DD RNS being more positive than AG by 1.27 or 1.52mm/yr and those based on BSW5.0 PPP GTS being more positive than AG by 0.56 or 0.59mm/yr. At this stage, therefore, considering all of the published evidence for changes in land level, and the fact that 80% of the differences presented in Table 6 are positive, it is reasonable to conclude that the CGPS, and not the AG, estimates of vertical station velocity are systematically offset from the published changes in land level, with the CGPS estimates of vertical station velocity being more positive than the published changes in land level. In our opinion, therefore, it can be concluded that the CGPS estimates of vertical station velocity presented thus far are systematically offset from the estimates based on AG, due mostly to a systematic bias in current CGPS estimates of vertical station velocity, which is apparent at this demanding, high level of accuracy.

AG-aligned CGPS estimates of vertical station velocity

With this in mind, the question “which is the more correct: AG or CGPS?” would perhaps be better rephrased as “considering that there is a potential systematic bias in the CGPS estimates of vertical station velocity at this demanding, high level of accuracy, how can CGPS and AG be best combined in order to provide an ‘engineering solution’ and obtain some estimates of changes in sea level (decoupled from changes in land level) based on the approximately 8.5 years of CGPS data and 10 or 11 years of AG data acquired to date?”

One such engineering solution was given in Teferle et. al. (2006), who presented a procedure for combining CGPS and AG estimates of vertical station velocities, based on aligning the CGPS estimates to the AG estimates using the systematic offset between them. In Table 6 in the previous subsection, a comparison of the CGPS and AG estimates of vertical station velocity for Newlyn and Lerwick were presented and a weighted mean offset (and corresponding standard deviation) computed to show that the CGPS estimates based on GAS2.4 DD RNS were more positive than the AG estimates by 1.52mm/yr for Solution 2 and 1.27mm/yr for Solution 3, and the CGPS estimates based on BSW5.0 PPP GTS were more positive than the AG estimates by 0.56mm/yr for Solution 4 and 0.59mm/yr for Solution 5.

Following the procedure of Teferle et. al. (2006), to compute an AG-aligned CGPS estimate of vertical station velocity, the systematic offset relating to a particular CGPS solution is basically subtracted from the CGPS estimate of vertical station velocity for a station. Through this procedure, the CGPS estimates of vertical station velocities presented in Table 3 in the previous subsection are changed to the following AG-aligned CGPS estimates given in Table 7, which only shows the reliable estimates (based on the discussions in the previous subsection).

It is clear from Table 7 that, when considering the five longest, homogeneous time series (LERW, LOWE, SHEE, PMTG and NEWL), the AG-aligned CGPS estimates of vertical station velocity from the four solutions are in much better agreement than the corresponding CGPS estimates of vertical station velocity. Without re-presenting Table 3 given in the previous subsection, it can be stated that the mean offset (and corresponding standard deviation) between the estimates of vertical station velocity from the two CGPS software/processing strategies are reduced from +0.89 ± 0.25mm/yr between Solutions 2 and 4, and +0.75 ± 0.23mm/yr between Solutions 3 and 5, when considering the CGPS estimates, to -0.04 ± 0.25mm/yr between Solutions 2 and 4, and +0.04 ± 0.23mm/yr between Solutions 3 and 5, when considering the AG-aligned CGPS estimates.

Table 7 AG-aligned CGPS estimates of vertical station velocities and uncertainties from Solutions 2, 3, 4 and 5 for a selection of eight CGPS stations in the national study

Station name	4 char station ID	AG-aligned CGPS vertical station velocity and uncertainty			
		GAS2.4 DD RNS		BSW5.0 PPP GTS	
		Solution 2 (mm/yr)	Solution 3 (mm/yr)	Solution 4 (mm/yr)	Solution 5 (mm/yr)
Lerwick	LERW	-0.63 ± 0.82	-0.50 ± 0.50	-0.69 ± 0.74	-0.65 ± 0.54
Aberdeen TG	ABER	+0.11 ± 0.68	0.00 ± 0.32		
N. Shields TG	NSTG	-0.97 ± 0.97	-1.20 ± 0.82	-0.48 ± 1.14	-0.26 ± 0.52
Liverpool TG	LIVE			+0.25 ± 1.09	+0.51 ± 0.43
Lowestoft TG	LOWE	-1.47 ± 0.64	-1.28 ± 0.50	-1.16 ± 0.73	-1.17 ± 0.40
Sheerness TG	SHEE	-1.09 ± 0.64	-0.74 ± 0.50	-0.81 ± 0.96	-0.77 ± 0.67
Portsmouth TG	PMTG	-0.85 ± 0.99	-0.79 ± 0.70	-1.15 ± 0.96	-1.15 ± 0.46
Newlyn TG	NEWL	-0.46 ± 1.13	-0.66 ± 0.91	-0.46 ± 0.86	-0.43 ± 0.70

