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Prepared on behalf of the Royal Society by the
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FOREWORD

This report outlines United Kingdom activities in geodesy for the period January 2007 to December 2010. It has been prepared for submission to the International Association of Geodesy (IAG) at its General Assembly in Melbourne, Australia, during the XXVth General Assembly of the International Union of Geodesy and Geophysics (IUGG) in June-July 2011. It is issued on behalf of the Royal Society, the UK's adhering body to IUGG.

Following the pattern of previous UK national reports, this document is not divided according to the four commissions of the IAG but is instead presented as a number of interlinked shorter sections. The objective of this is to emphasize the connections that exist between the various disciplines within the continuum of pure and applied geodesy, and to avoid the difficulties that exist in assigning certain activities to particular sections. It has been prepared by the geomatics research group of the School of Civil Engineering and Geosciences, Newcastle University, from information provided by UK geodesists. The editor wishes to thank all those who have provided this information, and in particular the producers of the 2003 and 2007 UK reports to IAG (Prof. Alan Dodson and Dr David Baker, University of Nottingham) on which this document is based.

The majority of the relatively small UK geodetic community work in the application of the discipline to problems within the full range of the Earth sciences and engineering, and no single learned body encompasses this entire scope. The British Geophysical Association (a joint association of the Royal Astronomical Society and the Geological Society comprising members of either society with interests related to solid Earth geophysics) is one natural "home" in which geodesists are represented, but so too is the Royal Institution of Chartered Surveyors, the Chartered Institution of Civil Engineering Surveyors, and the Royal Institute of Navigation, amongst others. All of these institutions hold meetings with a geodetic slant from time to time, but the majority of geodesy-focused communication within the UK takes place via the JISCmail email distribution lists "geodesy", "satellite-navigation" and "geomatics", or through international journals and institutions.

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1. SATELLITE LASER RANGING

NERC Space Geodesy Facility (SGF)

http://sgf.rgo.ac.uk/

The Space Geodesy Facility is located at Herstmonceux, UK, with funding from the Natural Environment Research Council and the UK Ministry of Defence. It is an observational and analytical facility with a highly productive and precise Satellite Laser Ranging (SLR) system, two continuously operating IGS GNSS receivers, one of the UK Ordnance Survey GeoNet GNSS receivers, a permanent FG5 absolute gravimeter and one of BGS' broadband seismometers that automatically contributes in real time to BGS' British Isles seismic network. A new and very stable active hydrogen maser frequency source drives the timing systems of both the SLR and the long-running HERS GPS/GLONASS receiver. On-site automated meteorological and water table depth observations augment the geodetic observations. The Facility is an International Laser Ranging Service (ILRS) Analysis Centre.

The system is a core ILRS station, making daytime and night- time range measurements to geodetic, gravity-field, altimeter and GNSS satellites at heights of from 300 to 23,000 km. The precision of the range normal points is about 1mm, and the station is ranked among the top ten in the ILRS global network in terms of data productivity and close to the top on precision. The two-laser system is unique in the ILRS worldwide network. One laser is a modern short-pulse, high repetition-rate (2 kHz) instrument, which, in combination with the high-precision event timer, delivers single-shot ranging precision at the 3 mm level. The original 10 Hz laser remains in operation when required for specific applications such as the LiDAR capability, and is also being used regularly for one-way ranging support of the NASA Lunar Reconnaissance Orbiter. Modelling work done by SGF has improved to the mm level the corrections required to relate the Herstmonceux 2 kHz laser measurements to the centres of mass of the geodetic spherical satellites, and this work has been extended to ranges made by the primary ILRS systems.

Laser tracking of the GNSS satellites is set to increase in importance for the ILRS community as new constellations are developed that include laser retro-reflectors on each vehicle for independent orbit determination and quality control. As part of the ILRS discussions about how best to meet this need, a study has been carried out by SGF to test the relative efficiencies of the laser retro-reflector corner-cubes on the orbiting GNSS satellites from the GPS, GLONASS, Galileo (GIOVE) and COMPASS constellations. The results show that the uncoated cubes on the COMPASS-M1 satellite perform better than any of the other, mostly-uncoated cubes in current operational use. This result confirms and supports results from the only other study, which used a ground-based test facility, and is likely to inform best practice standards for future high-orbiting missions.

The Facility is an ILRS Analysis Centre and daily computes seven-day-arc, global station coordinates and Earth orientation solutions in support of the ILRS’ contribution towards ITRF realisation work and rapid Earth orientation results for the IERS. A re-analysis of all global laser data taken since 1983 to the geodetic (two LAGEOS and two ETALON) satellites has been completed, taking account of historical range corrections and other modelling issues, and combined with all the AC's solutions by the ILRS Combination Centres to form the laser ranging contribution to the ITRF2008, published by the IERS in late-2010.

2. GLOBAL NAVIGATION SATELLITE SYSTEMS

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Determination of the effects of GPS performance and failures on aviation applications. The aim of this project was to answer the questions - how do GPS Signal-In-Space anomalies, GPS receiver failures, and abnormal events (e.g. interference, ionospheric effects or satellite outages) affect navigation performance of an aircraft, and how does an air traffic service deal with such events in the operational environment? The initial phase of this project identified the failure modes (or anomalies) and specified the failure (threat) models. The second phase then used the models to carry out a detailed assessment of the performance of the state-of-the-art integrity (anomaly protection) algorithms, identified a number of weaknesses and developed new algorithms, for example, for the detection of failures that grow slowly over time. A detailed simulation based methodology and software (that account for the relative movement between aircraft and satellites, and aircraft dynamics and attitude) were developed also for a realistic validation of the capability of GNSS to support air navigation and linked to actual operations – thereby enabling an assessment of how air traffic service providers deal with the effects of failures. This is superior to the methodology currently recommended by the International Civil Aviation Organisation involving a number of selected geometries at static locations around the world and with no obvious link to operations. The research was carried out by Imperial College London and initially with the University of Leeds and Helios Technology. The results of this research were presented at the US Institute of Navigation's GNSS Conference in September 2009 (in Savannah, Georgia) and won a Best Paper Award.

GNSS Availability Accuracy Reliability anD Integrity Assessment for timing and Navigation (GAARDIAN). The benefits GNSS and in particular GPS, have been demonstrated worldwide, and continue to accrue in the form of new applications. Many of these applications are mission (e.g. safety) critical, in the sense that if the service fails (provides a significantly erroneous solution without annunciation within a given time) or is unavailable (provides no solution or one with an insufficient guarantee), users are either placed in danger or negative financial and/or social consequences may occur. Today, mission critical applications (largely driven by safety) mostly in aviation and to a less extent maritime, rely on one or more of Ground Based Augmentation Systems (GBAS), Space Based Augmentation Systems (SBAS) or Receiver Autonomous Integrity Monitoring (RAIM), and its variations for the provision of integrity monitoring services. However, for many applications such as those associated with the emergency services, road user charging and personal navigation devices, no such monitoring exists and service validation is limited due to technical and cost constraints. The problem is exacerbated by a recent increase in more challenging problems particularly in the security industry in which jamming and interference devices have been used to disrupt the use of GPS. These complex situations make the detection, identification and isolation of failures a very difficult process.

GAARDIAN is designed to for the first time in the world, offer a cost effective (24x7) local solution to signal interference and jamming at the individual user level, by providing the user with information on Quality of Service (QoS). The system is based on the deployment of a single or network of probes (sensors) supported by an existing regional network. The probes communicate with a central server and are designed to detect localised events (through novel and innovative processes and algorithms in the measurement and positioning domains) whilst the regional network isolates space segment anomalies. GAARDIAN design includes novel techniques for the reduction of data transmitted between the probe network and server. The users access the QoS information via a common web browser quickly and easily. Imperial College London identified the relevant applications and their requirements, subsequently translated into system requirements and used in the specification of GAARDIAN's functional and physical architecture. The detailed design included the specification by Imperial, of novel measurement and position domain algorithms housed in the probes, and server algorithms that exploit a regional network of monitoring stations to detect and isolate regional anomalous events thus in addition, facilitating the reduction of data transmitted from the probes to the server. GAARDIAN was validated by UK-wide experimental network of probes that monitor signals from both GPS and eLORAN – an alternative system unaffected by GPS signal interference sources (http://217.204.106.234).