From Table 7, the reliable AG-aligned CGPS estimates of vertical station velocities for stations in Great Britain show a general pattern in which there are negative vertical station velocities for the CGPS stations in England (with the exception of CGPS@TG station LIVE at Liverpool tide gauge in North-West England) and the CGPS station LERW close to Lerwick on Shetland, and a zero or slightly positive vertical station velocity for the

CGPS@TG station ABER at the Aberdeen tide gauge in East Scotland. Expanding on this, it is possible to supplement the comparisons given in Table 7, with comparisons between the 'reliable' AG-aligned CGPS estimates of vertical station velocities for stations in Great Britain and the published changes in land level. These are presented in Table 8.

Table 8 Comparison of AG-aligned CGPS estimates of vertical station velocities from the national study and published changes in land level based on the GIA model of Lambeck and Johnston (1995), the GIA model of Peltier (2001) and the geological studies of Shennan and Horton (2002)

Published evidence from GIA/GEOL	**Stat.**	**AG-aligned CGPS minus GIA/GEOL difference in vertical station velocity**			
		GAS2.4 DD RNS		**BSW5.0 PPP GTS**	
		Solution 2 (mm/yr)	**Solution 3 (mm/yr)**	**Solution 4 (mm/yr)**	**Solution 5 (mm/yr)**
Lambeck and Johnston (1995)	Mean	-0.15	-0.12	+0.01	+0.10
	SD	±0.80	±0.80	±0.71	±0.74
Peltier (2001)	Mean	-0.69	-0.67	-0.54	-0.46
	SD	±0.47	±0.49	±0.37	±0.41
Shennan and Horton (2002)	Mean	-0.44	-0.43	-0.14	-0.04
	SD	±0.63	±0.64	±0.56	±0.60

From Table 8, unlike the consideration of the CGPS estimates of vertical station velocity where only six of the 12 differences could be considered zero within the 1-sigma uncertainties, it is clear that when considering the AG-aligned CGPS estimates of vertical station velocity, all 12 of the differences could be considered zero at the 1-sigma level. However, considering all of the individual values (not shown in Table 8), it is also clear that the best general agreements for all stations are with the published changes in land level based on the geological studies of Shennan and Horton (2002).

At this stage it is worth noting that we should not necessarily expect perfect agreement between the last decade, as represented by the AG-aligned CGPS estimates of vertical station velocities, and the last 10,000 years, as represented by the published changes in land level based on GIA models and geological studies. Nevertheless, for all four CGPS solutions, the AG-aligned CGPS estimates of vertical station velocity are generally more negative than both Peltier (2001) and Shennan and Horton (2002) for all stations; with the principle exception of the CGPS@TG station NEWL, at Newlyn tide gauge near to Land's End in South-West England, which has AG-aligned CGPS estimates of vertical station velocity which are consistently less negative than the published change in land level from Shennan and Horton (2002). This aside, it is reasonable to conclude that the AG-aligned CGPS estimates of vertical station velocity are not systematically offset from the published changes in land level, unlike the CGPS estimates of vertical station velocity which were found to be systematically more positive than the published changes in land level. Hence, the AG-alignment procedure carried out provides an 'engineering solution' from which we can obtain some estimates of changes in sea level (decoupled from changes in land level) based on the approximately 8.5 years of CGPS data and 10 or 11 years of AG data acquired to date, and answer the rephrased question posed earlier in this subsection.

Past changes in land and sea levels

Figures 9 and 10 show the negative of the 'emergence / subsidence (E/S) rate', which are the AG-aligned CGPS estimates of vertical station velocity given in Table 7, plotted against the 'MSL trends' for the past few decades/past century, which are the changes in sea level given in Table 1, based on PSMSL (2005) supplemented with a value for Brest tide gauge in Northern France, based on Woodworth et. al. (1999). The figures are presented in this manner so as to give a positive correlation between the different parameters, and to be consistent with similar plots given in Woodworth et. al. (1999), which used the published changes in land level based on the geological studies of Shennan (1989). When considering Figure 9 it is worth noting that this includes all eight of the CGPS stations listed in Table 7 plus the CGPS@TG station BRST at Brest tide gauge in Northern France, i.e. the CGPS@TG station LIVE at Liverpool tide gauge in North-West England is excluded from Solutions 2 and 3 in Table 7 but included in Figure 9. Similarly, when considering Figure 10 it is worth noting that this includes all eight of the CGPS stations listed in Table 7, i.e. the CGPS@TG station ABER at Aberdeen tide gauge in East Scotland is excluded from Solutions 4 and 5 in Table 7 but included in Figure 10.

In terms of changes in sea level, just considering the vertical spread of the points in Figures 9 and 10, these plots graphically present the values given in Table 1 and show that, with the exception of Lerwick tide gauge on Shetland, the British tide gauges all show a rise in sea level over the past few decades/past century, with a range of values from 0.86mm/yr at Aberdeen tide gauge in East Scotland to 2.49mm/yr at Lowestoft tide gauge on the East coast of England; Lerwick being exceptional as the tide gauge measurements suggest a fall in sea level, of 0.79mm/yr.

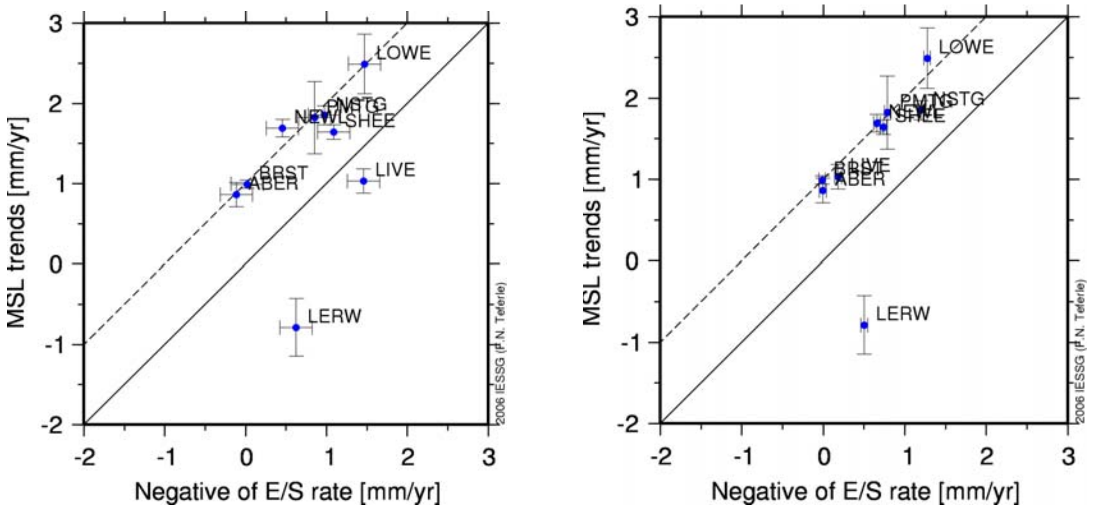

Figure 9 Changes in land and sea levels around the coast of Great Britain and Northern France based on AG-aligned CGPS estimates of vertical station velocities from Solution 2 (left) and Solution 3 (right) in the national study