Enhanced Precise Point Positioning with GNSS. High accuracy positioning with Global Navigation Satellite Systems (GNSS) requires the use of carrier phase measurements. The conventional approach for dynamic positioning referred to as Real Time Kinematic (RTK) employs at least two receivers operating simultaneously. Recently, significant research effort has been dedicated to the concept of Precise Point Positioning (PPP) in which a single receiver is used. This has the potential advantage over the conventional method of being less expensive and widespread application, particularly in remote and the developing parts of the world. Carrier phase measurements can be used directly as observations (e.g. in single frequency PPP) or through the derivation of observables based on the raw measurements (e.g. the double differenced observable in RTK). In both cases, the determination of the correct corresponding integer number of the carrier cycles (integer ambiguity) is the key to the high positioning accuracy. This project developed advanced techniques and algorithms that significantly improve the performance of the current PPP methods in terms convergence and positioning accuracy (through integer ambiguity resolution). Furthermore, it has made it possible, for PPP, for the first time, to be used for mission critical applications by developing the required integrity monitoring algorithms. The work was funded by the European Space Agency (ESA) and was carried out in close collaboration with the Universitat Politècnica de Catalunya (UPC) in Barcelona, Spain.

Future GNSS Integrity monitoring for Aviation. This work was undertaken in support of the European Space Agency's future research and development in GNSS and its applications. It's main aim was realise a deep understanding of the state-of-the-art in navigation system integrity monitoring with a particular focus at the user level. The work:

- reviewed the state-of-the-art in integrity monitoring covering three levels (ground segment, space segment and user segment),
- reviewed the state-of-the-art in user segment based integrity monitoring (i.e. Receiver Autonomous Integrity Monitoring – RAIM - and its variations,
- assessed the future developments (2020+) in RAIM taking account of the enhanced and new Global navigation Satellite Systems (GNSS) in terms of signal diversity, redundancy and better signal characteristics. Current ideas and concepts under discussion from around the world will be appraised including the GNSS Evolutionary Architecture Study (GEAS) commissioned by the US Federal Aviation Administration (FAA) to explore candidate integrity architectures for air navigation with modernised GNSS.
- investigated the feasibility of the evolution and apportionment of integrity monitoring to the ground, space and user segments, with the objective of supporting the navigation requirements for all phases of flight.
- recommended R&D activities and initiatives to support the European Space Agency.
- identified the issues of relevance to international agreements on the role of RAIM to safe air navigation.

iNSight (Innovative Navigation Using New GNSS SIGnals with Hybridised Technologies). New signals from developing and modernized satellite navigation systems will present opportunities for accurate and reliable positioning in many more situations than are possible with current systems.

Successful exploitation of these new signals will enable the development of markets and applications that will depend on positioning and timing information in all environments, not just the relatively benign outdoor environments that suit the current Global Navigation Satellite System (GNSS) systems. However, the full benefits of these new signals will only be realized when a number of significant scientific and technical barriers have been overcome. Therefore, the primary aim of iNsight is to undertake the basic research needed to exploit the new signals from modernised and new GNSSs, from receiver design to delivering positioning, tracking and navigation-based products to users. The main component research thrusts are (i) signal acquisition and tracking techniques, (ii) integrity, quality control and assessment, (iii) orbits and clock transformation models, (iv) multipath detection, modelling and mitigation, (v) modelling of atmospheric effects, (vi) systems integration, and (vii) development of evaluation platforms and testing.

The research is being undertaken by Imperial College London in collaboration with three other leading academic GNSS research centres at University College London, the University of Nottingham and the University of Westminster. Imperial College is leading the work on integrity monitoring (fault detection and exclusion) for centimetre level positioning with carrier phase measurements both for conventional Real-Time Kinematic Positioning (RTK) and Precise Point Positioning (PPP).

The project is funded the UK's Engineering and Physical Science Research Council (EPSRC). Furthermore, it is supported by, and involves collaboration with, eight commercial companies and government agencies: the Civil Aviation Authority, EADS Astrium, Leica Geosystems, Nottingham Scientific Limited, Ordnance Survey, QinetiQ, ST Microsystems, and Thales Research and Technology UK Limited.

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Precise Point Positioning (PPP). The major contribution of the University of Nottingham in PPP includes these following elements:

- Further development and enhancement to the PANDA software, a software tool originally developed by Wuhan University in China
- Implementation of PPP integer ambiguity resolution by applying improved satellite products (orbit and clock) and through use the fractional-cycle biases (FCBs) that have been separated from the integer ambiguities of a network solution
- Significant reduction in PPP convergence time through PPP integer ambiguity resolution
- Development of an effective approach for PPP re-convergence
- Use of the above PPP research achievements to tackle the issues in geo-hazard monitoring, especially for the development of tsunami early warning systems

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Real-time positioning. Newcastle's Engineering and Physical Sciences Research Council project ("AutoBahn") focused on real-time GPS satellite orbit and clock determination and subsequent ground-station positioning. The deterministic least-squares batch processor in BAHN has been replaced by an Extended Kalman Filter facilitating continuous computation of GPS satellite orbits and clocks and other receiver and satellite parameters. Zhang et al. [2007] describe the underlying methodology behind the Extended Kalman Filter approach as required to handle GPS phase and code data from a global network of GPS tracking stations. In addition, details are presented about the replacement of global, arc-dependent and epoch-dependent deterministic parameters by stochastic processes. Accuracies for the GPS orbits and clocks achieved with Auto-BAHN are illustrated through comparisons with IGS final solutions. 3D RMS values of the orbital differences varied between 10.0 and 29.9 cm with a mean RMS value of 13.6 cm. The mean difference compared against the IGS satellite clock corrections is about 0.29 ns with standard deviation of 0.04 ns.

More recent work (King, 2009) on kinematic positioning has focused on the use of GPS in support of airborne LIDAR measurements, and shown that advanced processing algorithms can achieve accuracies as good as 0.22 m (95th percentile) for baselines as long as ~1000 km, in contrast to commercial software which exceeds this for baselines as short as ~50 km.

Systematic Errors. Extensive studies of the propagation of unmodelled periodic ground displacements into GPS coordinate estimates and time series used in geophysical studies are detailed in Penna et al. (2007). It has been demonstrated that unmodelled semi-diurnal and diurnal tidal displacements can propagate to fortnightly, semi-annual and annual signals, purely due to the GPS constellation repeat period and basic functional model used. Unless all tidal displacements are perfectly modelled, geophysical interpretation of such GPS coordinate time series can be problematic, and provides further evidence of how tidal models must be as accurate as possible across all regions of the world. Building on this work, King et al. (2008) examined sub-daily signals in satellite orbits and clocks and showed how they propagated to longer periods in conventional 24 h solutions. Unmodelled sub-daily signals with amplitudes up to 10-15 mm were observed, including at the frequencies of S1 and S2 and near those of K1 and K2. These were shown to propagate into 24 h solutions with (among other frequencies) annual and semi-annual periods with amplitudes up to 5 mm, with a median amplitude in the height component of 0.8 mm (annual) and 0.6 mm (semi-annual). They are shown to bias low-degree spherical harmonics estimates of geophysical loading at the level of 5–10%, although the exact effect will be network dependent. More recent GPS signal modelling studies have focused on the propagation of unmodelled subdaily signals into spurious long period signal, including mean bias, offsets, periodic signal, velocity bias and high frequency noise (King and Watson, 2010).

By considering sites around the southern North Sea, Williams and Penna (2011) showed that reprocessed GPS height time series exhibit non-tidal ocean loading effects of comparable size to atmospheric pressure loading, and hence should be modelled. Correcting for the effect using a high-resolution numerical ocean model achieved an 11% better GPS height variance reduction than when using a lower resolution global ocean model

Sidereally-repeating (predominantly multipath) error has been studied by Ragheb et al (2007), who confirmed previous findings that the dominant “sidereal” repeat period is in fact 10 s less than the true sidereal interval. They showed that in a double-difference single epoch processing strategy, the use of a common repeat period is adequate and that a filter based on residual coordinate differences is marginally superior in precision but significantly slower than one based on double difference residuals. Stacking of residuals for 7 days prior to filter application yields the most effective filter.

Stability of monumentation has been addressed by King and Williams (2009), who concluded that this can induce time-correlated errors with significant effects at sub-daily and annual periods. Multipath errors can cause similar effects, and when coupled with changes in the GNSS constellation may induce velocity errors (King and Watson, 2010).

2a. GNSS – ATMOSPHERIC STUDIES

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The international reference ionosphere (IRI2007) and International Geomagnetic Reference Field (IGRF2005) models are used to create a worldwide model of apparent Global Navigation Satellite Systems (GNSS) site displacements due to unmodelled higher-order ionospheric delays for different time, seasons, and phases of the solar activity cycle. It is shown that diurnal and seasonal variability of the higher-order ionospheric delays causes apparent oscillations of the geometric centre of the Earth's figure as determined by GNSS. The amplitude of the oscillations in the z direction reaches 2.5 mm for the semiannual and 3.5 mm for 11 year components when satellite orbits are considered fixed and degree 1 parameterization is used. Failure to account for the higher-order ionospheric delay when performing precise orbit determination for space-borne receivers, flying above, while the ground-based fiducial network is located below the ionosphere, will result in biases between the ground and the space segment. Such biases, changing with time and location, can cause difficulties in interpretation of results from satellite altimetry and satellite gravity missions, as systematic biases in orbital parameters can be interpreted as manifestations of geophysical processes. On the basis of the results presented, it is recommended to introduce the modelling of the second-order ionospheric delay in routine GNSS processing for global geodetic networks, especially in view of the forthcoming solar activity maximum.