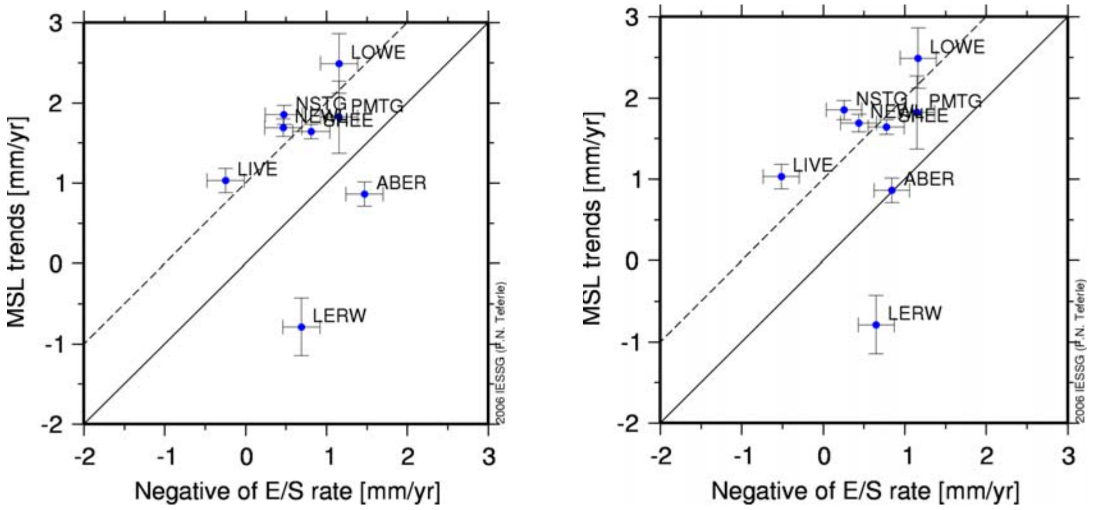

Figure 10 Changes in land and sea levels around the coast of Great Britain and Northern France based on AG-aligned CGPS estimates of vertical station velocities from Solution 4 (left) and Solution 5 (right) in the national study

In terms of changes in land level, just considering the horizontal spread of the points in Figures 9 and 10, and ignoring LIVE in Figure 9 and ABER in Figure 10, these plots visually confirm the results given in Table 7 as showing:

- subsidence (shown by a value greater than zero for the negative of E/S rate) at the non-TG CGPS station LERW, close to Lerwick on Shetland.
- subsidence (shown by a value greater than zero for the negative of E/S rate) at most of the CGPS@TG stations in England: namely NSTG, at North Shields tide gauge in the North-East of England; LOWE, at Lowestoft tide gauge on the East coast of England; SHEE, at Sheerness tide gauge on the Thames Estuary to the East of London; PMTG, at Portsmouth tide gauge on the South coast of England; and NEWL, at Newlyn tide gauge near to Land's End in the South-West of England.
- slight uplift (shown by a value of less than zero for the negative of E/S rate) for the CGPS@TG station ABER, at Aberdeen tide gauge in East Scotland.
- stability or slight uplift (shown by a value of zero or less than zero for the negative of E/S rate) for the CGPS@TG station LIVE, at Liverpool tide gauge in the North-West of England.

In terms of an average change in sea level (decoupled from changes in land level) around the coast of Britain over the past few decades/past century, the solid diagonal line in Figures 9 and 10 would imply a zero average change; whereas the dashed diagonal line would represent an average change of 1.0mm/yr.

Ignoring LIVE in Figure 9 and ABER in Figure 10, as being unreliable estimates of changes in land level, the plots clearly show that for LERW, the fall in sea level from the tide gauge measurements is not matched by an uplift in land level from the AG-aligned CGPS estimates of vertical station velocity. In other words, this would seem to suggest that the Lerwick tide gauge measurements are an anomaly specific to this tide gauge, which is worthy of further investigation.

From Figure 9, excluding LERW and LIVE, an average sea level rise (decoupled from changes in land level) of 0.9 ± 0.2mm/yr is obtained for both Solution 2 and 3; with a clear agreement between NEWL and BRST, i.e. the changes in land level from the AG-aligned CGPS vertical station velocities clearly account for the 0.7mm/yr difference in the change in sea level obtained from the two sets of tide gauge measurements alone. From Figure 10, excluding ABER and LERW, an average sea level rise (decoupled from changes in land level) of 1.1 ± 0.3mm/yr is obtained for Solution 4 and 1.2 ± 0.8mm/yr is obtained for Solution 5. These are slightly greater than those from Solutions 2 and 3, and all four estimates of average sea level rise (decoupled from changes in land level) are slightly less than the value of 1.3 ± 0.3mm/yr given in Bingley et. al. (2006); based on CGPS and AG data for the period up to the end of 2004 only.