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Troposphere. Thomas et al. (2011) produced precipitable water vapour (PWV) estimates from a global GPS reanalysis and compared them to estimates from independent radiosonde and satellite based techniques. They showed a reduced bias in the GPS PWV compared to those from radiosonde data, and concluded that much of the bias in previous GPS-radiosonde studies could be attributed to deficiencies in the GPS observation modelling.

Ionosphere. Several outputs (Petrie et al., 2010a, 2010b, 2011) considered the effects of higher order ionospheric terms on GPS coordinate time series, velocities, reference frame parameters and tropospheric zenith delay terms, again within the context of a global GPS reanalysis.

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Modelling, Forecasting and Mitigation of Ionospheric Scintillation on GPS. Recently, the School of Electrical Electronics and Computer Engineering (EECE) extended its area of research to the field of GNSS. This includes ionospheric scintillation monitoring, modelling, forecasting and mitigating its effects on GPS positioning. Currently main topics of investigation in the GNSS and Ionospheric Group in the EECE include the investigation of ionospheric scintillation effects on GPS receivers, modelling transionospheric propagation (including "higher order" errors) and scintillation for different conditions and developing tools/algorithms to accurately correct for the ionosphere delay/phase advance and mitigate scintillation effects.

Ionospheric Effect on GNSS. A major threat to GNSS is in the equatorial and high latitude regions where large GPS range errors are observed [*Tiwari et al*., 2008; 2009; 2010; 2011a,b;]. In addition to the poor precision if these are not corrected, the rapid random fluctuation of phase and amplitude of GPS signal called scintillation are also observed. *Tiwari et al*., (2011) have observed the effect of scintillation on PLL of GPS receivers and it is observed that, during strong scintillation, the PLL of the GPS receiver loses phase lock, resulting in no availability. *Gherm et al*., (2011) investigated the effect on dual frequency GPS range error due to diffraction on local random inhomogeneities of the ionosphere which results to some tens of centimetres during strong scintillation. Since the errors are random, dual frequency ionospheric correction models won't be an effective solution during scintillation periods. In order to mitigate these effects, various GISTM based (GPS Ionosphere Scintillation and TEC Monitoring) GPS receivers are being installed over the European region in collaboration with Bath and Nottingham universities with also the participation of four companies with interests in GNSS. These receivers will enable extensive monitoring of scintillation activities in both the European high latitude region and at low latitude stations. Collaborative work with University of Calgary, Canada also enables access to the Canadian GPS Ionospheric Monitoring stations for study of the characteristic of high latitude ionospheric scintillation in Canadian region.

Ionospheric Scintillation Monitoring and Modelling. *Tiwari et al*. (2010) investigated the high-latitude ionospheric scintillation over the Canadian region using GPS receivers covering sub-auroral and polar regions. In addition, a network of ground-based magnetometers was used in estimating dynamic auroral boundaries. Based on the auroral boundaries, auroral and polar scintillation is clearly differentiated. The study also observed that the maximum scintillation is well-correlated with the peak in electron density at 115 km altitude. This E-region enhancement is due to the precipitating electrons [*Skone et al.,* 2008; 2009; *Tiwari et al*., 2010]. Furthermore, *Tiwari et al*., (2011) extended the investigation of characteristics of high latitude ionospheric scintillation over the European region utilising an extensive data set of GPS observations made between 50° N and 75° N latitude for year 2003 in Northern Europe. A novel method of determining the spectral parameters, the value of *p* and hence also *pi* from just scintillation indices is proposed in *Strangeways (2009)* and used in *Strangeways et al (2011)* and *Tiwari* (2011). This method obviates the need for *in-situ* measurements or calculating PSDs from high (e.g. 50 Hz) rate data for determining scintillation parameters used to estimate tracking jitter variance in GPS receivers. Further, in "Effects of diffraction by ionospheric electron density irregularities on the range error in GNSS dual-frequency positioning and phase de-correlation" by *Gherm et al*. (2011), the correlation of the received signals at different frequencies is determined for different scintillation levels including the case of strong scintillation. This is accomplished by simulating the fields for two frequencies on the ground, and taking account of their cross-correlation. Also the errors in the two-frequency range finding method caused by scintillation are determined for a realistic fully three-dimensional model of the ionospheric turbulence for 5 different frequency pairs [L1/L2, L1/L3, L1/L5, L2/L3, and L2/L5]. The results show the dependence of diffractional errors on the scintillation index S4 and that the errors diverge from a linear relationship, the stronger are scintillation effects, and may reach up to ten cm, or more. It also shows that the correlation coefficients for different pairs of frequencies depend on the procedure of phase retrieval, and reduce slowly as both the variance of the electron density fluctuations and cycle slips increase.

Over a number of years, a physics-based transionospheric simulator, the SPLN (St. Petersburg-Leeds-Newcastle) has been developed in collaboration with the Dept. of Radio Physics, University of St. Petersburg to simulate the ionospheric scintillated radio signal. The vision is to use the SPLN in conjunction with the GPS software receivers to mitigate the ionospheric scintillation affect in real time. The SPLN transionospheric simulator is capable of estimating the statistical characteristics of transionospheric radio signals in strong scintillation conditions and can simulate time series of the phase and log-amplitude of the signal, as well as its amplitude and phase spectra at a ground-based receiver. The input parameters for this simulator are: electron density profile for background ionosphere obtained from the NeQuick model, the geomagnetic and solar activity indices, the spectral index, cross-field outer scale and aspect ratios of the irregularities and the carrier frequency of signal along with the elevation and azimuth angle of the visible satellite. *Maurits et al*., (2008) used three-dimensional inverse power law spectrum of time-varying irregularities over UAF EPPIM (University of Alaska Fairbanks Eulerian Parallel Polar Ionosphere Model) to simulate realistic scintillation effect in high latitude region where and polar patches occur. Zernov et al. (2009) have also determined the effects of scintillation of low latitude bubbles on transionospheric paths of propagation and shown that theoretical results compare favourably with experimental results. The active participation of group members in the European ionospheric research under COST can be discerned in the joint review papers *Beniguel et al*. (2009), *Warnant et al*. (2009) *Radicella et al, 2009* and *Strangeways et al (2009)* which, inter alia, include many results on scintillation monitoring and modelling results.

Ionospheric Scintillation Mitigation on GPS. The GNSS and Ionospheric Group at EECE works is also working in joint collaboration with the University of Nottingham and Sao Paulo State University to mitigate ionospheric scintillation effect on the GPS position solution. There are some effective algorithms such as double difference, dual frequency and ionosphere-free method to improve GPS positioning. However these algorithms have some shortcomings and are not effective during strong ionospheric scintillation or for correction of "higher order" errors. In particular, in the double difference method, fixing the ambiguity resolution is the major concern in GPS positioning in addition to the rate of fixing. *Abdullah et al*. (2009; 2010) proposed a model "improve ambiguity resolution rate with an accurate ionospheric differential correction", which shows significant improvement in rate of and the accurate correction of the differential ionospheric delay. The most significant threat in GNSS is, however, the loss of lock. S*trangeways et al*. (2011) determined the spectral parameters and tracking jitter to improve the GPS solution during strong scintillation period. The group also works on GPS software receivers that will be more robust in scintillation conditions. Generally, the scintillation induces excess carrier phase jitter in the phase lock loop (PLL) of the GPS receiver, and strong scintillation can cause a conventional PLL to lose phase lock resulting in no GNSS signal available at that time. GPS software receivers assisted with an ionospheric model have been used to prevent loss of lock during ionospheric scintillation periods by *Tiwari et al*. (2011).