All of these estimates of average sea level rise (decoupled from changes in land level) compare well with previously published estimates such as: Woodworth et al. (1999), who computed a value of 1.0 mm/yr using changes in sea level based on the annual MSL time series for the period from ~1900-1999 for Aberdeen, Liverpool, Newlyn, North Shields and Sheerness tide gauges, and changes in land level based on the geological studies of Shennan (1989); and Holgate and Woodworth (2004), who computed a value of 1.5 mm/yr, but which specifically considered changes in sea level based on decadal MSL time series for the more recent period from 1948-2002, for tide gauges in the British Isles and along the North Sea coast in Northern Europe, and changes in land level based on a GIA model of Peltier (2001).

Possibly more interesting than this, in view of the AG-alignment procedure used in the national study, are the recent results of Wöppelmann et al. (2007). These are based on a global study of data from CGPS@TG stations and non-TG stations within 10km of a tide gauge. This study used changes in sea level based on annual MSL time series, in a similar way to Woodworth et. al. (1999), but with changes in land level based on CGPS estimates of vertical station velocity. Furthermore, as this study was carried out as part of the IGS Tide Gauge Benchmark Monitoring (TIGA) Project, the CGPS estimates of vertical station velocity were based on a GAMIT Double Difference (DD) Global Network Solution (GNS) in which absolute antenna phase centre variation (PCV) models were used along with a pre-released version of the ITRF2005; effectively a test of something similar to the new IGS data processing strategy. From this study, Woppelmann et. al. (2007) computed a 'best estimate' of global average sea level rise over the past few decades/past century of 1.3 ± 0.3mm/yr; within which were individual estimates of the change in sea level (decoupled from change in land level) at both Aberdeen and Newlyn tide gauges of +0.7 mm/yr.

In conclusion, therefore, our 'best estimates' for the average change in sea level (decoupled from changes in land level) around the coast of Britain over the past few decades/past century of +0.9 to 1.2mm/yr is slightly higher than the Woodworth et al. (1999) value of +1.0 mm/yr and slightly higher than the Wöppelmann et al. (2007) value of +0.7 mm/yr; but all within agreement, really, when considering the uncertainties in the CGPS and AG estimates at the present time. Apart from this, it is comforting that the AG-alignment procedure appears to have led to AG-aligned CGPS estimates of vertical station velocities that are comparable with CGPS estimates of vertical station velocity which are based on something similar to the new IGS data processing strategy.

Future changes in land and sea levels

The UKCIP has previously calculated regional net sea level change estimates for Great Britain, using predictions of future changes in global sea level and changes in land level based on geological studies. In the UKCIP02 Scientific Report (Hulme et. al. 2002), the predictions of future changes in global sea level were based on (Church et. al. 2001), part of the Third Assessment Report of the IPCC, and the changes in land level were based on Shennan (1989). Since then, these have been updated in November 2005 and August 2006 with the changes in land level based on Shennan and Horton (2002).

The August 2006 UKCIP update presents the net sea level change (relative to 1961-1990) for Scotland and the administrative regions of England. In this respect it should be noted that UKCIP does not provide any estimates for Shetland due to the unavailability of information on changes in land level for this region in Shennan and Horton (2002). Through the national study, an alternative assessment was carried out, with the changes in land level based on Shennan and Horton (2002) replaced by the changes in land level based on the 'most reliable' AG-aligned CGPS estimates of vertical station velocity; these being estimates from Solution 2 for the CGPS@TG stations ABER, LOWE, SHEE, PMTG and NEWL and estimates from Solution 4 for CGPS@TG stations NSTG and LIVE. The results of this are summarised in Table 9.

Table 9 Difference in change in land level (AG-aligned CGPS estimates of vertical station velocity minus values used in the August 2006 UKCIP update based on Shennan and Horton (2002)) and the effect on UKCIP-style rates of net sea level change (relative to 1961-1990) for Great Britain; values from the national study are shown first followed by [values based on the August 2006 UKCIP update]

Station name	**4 char sta ID**	**Diff. in change in land level (mm/yr)**	**Net sea level change relative to 1961-1990 (cm)**					
			Low Emissions 'Low' IPCC Estimate			**High Emissions 'High' IPCC Estimate**		
			2020s	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
Aberdeen TG	ABER	-0.69	+3 [0]	+6 [+1]	+8 [0]	+13 [+10]	+35 [+30]	+68 [+60]
N. Shields TG	NSTG	-0.68	+6 [+3]	+11 [+5]	+14 [+6]	+16 [+13]	+40 [+34]	+74 [+66]
Liverpool TG	LIVE	-0.35	+3 [+1]	+5 [+2]	+6 [+3]	+13 {+11]	+34 {+31]	+66 [+63]
Lowestoft TG	LOWE	-0.67	+11 [+8]	+19 [+13]	+25 [+17]	+21 [+18]	+48 [+42]	+85 [+77]
Sheerness TG	SHEE	-0.29	+9 [+8]	+16 [+13]	+21 [+17]	+19 [+18]	+45 [+42]	+81 [+77]
Portsmouth TG	PMTG	-0.35	+8 [+6]	+14 [+11]	+18 [+14]	+18 [+16]	+43 [+40]	+78 [+74]
Newlyn TG	NEWL	+0.54	+6 [+9]	+11 [+15]	+14 [+20]	+16 [+19]	+40 [+44]	+74 [+80]

When viewed in this manner, it is clear that the overall effect of replacing the changes in land level based on Shennan and Horton (2002) with changes in land level based on the AG-aligned CGPS estimates of vertical station velocity from the national study is that the net sea level change is increased by a few centimetres in all cases except when considering CGPS@TG station NEWL at Newlyn tide gauge near to Land's End in South-West England where the effect is a decrease of a few centimetres. This is obviously a function of the fact that, with the principle exception of the CGPS@TG station NEWL, the AG-aligned CGPS estimates of vertical station velocity are consistently more negative than the published change in land level from Shennan and Horton (2002), as concluded earlier in the subsection.

When considering the predicted changes in global sea level by the 2080s for the high emissions scenario, as these are significantly greater than the changes in land level, such increases or decreases are at the 5 to 13% level of the values given in Table 9. However, when considering the same scenario for the 2050s and 2020s, their effect is increased to 7 to 18% and 6 to 30% respectively. Furthermore, when considering the predicted changes in global sea level for the low emissions scenario, the increases and decreases shown in Table 9 have an effect of between 13 and 200%.

Based on this comparison, it can be concluded that, just as there is a wide range of estimates for changes in global sea level from the various IPCC emissions scenarios, subtle differences in estimates of changes in land level at the sub-millimetre per year level can have a significant impact on the net sea level change, particularly when considering the next few decades.

Main implications of the findings

Considering the information presented in this SID5, the results for the national study demonstrate how:

- the combined CGPS and AG estimates of changes in land level correlate with long term geological and geophysical evidence for the 'tilt' of Great Britain, which have Scotland rising by 1 to 2 mm/yr and the South of England subsiding by up to 1.2 mm/yr.
- the combined CGPS and AG estimates of changes in land level are in general agreement with long term geological and geophysical evidence, in terms of whether there is subsidence or uplift at individual stations, although in some cases there are differences which are of the same order as the changes in land level themselves and are, therefore, significant in relation to any assumptions made regarding future changes in land level:
    - for station LERW, close to Lerwick on Shetland, the estimated subsidence of about 0.5 to 0.7mm/yr is in agreement with the geophysical evidence;
    - for station ABER, close to Aberdeen tide gauge in East Scotland, the estimated slight uplift of up to 0.1mm/yr is about 0.6mm/yr less than both that of the geological and geophysical evidence;
    - for station NSTG, at North Shields tide gauge in the North-East of England, the estimated slight subsidence of 0.3 to 0.5mm/yr is contrary to the geological and geophysical evidence which suggests uplift of 0.2 to 0.4mm/yr;
    - for station LIVE, at Liverpool tide gauge in the North-West of England, the estimated slight uplift of 0.3 to 0.5mm/yr is in agreement with the geophysical evidence but contrary to the 0.2mm/yr subsidence from the geological evidence;
    - for station LOWE, at Lowestoft tide gauge on the East coast of England, the estimated subsidence of 1.2 to 1.5mm/yr is about 0.6 to 1.1mm/yr greater than the geological and geophysical evidence;
    - for station SHEE, at Sheerness tide gauge on the Thames Estuary to the East of London, the estimated subsidence of 0.7 to 1.1mm/yr is up to 0.4mm/yr greater than the geological evidence and 0.5 to 0.9mm/yr greater than the geophysical evidence;