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http://www.nottingham.ac.uk/iessg/

Meteorology – GPS near real-time processing. Since 2002, the IESSG has been developing GPS near real-time (NRT) processing systems for the UK Met Office. The original system provides hourly updates of 15-minute tropospheric zenith total delay (ZTD) and integrated water vapour (IWV) estimates and, since 2007, these have been included in the EUMETNET (Network of European Meteorological Services) GPS water vapour project (E-GVAP) Project and assimilated in the Met Office's operational numerical weather prediction model. In this regional (European) hourly GPS ZTD/IWV NRT processing system (METO), the processed network includes about 300 stations and fully covers the British Isles and, with a lower density, most Western European countries. Over the period from 2007 to 2010, the original system has been complemented by a global hourly GPS ZTD/IWV NRT processing system (METG), for which the processed network of about 300 stations includes a sampling of UK and European stations integrated with stations in the global International GNSS Service (IGS) network. Following on from these, the most recent development has been a regional (European) sub-hourly GPS ZTD/IWV NRT processing system (METS). This is a move from processing data every hour to processing data every 15 minutes, thereby reducing the latency of the output so that the estimates are not just useful for assimilation in numerical weather prediction runs that take place every few hours, but can also be used in relation to severe weather events, such as thunderstorms.

2b. GNSS – ENGINEERING APPLICATIONS

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Vertical land motion – CGPS processing and coordinate time series analysis. Through involvement in the EU-funded European Sea Level Service – Research Infrastructure (ESEAS-RI) project, the IESSG has carried out research on GPS Precise Point Positioning (PPP), continuous GPS (CGPS) processing/analysis strategies and the time series analysis of CGPS coordinates for studying high accuracy vertical land motion. In Teferle et al. (2007b), we assessed the use of PPP within the Bernese GPS software (BSW) version 5.0 using data from the global International GNSS Service (IGS) network for the period from 2000 to 2004. Following this, in Kierulf et al. (2008), we compared the independent results from six different ESEAS analysis centres (ACs), using three different GPS processing softwares and a number of different analysis strategies on data over a period from 2000 to 2003. This comparison revealed differences in the day-to-day variations of the coordinate time series and in the seasonal cycle contained in these, along with systematic differences in vertical velocities, depending on software and strategy used, and suggested that the reference frame and its relation to the centre of mass of the Earth system may be the main limitation in achieving the accuracy goals of better than 1mm/yr for vertical land motion. Then, in Teferle et al. (2008), the same CGPS coordinate time series were analysed, using the coordinate time series analysis software (CATS), to determine highly accurate vertical station velocity estimates with realistic uncertainties, using maximum likelihood estimation (MLE). Empirical orthogonal function (EOF) analysis was also used to study both the temporal and spatial variability of the common modes in the different ESEAS AC solutions.

Monitoring changes in land levels for flood risk management along the Thames Estuary. Since 1997, Defra and the Environment Agency have been funding research to measure long term changes in land and sea levels around the coast of Great Britain and along 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). Such measurements represent a major challenge and the research carried out included three complementary monitoring techniques: continuous GPS (CGPS); absolute gravity (AG); and persistent scatterer interferometry (PSI) and an investigation of how best to combine the information from these to meet these aims. From 2003 to 2007, the research work was carried out as a national study and a regional study. For the national study, CGPS stations were established at ten tide gauges around the coast of Great Britain and AG measurements were 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 were analysed and the changes in land level interpreted using various geoscience data sets. The regional study was funded by the Environment Agency and was a collaboration between the IESSG, the Natural Environment Research Council (NERC) British Geological Survey (BGS), the NERC National Oceanography Centre, Liverpool (formerly Proudman Oceanographic Laboratory) and Nigel Press Associates Ltd (NPA). The results for the regional study demonstrated how when the AG and CGPS estimates of changes in land level from the national study were 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, correlated with certain aspects of the geoscience data sets to explain the pattern of land movements observed on a regional scale (Bingley et al. 2007).

Furthermore, when these results were considered along with the results of a new analysis of tide gauge data, the combined effect of changes in land and sea levels was 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 (Bingley et al. 2007). The results were also published as (Bingley et al. 2008) which considered how long term planning for flood risk management in coastal and estuarine areas requires timely and reliable information on changes in land and sea levels, described how we produced the detailed, high resolution map of current changes in land levels for the Thames region, and discussed the potential benefits of extended monitoring for the long term planning of flood and coastal risk management in that region.

Network RTK GNSS and its wide applications to ITS and LBS. In partnership with Leica Geosystems (UK), the University of Nottingham has established a test-bed Network RTK GNSS facility that consists of 16 reference stations and covers 20,000 square kilometres in the Midlands region of the UK. This facility has been extensively used to assess and implement the quality assurance measures of NRTK data services from an end user point of view, support research projects sponsored by ESA, EU FP6 and FP7 and national research agencies, and assist various teaching activities at the University of Nottingham. Wide exploitation of NRTK GNSS for Intelligent Transport Systems and Services and Location-based Services has also been conducted in recent years and this has stimulated very fast adoption of NRTK GNSS positioning for mass-market applications and provided opportunities to explore its future potentials for many new applications. In this period of time, a NRTK enabled low-cost open positioning platform could provide better than decimetre real-time positioning solutions has been developed and is used for the feasibility studies in road user charging, precision agriculture and lane departure warning applications.

School of Civil Engineering and Geosciences, Newcastle University

http://www.ceg.ncl.ac.uk/geomatics/research/geodesy.htm

Newcastle University have produced Best Practice Guidelines for using Network RTK in Great Britain, through a study commissioned by The Survey Association, Leica Geosystems, Trimble, Ordnance Survey and the Royal Institution of Chartered Surveyors, the scientific findings of which are detailed in Edwards et al. (2010).

2c. GNSS – OCEANOGRAPHIC STUDIES

National Oceanography Centre Southampton

http://noc.ac.uk/

Applications of GNSS-Reflectometry for ocean remote sensing. Over the past decade, scientists at the National Oceanography Centre Southampton have investigated applications of reflected GNSS signals for ocean remote sensing. The technique, known as GNSS-Reflectometry (GNSS-R), is an innovative concept that relies on detecting signals from navigation satellites such as the Global Positioning System (GPS), GLONASS or Galileo constellations after they are reflected from the ocean surface. Reflected GNSS signals carry information about the roughness of the sea surface (related to ocean surface winds and sea state) and about mean sea level, making it relevant to both scatterometric and altimetric applications. Thanks to the dense and global coverage of GNSS signals, this application of GNSS signals of opportunity could lead to dramatic improvements in spatio-temporal sampling of the ocean surface, with particular relevance to near-real time operational ocean forecasting.

Working closely with engineers at Surrey Satellite Technology Ltd (SSTL) and at the University of Sannio, Italy, NOC recently demonstrated that signals of opportunity from GPS satellites can be successfully exploited to measure directional roughness of the sea surface from space (Clarizia et al., 2009). Based on data from the pioneering experiment onboard SSTL's UK-Disaster Monitoring Satellite (Gleason et al. 2005), this is the first time that directional mean square slope estimates were retrieved from a GNSS-R receiver flown on a Low-Earth Orbiting satellite. Validation against in situ and models confirmed that the measurements have scientific value. The method offers improved sampling capability of ocean wind and waves by means of a very modest instrument that can easily be fitted on small satellites. Further developments of the inversion algorithms (Clarizia et al., 2011) and of the hardware GNSS-R receivers are taking place at NOC and SSTL, with support from the Centre for Earth Observation Instrumentation (CEOI; htp://www.ceoi.ac.uk/) and NERC. Further work is anticipated in preparation for the launch by SSTL of the UK TechDemoSat satellite in 2012, that will carry a new generation of GNSS-R receivers for ocean remote sensing.

Staff at NOC are also engaged in the development of new GNSS-R hardware receivers designed to exploit the capability of GNSS-R for ocean altimetry, working with engineers at EADS Astrium, UK and Starlab, Barcelona, Spain. For example, NOC recently provided data and oceanographic support for the processing and validation of mean sea level measurements from the PARIS Airborne Demonstrator system developed by EADS Astrium in a project funded by the European Space Agency.

3. NATIONAL AND CONTINENTAL NETWORKS

Department of Earth Sciences, Oxford University

http://www.earth.ox.ac.uk/

Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET+). COMET+ continues to maintain and develop regional continuously operating GPS networks in Greece (in cooperation with the National Technical University, Athens) and Turkey (in cooperation with General Command of Mapping). Considering the value of real-time cGPS data for tsunami warning systems in the Eastern Mediterranean, efforts have been made to establish real-time communications with the sites using ADSL and GPRS technology.