  - for station PMTG, at Portsmouth tide gauge on the South coast of England, the estimated subsidence of 0.8 to 1.2mm/yr is 0.2 to 0.6mm/yr greater than the geological evidence and 0.7 to 1.1mm/yr greater than the geophysical evidence;
  - for station NEWL, at Newlyn tide gauge near to Land's End in the South-West of England, the estimated subsidence of 0.4 to 0.7mm/yr is 0.4 to 0.7mm/yr less than the geological evidence but only up to 0.4mm/yr less than the geophysical evidence.
- when the combined CGPS and AG estimates of changes in land level are considered along with tide gauge estimates of changes in sea level, two estimates for the average change in sea level (decoupled from changes in land level) around the coast of Great Britain over the past few decades/past century can be obtained: the first, based on CGPS and AG data for the period up to the end of 2004, suggests that sea level has risen by 1.3mm/yr, and the second, based on CGPS data for the period up to the end of 2005 and AG data for the period up to September 2006, suggests that sea level has risen by 0.9 to 1.2mm/yr, which is on the low side when compared to published studies of changes in globally averaged sea level.
- the direct estimates of changes in land level at specific tide gauges can be combined with IPCC predictions of future changes in sea level to provide an alternative UKCIP-style assessment of future changes in sea level around the coast of Great Britain.

Further to this, the results for the regional study (Bingley et. al. 2007) demonstrate how:
- when the CGPS and AG estimates of changes in land level from the national study are combined with the EGPS and PSI estimates of changes in land level from the regional study, the estimates of changes in land level for the Thames Region, which range from approximately 0.3mm/yr uplift to 2.1mm/yr subsidence, correlate with certain aspects of the geoscience data sets to explain the pattern of land movements observed on a regional scale.
- when the CGPS and AG estimates of changes in land level from the national study are combined with the EGPS and PSI estimates of changes in land level from the regional study and considered along with the results of a new analysis of the tide gauge data for the Thames Estuary and River Thames, the estimates for the changes in sea level (decoupled from changes in land level) along the Thames Estuary are consistent with those obtained around the coast of Great Britain, i.e. they suggest that sea level has risen by 0.9 to 1.2mm/yr over the past few decades/past century.
- when the CGPS and AG estimates of changes in land level from the national study are combined with the EGPS and PSI estimates of changes in land level from the regional study and considered along with the results of a new analysis of the tide gauge data for the Thames Estuary and River Thames, the combined effect of changes in land and sea levels is a 1.8 to 3.3mm/yr rise in sea level with respect to the land along the Thames Estuary and River Thames over the past few decades/past century.

Possible future work and actions resulting from the research

Throughout this SID5 and Bingley et. al. (2007), the results obtained have served to demonstrate the capability for monitoring long term changes in land and sea levels by using a combination of three complementary monitoring techniques: CGPS and AG on a national scale and CGPS/EGPS, AG and PSI on a regional scale. The results also highlight that the formal uncertainties in any estimates are at about the 0.5 to 1.0mm/yr level, with a further 0.5 to 1.0mm/yr of potential systematic bias being apparent in some instances. The study has also tackled the issue of 'aligning' the CGPS to the AG to overcome the small but significant systematic bias currently present in the vertical station velocity estimates from CGPS at the demanding, high level of accuracy required.

Considering all of the above, this subsection contains a number of recommendations for either improving the confidence we can place on the current results or further actions relating to long term monitoring.

In terms of improving the confidence we can place on the current results, it is recommended that the archived CGPS data for the period from 1997 to 24 November 2006 is re-processed using the IGS's new GPS data processing strategy along with re-analysed global products (satellite orbits, clocks and Earth orientation parameters), either computed by the IGS over the next three years or computed in-house; taking into consideration the latest TRF, using absolute antenna PCV models and applying corrections for ocean tide loading. In principle, this should remove the need for 'aligning' the CGPS to the AG and could result in CGPS coordinate time series with less coloured noise and, therefore, vertical station velocities with lower formal uncertainties. It would then result in new, more reliable, estimates for the changes in land and sea levels for both the national and regional studies.