Institute of Engineering Surveying and Space Geodesy, Nottingham University

http://www.nottingham.ac.uk/iessg/

The British Isles continuous GNSS Facility (BIGF), http://www.bigf.ac.uk. BIGF, hosted by the IESSG, has been operating since 1998 and is the long term repository for continuous GNSS (CGNSS) data recorded by a network of over 160 CGNSS stations established throughout the British Isles; including the Ordnance Survey of Great Britain and Ordnance Survey of Northern Ireland active stations along with other stations provided by Defra, the Environment Agency, the IESSG, Leica Geosystems, the UK Met Office, the National Physical Laboratory, the Natural Environment Research Council (NERC) National Oceanography Centre, Liverpool (formerly Proudman Oceanographic Laboratory), the NERC Space Geodesy Facility at Herstmonceux, and Newcastle University. In 2002 BIGF gained funding from NERC to become one of its prestigious facilities. BIGF collects raw data, archives quality-assured raw data, and acts as the expert interface between the scientific user population and the archive. In general the quality-assured raw data have a two-fold utility: in the improvement of positional accuracy for a wide range of scientific applications; and in the study of embedded environmental signals, notably long-term land motions and changes in atmospheric water vapour. Total usage by scientists since inception amounts to around 2.75 million station-days of quality-assured raw data, supplied to over 1,000 discrete projects. Science involving very high precision studies of global and regional change, that have been carried out by users of quality-assured raw data includes: studies of changes in sea level related to the validation of climate models and flood and coastal risk management by monitoring vertical land motion at tide gauges; testing and developing models for geophysical effects such as glacial isostatic adjustment and tidal loading; monitoring horizontal land motion in relation to geophysical and geological phenomena occurring on a national or regional scale, such as plate tectonics, intra-plate tectonics and faults; integration with persistent scatterer interferometric SAR as used in regional and local deformation monitoring, and in studies of neotectonics, sediment compaction and shrink/swell; assimilation of near real-time tropospheric integrated water vapour estimates into high resolution models for understanding the processes governing hazardous weather, storms and floods; studies of long-term variations in tropospheric integrated water vapour estimates for the validation of climate models; and atmospheric sensing in the estimation of ionospheric total electron content. Scientific applications using CGNSS station reference data have included: wildlife and farm animal tracking; forestry surveys; vegetation and habitat mapping; landscape monitoring and management; spatial and temporal aspects of foraging and grazing; topographic surveys for the evaluation of renewable energy sites; coastal cliff erosion monitoring; hydrological and hydraulic modelling of rivers and estuaries; urban and mining subsidence; beach surveys; slope stability and landslides; sea state monitoring; hydrological and hydraulic modelling of rivers and estuaries; spatial and temporal monitoring and tracking of ground-based contaminants; geo-referencing of ground-based and airborne air quality sensors; the development of geospatial acquisition, visualisation and analysis tools for field-based scientists; improved tropospheric corrections for satellite altimetry, space-borne imaging, airborne LiDAR and multi-spectral imaging; calibration and validation of novel techniques for the processing of interferometric SAR data. Following its latest funding renewal in 2008, BIGF has moved forward to widen its scientific user base by: handling both 30 second and 1 Hz data, to enable increased positioning rates for dynamic applications; developing derived products, in the form of homogenous time series of parameters including station velocities, tropospheric integrated water vapour and ionospheric activity, to facilitate scientific users who are interested in these parameters but do not want to carry out their own high-level processing of GNSS data. The archive currently comprises 1,150 station-years of 30 second, primarily GPS data, with some stations operating since 1996/7; and since August 2009, 30 second GPS+GLONASS and 1Hz GPS+GLONASS data from about 100 CGNSS stations. Six of the stations are part of the IGS and European Permanent Network (EPN), namely DARE, HERS, HERT, INVR, MORP, and NEWL; and ten CGPS@TG stations contribute to the International GNSS Service (IGS) Tide Gauge (TIGA) Project, namely ABER, DVTG, LWTG, LIVE, LOWE, NEWL, NSTG/NSLG, PMTG, SHEE and SWTG.

NERC Space Geodesy Facility (SGF)

http://sgf.rgo.ac.uk/

The two IGS stations HERS and HERT remain in continuous operation, with HERT, a Leica GRX GG Pro system, also streaming GPS and GLONASS navigation data into the Internet in support of the EUREF-IP and IGS Real-time Projects. A modern GPS/GLONASS Septentrio Timing receiver has replaced in 2010 the HERS Ashtech Z12 receiver. The Ordnance Survey GeoNet system HERO, installed by the OS in 2009 close to the SOLA trig pillar, continues to be fully operational and has become useful as a fourth site for the local stability monitoring work. A newly purchased active hydrogen maser has been installed in an air-conditioned room in the Facility basement, and its highly-stable frequency source and one-second tick pulse are driving both the HERS Septentrio receiver and the SLR event timer. The timescale derived from the H-maser, unofficially named UTC(SGF), is continuously compared with UTC(GPS), and in this way the SLR observations continue to be time-tagged with respect to UTC(GPS), but greatly benefit from the high-precision and stability of the frequency source. A published study into local site stability using daily GAMIT-based solutions for HERS and HERT coordinates and precise HERS-HERT and HERS- and HERT-SOLA baselines has revealed near-annual periodic baseline variations of amplitude close to 1mm. This study has been extended to include baselines to additional nearby systems and other UK and worldwide short-baselines, all of which exhibit periodic variations in length.

Ordnance Survey of Great Britain

http://www.ordnancesurvey.co.uk/

Ordnance Survey's national RTK GPS network OS Net™ has been developed since 2003 and now covers the whole of Great Britain with 109 (as of June 2011) stations. Expansion into the north west of Scotland to complete the coverage of GB took place between 2007 and 2009 and coverage was completed in early 2010 with the final 2 stations – Tiree off the west coast of Scotland and the Scilly Isles in the far south west of GB. To increase the coverage and improve error modelling some stations from Ireland and Northern Ireland are also used in the RTK processing.

During 2008/2009 a complete upgrade of all the station hardware was carried out. Receivers and antennas are now GNSS capable and will be upgraded to be compatible with Galileo signals as soon as it practical.

A "zero order" subset of OS Net stations was also completed in 2009. This subset of 12 stations, known as GeoNet, has been emplaced and monumented to the highest possible standards. A new EUREF campaign based around the GeoNet stations and similar stations in Ireland and Northern Ireland was completed in 2010 and ratified by EUREF as an official realisation of ETRS89. The realisation is known as EUREF IE/UK 2009.

OS Net is managed via the GPSNet™ software from Trimble and delivers RTK corrections via GSM and GPRS. The correction data is used by approximately 130 Ordnance Survey surveyors. Public services are available via Ordnance Survey commercial partners. There are currently four partners – AXIO-NET, Leica, Topcon and Trimble. Partners take the raw GNSS data streams from OS Net servers via the NTRIP (Network Transport of RTCM via Internet Protocol) protocol and use them to generate their own correction services.

The 30 second RINEX data from all OS Net stations is freely available via a web site (http://www.ordnancesurvey.co.uk/gps).

School of Civil Engineering and Geosciences, Newcastle University

http://www.ceg.ncl.ac.uk/geomatics/research/geodesy.htm

Newcastle University continues to contribute to the International GNSS Service as an Associate Analysis Centre, providing weekly global coordinate combinations in parallel with the official IGS product. The new IGS08 reference frame is now being used to align the weekly solutions.

The current IGS reprocessing effort aims to reanalyse prior data back to 1994 using the same processing strategy and models as the present-day operational solutions. Solutions back to year 1994 have been generated by several analysis centres and combined at Newcastle.

A reprocessing effort is under way at Newcastle to produce a time series of site coordinates incorporating newer analysis models not included in ITRF2008, for example the second-order ionospheric effect. A recent study of this (Petrie et al., 2010a) indicated small but significant effects on the geocentre, and, depending on the time period of analysis in relation to the solar cycle, possible effects on site velocities.

Newcastle hosted the 2010 IGS Workshop with over 200 delegates from 29 countries, followed by a one-day COST Action ES0701 symposium on vertical rates of land motion relating to improved estimates of glacio-isostatic adjustment and sea level.

4. INTEGRATED SYSTEMS AND INERTIAL NAVIGATION SYSTEMS

Imperial College London

http://www.geomatics.cv.imperial.ac.uk/

Improved Time Estimation for High Accuracy WLAN based Positioning. There is significant potential in the provision of Location Based Services (LBS) in indoor and dense urban environments. However, the use of the most common location determination technology, Global Navigation Satellite Systems (GNSS) and particularly GPS, in these environments is limited by the impact of signal attenuation and blockage. While research is ongoing on GNSS positioning in indoor and urban environments, real time high accuracy positioning remains a challenge. Alternatively, there is a variety of proprietary systems that can achieve sub-metre accuracy such as CRICKET, Active Bat and Ubisense. However, their high cost and short range limit their scalability and hamper their use.

The widespread availability of wireless communications networks has attracted interest in their use for positioning. Such networks include mobile phone networks, Bluetooth and Wireless Local Area Networks (WLAN). The widespread deployment of these networks is an incentive for low cost positioning. However, the current positioning techniques based on these networks are not capable real time high accuracy positioning. This project (funded by the UK's Engineering and Physical Sciences Research Council – EPSRC) developed a low cost WLAN based real time positioning system capable of metre-level positioning accuracy. It is based on a new time estimation technique for sub-metre ranging accuracy in operational WLAN propagation environments. The time estimation technique employs high rate sampling clocks, an adapted model for the received signal and an improved sparse estimation technique. Additionally, this technique exploits the preamble of the WLAN data frames to enable the use of standard devices, minimise the effect on the throughput and support a variety of LBS including security and privacy oriented services. An added value of the time estimation technique developed is that it is transferable across networks and should deliver the same level of time estimation (ranging) performance, if configured correctly. This has the added benefits of not only increasing the number of applications but also the spatial coverage.

Integration of positioning systems with spatial data for transport Applications. Intelligent Transport Systems (ITS) have the potential to play a crucial role in facilitating not only the alleviation of congestion and its negative impacts, but also the capture of the data required to plan future transport services. A key component of ITS is the positioning and navigation function, responsible for the spatial and temporal data, and derivative information required to underpin the provision of most ITS services. Although the GPS has been used to support many ITS services, the stringency of the requirements of others means that GPS alone is insufficient. This has been addressed by augmenting GPS with terrestrial sensors (mainly through the deduced reckoning – DR - concept) and the use of spatial digital road network data through map matching. However, system/sensor integration is traditionally accomplished in the position domain rather than the more beneficial measurement domain. Furthermore, the integration of the system/sensor output with spatial data through map matching is not carried out in an optimal single process and no credible integrity (quality) monitoring method has been developed. In addition, for some services such as Road User Charging (RUC), there is no agreed process for the specification of the level of performance expected of the positioning and navigation systems.

This project (funded by the Engineering and Physical Sciences Research Council and Thales) is developing (i) a framework for the specification of the required navigation performance for ITS services, (ii) algorithms for integrating GNSS with DR sensors and digital spatial data in the measurement domain, and (iii) the necessary integrity algorithms for the various aspects of the integration process. It is expected that this integration will significantly increase the navigation performance, satisfying the requirements of existing and future ITS services.

5. SATELLITE ALTIMETRY

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Improving ocean signals in satellite derived mean dynamic topography: The ocean mean dynamic topography (MDT) is derived as the difference between the altimetrically measured mean sea surface (MSS) and the geoid. The resulting MDT is a small residual of two very large fields measured in entirely different ways with different error structures, see Bingham et al (2008). We have worked to define better ways of improving the MDT by matching the omission errors between the MSS and geoid field more closely. Spectral calculations have been advocated. A remove restore procedure may give the best match allowing the MSS-MDT over the ocean to match with the geoid over land to give a globally consistent first guess solution which can be used within the spectral approach. Some of these ideas were developed within the activities of the ESA GOCE User Toolbox GUT program which Reading was a contributor.

National Oceanography Centre Liverpool
(formerly Proudman Oceanographic Laboratory)

http://noc.ac.uk/

NOCL has continued to a member of international altimeter working teams with studies undertaken on altimeter calibration and ocean circulation variability. Most recently NOCL has taken part in studies initiated by the European Space Agency on the use of altimeter data close to the coast, thereby filling the observational gap between deep-ocean altimetry and measurements of sea level by coastal tide gauges.

National Oceanography Centre Southampton

http://noc.ac.uk/

NOC staff have been valued members of the international altimetric community for many years by contributing studies on large scale ocean circulation and propagating systems. In recent years NOC has contributed to the foundation and growth of the new topic of coastal altimetry, i.e. the extension of altimetric measurements as close as possible to the coast. NOC's prominent role in this novel field is twofold: on the scientific side we are the leaders of the ESA-funded COASTALT project for the development of altimetry in the coastal zone for Envisat (http://www.coastalt.eu/), we continue to participate steadily in innovative technical studies (Bouffard et al., 2008, Gómez-Enri et al., 2010), and we have contributed several technical papers and one of the book editors to the recent, state-of-the-art Coastal Altimetry book by Springer (Vignudelli et al., 2011); on the coordination side, we have co-organized the International Coastal Altimetry workshops since 2008, and we led the OceanObs'09 Community White Paper on the role of altimetry in coastal observing systems (Cipollini et al., 2010).

NOC are also expert on the oceanographic applications of the new family of SAR altimeters, like the SIRAL instrument on ESA's Cryosat-2 mission, having contributed to the characterization of the instrument performance over a range of sea conditions within the ESA SAMOSA study.

Improvements in determination of absolute ocean circulation from satellite altimetry are dependent on determinations of the geoid that are independent of the altimetric measurements, and their correct integration with altimetric data. To this end, NOC has been a key partner in the development and validation of the ESA GOCE User Toolbox.

6. SYNTHETIC APERTURE RADAR

School of Geographical and Earth Sciences, Glasgow University

http://www.gla.ac.uk/schools/ges/

Advanced InSAR atmospheric correction. Atmospheric water vapour effects represent one of the major limitations of repeat-pass Interferometric Synthetic Aperture Radar (InSAR), especially for small amplitude geophysical signals with long wavelengths such as interseismic deformation and some anthropogenic processes. Two advanced InSAR water vapour correction models were developed using the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) and the ESA MEdium Resolution Imaging Spectrometer (MERIS) data: (1) The MERIS/MODIS combination correction model (MMCC); and (2) the MERIS/MODIS stacked correction model (MMSC). The applications of both the MMCC and the MMSC models to ENVISAT ASAR data over the Southern California Integrated GPS Network (SCIGN) region showed a significant reduction in water vapour effects on ASAR interferograms, with the RMS differences between GPS and InSAR derived range changes in the LOS direction decreasing from ~10 mm before correction to ~5 mm after correction (Li et al., 2009).

Since the ionosphere is dispersive, its impact on microwaves depends on the frequency of the signal and is ~17 times greater at L-band than at C-band. This indicates that caution needs to be exercised when interpreting L-band interferograms and promotes investigation into ionospheric correction models (Li et al., 2008a, 2008b). A new technique was developed for 2-D ionospheric imaging using a spaceborne L-band polarimetric SAR system (i.e. ALOS PALSAR). The observed phenomena included aurora-associated ionospheric enhancement arcs, the middle-latitude trough, traveling ionospheric disturbances, and plasma bubbles, as well as ionospheric irregularities (Pi et al., 2011). These demonstrate a new capability of spaceborne synthetic aperture radar that will not only provide measurements to correct for ionospheric effects in radar images, but also significantly benefit ionospheric studies.

InSAR Time Series with Atmospheric Estimation Model. InSAR Time Series analysis with Atmospheric Estimation Models (InSAR TS + AEM), developed at the University of Glasgow, is an advanced InSAR time series analysis approach that uses multiple interferograms with small geometric baselines to minimize the effects of decorrelation and inaccuracies in topographic data. InSAR TS + AEM can be used to separate deformation signals from atmospheric effects and orbital ramps, in order to recover the evolution of surface deformation. An independent validation was performed over the Yucca Mountain region by comparing a 10-year GPS dataset with the InSAR TS + AEM mean velocity map derived from 18 years of ERS and Envisat images. The InSAR TS + AEM results agreed with GPS data to within 0.46 mm/yr RMS misfit at the stations (Li et al., 2010; Hammond et al., 2010). The validation study also showed that the RMS differences between InSAR TS + AEM and GPS derived path delays were about 5 mm (Li et al., 2010).

7. SATELLITE ORBIT AND GRAVITY FIELD DETERMINATION

School of Civil Engineering and Geosciences, Newcastle University

http://www.ceg.ncl.ac.uk/geomatics/research/geodesy.htm

Moore and King (2010) considered the potential for GOCE to be used to determine secular mass change over polar regions. They found that with the pre-launch GOCE noise levels and mission duration that reasonable mass changes would not be detected by GOCE.

Lavallée et al. (2010) reported on new estimates of the non-secular variation in J2 from a global GPS reprocessing, GRACE, load models and SLR and found that previously reported SLR-derived J2 anomalies may be SLR analysis artefacts.

8. GRAVITY SURVEYS

National Oceanography Centre Liverpool (formerly Proudman Oceanographic Laboratory)

http://noc.ac.uk/

Absolute gravimetry: NOCL has continued to use the FG5 absolute gravimeter FG5-103 to make measurements of vertical crustal movements near UK tide gauges with long mean sea level records (Newlyn, Lerwick and Aberdeen). This work has contributed to many papers during the period looking at measuring changes in ground level at tide gauges using GPS, AG, PS-INSAR and Holocene sea level data in collaboration with the University of Nottingham and BGS. During this period we have also begun measuring at the British Geological Survey site Eskdalemuir which is situated in southern Scotland. To ensure that our AG measurements are accurate our machines have been regularly intercompared with other absolute gravimeters at sites in the USA and Luxembourg. We, in conjunction with colleagues in Europe, have studied the long-time scale hydrological effects on gravity in order to improve the ability of AG and SG to monitor long-term geophysical movements.