In terms of further actions relating to long term monitoring it is recommended that on a national scale:
- the CGPS and AG measurements, and their processing and analysis, are continued at thirteen tide gauges around the coast of Great Britain.
  - CGPS measurements at the current ten tide gauges of Sheerness, Newlyn, Aberdeen, Liverpool, Lowestoft, North Shields, Portsmouth, Lerwick, Stornoway and Dover, plus Portpatrick and two others,

    i.e. not necessarily Holyhead and Millport, depending on the Environment Agency's requirements; AG measurements at the three tide gauges of Newlyn, Aberdeen and Lerwick.
  - This should lead to a convergence of the vertical station velocity estimates, removing the changes currently seen when 1 or 2 more years of data are added, and will lead to lower formal uncertainties for any vertical station velocity estimates.
- the AG measurements, and their processing and analysis, are extended to three other CGPS stations in Great Britain, selected based on geological setting.
  - This will enable more comparisons between CGPS and AG vertical station velocity estimates.
- the tide gauge measurements are subjected to a refined analysis, in order to obtain revised estimates of changes in sea level at the thirteen tide gauges which have CGPS stations, considered over specific time periods rather than just taken from PSMSL.
  - This will enable a focus on changes in sea level over the past few decades rather than the past few decades/past century.
- the use of PSI measurements, and their processing and analysis, is extended, following the success of their application in the regional study, to tide gauge sites around the coast of Great Britain which have CGPS stations.
  - This will be a means for assessing the 'local stability' of the CGPS stations and provide information on how applicable the CGPS estimates of vertical station velocity are over a larger coastal area.

All of these will lead to improved estimates for the changes in sea level (decoupled from changes in land level) around the coast of Great Britain over the past few decades/past century but, perhaps more importantly, will establish the selected tide gauges as devices with increasingly concurrent sea level and land level data from where estimates for any accelerations in changes sea level can be obtained. This will enable the validation of climate change model predictions of sea level rise around Great Britain, particularly as we move into the period of increasing variance between the different IPCC scenario predictions, which will lead to a better assessment of risk and more informed decisions on planning and managing flood risk at the coast and in our estuaries.

In terms of further actions relating to long term monitoring it is recommended that on a regional scale:

- the CGPS and EGPS measurements, and their processing and analysis, are continued at three non-tide gauges and four other tide gauges in the Thames Region.
  - CGPS measurements at Barking and EGPS measurements at Riddlesdown and Greenwich Park; EGPS measurements at the four tide gauges of Richmond, Tower Pier, Silvertown and Tilbury.
  - This should lead to improved vertical station velocity estimates and lower formal uncertainties for any vertical station velocity estimates.
- the PSI measurements, and their processing and analysis, are continued in the Thames Region, with the introduction of PSI corner reflectors at selected CGPS and EGPS stations also considered.
  - Further measurements should lead to improved vertical velocity estimates and lower formal uncertainties for all PS points.
  - The use of corner reflectors will enable a direct estimate of changes in land level at a specific location to be obtained and remove the issues over the variations in the values obtained for PS points over relatively small areas of a few hundred metres; however, it should be recognised that their data cannot then go back in time.
- the TG analysis is extended for the Thames Estuary and River Thames.
  - This should lead to improved estimates for changes in sea level, especially considering the number of tide gauges which currently have short period time series.

The recommendations for long term monitoring on a national scale are particularly important in the context of policy needs from the sciences over the next 10 years which were set out in Defra (2004) and include the need for key long-term evidence relating to climate change and the specific requirements for monitoring, reliable regional predictions and a comprehensive understanding of the range of climate change impacts, including sea level rise. In addition to this, the recommendations for long term monitoring on a regional scale are also important in terms of providing a monitoring solution for the Thames Estuary and River Thames that could form part of an adaptive strategy for the long term planning of flood and coastal defences in that region, established as a result of the EA Thames Estuary 2100 project.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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