9. THEORETICAL GEODESY, EARTH TIDES, EARTH ROTATION AND MISCELLANEOUS GRAVIMETRIC STUDIES

National Oceanography Centre Liverpool (formerly Proudman Oceanographic Laboratory)

http://noc.ac.uk/

Stochastic analysis of GPS coordinate time series. NOCL, together with colleagues in Portugal, have been investigating methods to improve the computational time for Maximum Likelihood Estimation of continuous GPS coordinate time series. We presented a modification of the MLE equations that allows us to reduce the number of computations within the algorithm from a cubic to a quadratic function of the number of observations without loss of accuracy. During this period the CATS software for analysing the noise in GPS time series was released to the public with an introductory paper in GPS solutions.

NERC Space Geodesy Facility (SGF)

http://sgf.rgo.ac.uk/

Regular weekly operations of the FG5 absolute gravimeter have continued since operations began in October 2006, but with some several months' loss of observing time during 2010 due to problems with the laser. The baseline observational programme is a 24-hour session centred on mid-GPS week, resulting in hourly average gravity values of precision about 1-2 µgal, equivalent to a daily vertical precision of around 1mm. Analysis of the results, in combination with SGF-derived space geodetic station-height solutions and local groundwater measurements, are underway in collaboration with the Proudman Oceanographic Laboratory and UCL. Results to date suggest that the gravity environment is quite stable and that the effects of seasonal hydrological changes are less marked than may have been expected. A study is underway to use the observations to compare and assess different ocean-loading models.

School of Civil Engineering and Geosciences, Newcastle University

http://www.ceg.ncl.ac.uk/geomatics/research/geodesy.htm

Ocean tide loading. Thomas et al. (2007, 2008) continued Newcastle's development of GNSS techniques for measuring tidal loading displacements. Comparing estimates of periodic displacement (dominated by ocean tide loading displacements) at ~20 GPS sites with previously published VLBI estimates and those from recent numerical tide models, GPS-derived estimates were shown to be generally as accurate as VLBI, except at K1 and K2 where GPS-related systematic errors dominate. This was the first time that GPS-derived periodic motions had been shown to be as accurate as those from VLBI. Penna et al. [2008] assessed the prediction accuracy of various ocean tide loading displacement software packages, including the widely used online ocean tide loading provider based on the OLFG/OLMPP software. The accuracy of ocean tide loading (OTL) displacement values has long been assumed to be dominated by errors in the ocean tide models used, with errors due to the convolution scheme used considered very small (2–5%). However, this paper shows that much larger convolution errors can arise at sites within approximately 150km of the coastline, depending on the method used to refine the discrete regularly spaced grid cells of the ocean tide model to better fit the coastline closest to the site of interest. As a result of this study, the coastal refinement approach used in the OLFG/OLMPP software was therefore changed in

August 2007 to use bilinear interpolation only. King et al. (2011) report on a new GPS data set of ocean tides in the Weddell Sea – namely on the floating Filchner-Ronne and Larsen C ice shelves. Accuracy of several ocean tide models was tested against the data and errors remain at the 5-20 cm level in the most energetic constituents, although with spatial variation. The error budget due to unmodelled ocean tide loading (OTL) when using the GNSS base station network in the British Isles has been examined by Clarke and Penna (2010), who make several recommendations as to possible averaging and mitigation strategies.

Non-tidal surface mass loading. Inversion of geodetic site displacement data to infer surface mass loads has previously been demonstrated using a spherical harmonic representation of the load. Clarke et al. (2007) investigated basis functions that allow variability of the load over continental regions, but impose global mass conservation and equilibrium tidal behaviour of the oceans. Compared to standard spherical harmonics, these basis functions yield a better fit to the model loads over the period 1997–2005, for an equivalent number of parameters, and provide a more accurate and stable fit using the synthetic geodetic displacements. In particular, recovery of the low-degree coefficients is greatly improved. GPS and GRACE estimates of the degree-2 surface mass load were compared with Earth rotation data corrected for atmospheric and oceanic angular momentum and with climatological surface mass load models (Gross et al, 2009). The GPS estimates best explain the degree 2, order 1 model data, whereas the GRACE estimates best explain the order 0 and order 2 data.

10. GEOID DETERMINATION

Department of Earth Sciences, Oxford University

http://www.earth.ox.ac.uk/

Geoid Determination: In continuation of the ongoing studies of the geoid in East Africa, the first gravimetric geoid of Tanzania was produced, using 1-D Fast Fourier Transforms and based on the EIGEN-GRACE02 geopotential model, with heights from the Shuttle Radar Topography Mission. Gravity anomalies were provided by Bureau Gravimétrique International and Leeds University.

Work is continuing using the latest GOCE gravity models and more refined integration techniques.

11. DEFORMATION MONITORING

Institute of Engineering Surveying and Space Geodesy, Nottingham University

http://www.nottingham.ac.uk/iessg/

Using GNSS positioning, especially GPS for long bridge deformation monitoring started in the middle of 1990s and it still forms a core research and development area at the University of Nottingham. Current work mainly focuses on the enhancement of an existing prototype structural health monitoring (SHM) system through research and development of more reliable sensor sub-system and a highly efficient real-time data processing and deformation analysis sub-system, use of multi-constellation GNSS signals and EGNOS data, and wide engagement with bridge engineering community for the reliable deformation analysis and provision of trusted early warming. Work in this area has been further extended through modifying the system to monitor landslides and other natural hazards. The ultimate goals are to form a universal monitoring platform that could process data sets from earth observation satellites, GNSS and terrestrial sensor network.

School of Civil Engineering and Geosciences, Newcastle University

http://www.ceg.ncl.ac.uk/geomatics/research/geodesy.htm

Research by Ragheb et al. (2010) has shown that local deformation monitoring networks using a switched antenna system with a single receiver can achieve coordinate precisions of better than 5 mm in plan and 8 mm vertically, with a recommended antenna switching interval of 119 s or a multiple thereof.

School of Earth and Environment, Leeds University

http://www.environment.leeds.ac.uk/see/

Our work at Leeds has concentrated on using synthetic aperture radar interferometry to measure deformation associated with volcanic and tectonic activity. A particular focus has been the Afar region of Northern Ethiopia, where a series of dyke intrusions have been intruded along the plate boundary. For example, we have measured the deformation associated with the dyke intrusions and produced simple elastic deformation models (Hamling et al, 2009). The models show that the stress changes caused by individual dykes can influence the location of subsequent activity (Hamling et al., 2010). At the same time, we continue to be active in the area of co-seismic (Funning et al., 2007, Baer et al., 2008; Fukahata and Wright , 2008), post-seismic (Ryder et al., 2007; Biggs et al., 2009) an inter-seismic deformation (e.g. Biggs et al, 2007; Elliott et al., 2008; Wang et al., 2010.). In the latter area, our code, pi-rate, which is optimised for measuring slow deformation in areas of partial coherence, is now available to download from the web.

School of Geographical and Earth Sciences, Glasgow University

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City subsidence in the Wuxi-Changzhou region, Eastern China: The InSAR TS + AEM developed at the University of Glasgow was employed to process ESA's ERS and Envisat SAR images collected during the period between 1992 and 2008 over the Wuxi-Changzhou region, Eastern China. Validation with precise levelling and GPS data suggested: (1) the accuracy of the InSAR-derived mean velocity map was 3.7 mm/yr; (2) InSAR-derived deformation agreed with precise levelling as root mean squares ranged from 2.4 mm to 6.7mm; (3) the accuracy of InSAR-derived atmospheric signals was 6.5 mm (Li et al., 2009, 2010). It is evident that InSAR TS + AEM can be used to image the evolution of the deformation patterns of the Wuxi-Changzhou region over time: the maximum mean velocity decreased from 6-15 cm/yr during the period of 1992-1993 to 2~3 cm/yr between 2003-2008. This is believed to be a result of groundwater extraction being prohibited by the Jiangsu provincial government. It is worth pointing out that the Space Geodesy Research Group in the University of Glasgow is currently working on landslide and mining subsidence hazards in Scotland, China and Spain using space geodesy.

12. MEAN SEA LEVEL STUDIES

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Monitoring of vertical land movements at tide gauge sites in the UK: The application of GPS to the monitoring of vertical land movements at sites of the UK National Tide Gauge network has been on-going at the IESSG, in collaboration with the Natural Environment Research Council (NERC) National Oceanography Centre, Liverpool (formerly Proudman Oceanographic Laboratory), since 1990. The initial developments at the IESSG closely followed the recommendations of the "Carter reports" in 1989 and 1994 and the International GNSS Service (IGS)/Permanent Service for Mean Sea Level (PSMSL) workshop in 1997. As such, ten CGPS@TG stations have been established in the UK at Aberdeen (ABER), Dover (DVTG), Newlyn (NEWL), Lerwick (LWTG), Liverpool (LIVE), Lowestoft (LOWE), North Shields (NSTG/NSLG, established by Newcastle University), Portsmouth (PMTG), Sheerness (SHEE) and Stornoway (SWTG), with the first being established at Sheerness in 1997 and the latest at Dover in 2005. These are complemented by three Absolute Gravity (AG) stations at Newlyn, Lerwick and Aberdeen, for which episodic (annual) campaign measurements have been made by the NERC National Oceanography Centre, Liverpool since 1995/6. With funding from Defra and the Environment Agency, from 2003 to 2007, research work was carried out as a national study based around the data from the ten CGPS@TG stations and the three AG@TG stations. The results for the national study demonstrated how the combined AG and CGPS 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 (Bingley et al. 2007). They also highlighted that the estimates 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. Furthermore, when the combined AG and CGPS results were considered along with tide gauge estimates of changes in sea level, an estimate 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 was obtained, which suggested that sea level had risen by 0.9 to 1.2mm/yr (Bingley et al. 2007). Since then, further results have been published as Teferle et al. (2009) and Woodworth et al. (2009) which presented estimates of change in sea level (decoupled from changes in land level) around the coast of Great Britain, based on a larger tide gauge data set and more accurate analysis methods than had been employed previously. Woodworth et al. (1999) concluded that there had been a 1.4mm/yr regional sea level rise of climate change origin, which was several one-tenths of mm per year lower than global estimates for the 20th century, but noted that such a change cannot be described in terms of a simple linear increase alone as it includes variations on inter-annual and decadal timescales, with possible sources of variation in a 'UK sea level index' being explored. Lastly, as regards future regional sea level changes, Woodworth et al. (1999) concluded that there was no basis for major modification to existing projections for the 2080s that were included in the 2002 UK Climate Impacts Programme studies.

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MSL studies at NOCL have resulted in many research papers over the past 4 years (see accompanying list of publications). These have included investigations of sea level change in the past few centuries from tide gauge, altimeter and other data sets, and those of the future predicted by different statistical techniques. Both secular trends and variability on different timescales have been studied and investigations have been undertaken both globally and regionally (e.g. UK). Of particular interest has been why trends differ spatially due to various processes. Extreme sea level changes have also been an important feature of the work, especially insofar as they follow, or are different to, MSL changes. Space gravity (temporal using GRACE data and spatial using GOCE data) have also been applied to MSL studies and will form an increasingly important component of future work. Collaboration with other groups has provided insight into the complementary value of tide gauge and altimeter data sets with those from geology (e.g. salt marshes) and archaeology.

Sea level measurements provide insight into ocean circulation change and many papers have demonstrated how either the global or regional (e.g. Antarctic Circumpolar, North Atlantic) circulation varies on various timescales. A notable anniversary has been the 20th year of NOCL monitoring of sea levels at, and thereby transports through, Drake Passage. A number of papers have focused on the science and technology of higher frequency sea level variability, including the reasons for changes in tides, for energetic seiche activity, and methods for monitoring tsunamis. One tsunami-related paper resulted in the award of an IMAREST medal.

NOCL has played a major international role in Sea Level Science through the organisation of two major World Climate Research Programme conferences (the first of which resulted in the Church et al. 2010 Wiley-Blackwell book). It has provided ongoing assistance given to the Intergovernmental Oceanographic Commission via contributions to the Global Sea Level Observing System in Africa and the Indian Ocean, and via the operation of its own sea level network in the South Atlantic and Antarctica. It has provided major international sea level data banks (especially the Permanent Service for Mean Sea Level, PSMSL) and for these reasons has been able to contribute strongly to the research assessments of the Intergovernmental Panel on Climate Change. Within the IAG, it has been a strong supporter of the Global Geodetic Observing System and, the PSMSL being an IAG Service, has been represented on the GGOS Steering Committee.

National Oceanography Centre Southampton

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Mean sea level studies at NOCS Southampton has resulted into several research papers over the last years. The sea level expertise is focused on regional sea level variability. Secular trends, variability inter-annual and inter-decadal, sea level extremes and changes in the tidal constituents have been studied. Reconstruction of sea level and analysis of projections under climate change scenarios have also been made. Particular attention has been given to uncertainties in the underlying forcing, that is the steric, atmospheric and land based components.

Extensive collaboration with researchers around Europe and leadership in international climate variability projects in the Mediterranean and national research projects in Spain have assisted in building an efficient network of research.

Within the context of Medclivar-ESF NOC Southampton has contributed to the running of five workshops and two summer schools all of which had a sea level component, with two of them having an explicit sea level training and research character.

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Newcastle contributions to the GOCE User Toolbox (Knudsen et al., 2011; Bingham, 2011) have used new high-resolution geoids derived from GOCE satellite data to obtain significantly improved estimated of mean dynamic ocean topography both globally and with a focus on the North Atlantic circulation. Bingahm et al. (2010) have investigated optimal filtering strategies for use with these and similar datasets.

Immediately following the 2010 IGS Workshop, Newcastle hosted a one-day ES0701 symposium on vertical rates of land motion relating to improved estimates of glacio-isostatic adjustment and sea level. King et al (2010 reviewed the state-of-the-art in modelling and GPS observations of GIA, particularly for Greenland and Antarctica and with a focus on GPS vertical velocities.

13. GEOPHYSICAL, GLACIOLOGICAL, AND OCEANOGRAPHIC APPLICATIONS OF GEODESY

Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET+), Universities of Oxford, Cambridge, Leeds, and Glasgow

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A new set of geodetic velocities for Greece and the Aegean, derived from 254 survey-mode and continuous GPS sites, is used to test kinematic and dynamic models for this area of rapid continental deformation. A continuous field of velocity calculated from the GPS velocities by assuming that strain rates are homogeneous on the scale of 120 km fits the observed velocities with systematic misfits, representing more localized strain, confined to a region around the western Gulf of Corinth. This velocity field accounts for the major active tectonic features of Greece and the Aegean. These observations suggest that the faulting within the upper crust of the Aegean region is driven by forces that are coherent over a scale that is significantly greater than 100 km. It is likely that those forces arise primarily from differences in gravitational potential energy within the lithosphere of the region.

COMET+ was the first research group in the world to produce a surface rupture map for the 2010 Mw 6.9 Yushu (Qinghai, China) earthquake from radar images. These results were used by the Chinese Earthquake Administration Field Team in their field visits. By combining observations from satellite radar, body wave seismology and optical imagery, we have determined the fault segmentation and sequence of ruptures for the 2010 Mw 6.8 Yushu (China) earthquake. We also found that strain accumulation since the last earthquake on the continuation of the fault beyond Yushu has the potential to produce an Mw 6.5 event. A paper on these results is under review for JGR.

The M 7.1 Darfield earthquake in September 2010 ruptured a previously unknown shallow strike-slip fault west of Christchurch, New Zealand. We have analysed surface displacements from InSAR and GPS measurements and sub-pixel matching of SPOT images to generate a model of the fault displacement and segmentation in this event. The aim was to establish the distribution of slip of the various segments and the implications for the seismic hazard of Christchurch. Unfortunately, a large aftershock (M6.3) did subsequently occur under Christchurch, and we have refocussed our efforts on this event. The InSAR and GPS analysis indicates a potentially worrying gap in the faulting south-west of the city of Christchurch.

On the 6th April 2009 a magnitude 6.3 earthquake struck L'Aquila, the capital city of the Abruzzo region, central Italy. The earthquake killed around 300 people and made tens of thousands of people homeless. L'Aquila is a mediaeval city, nestled in the Apennines, and it has a long history of earthquakes that have repeatedly damaged the city. The Envisat InSAR images analysis allowed to create the rupture model that was later confirmed by the in situ measurements.

We used satellite radar measurements to show that the ruptures of two Mw 6.3 earthquakes, occurring in almost the same epicentral location ten months apart in the Qaidam region, China, were nearly coplanar. The 2008 earthquake ruptured the lower half of the seismogenic layer, the 2009 event the upper half. Fault segmentation with depth allows a significant seismic hazard to remain even after a moderate & potentially devastating earthquake. This depth segmentation possibly exists in the case of the 2003 Bam earthquake where satellite radar & aftershock measurements showed that it ruptured only the upper half of the 15–20 km deep seismogenic region, and that the lower, unruptured part may remain a continuing seismic hazard.

Previous studies of interseismic strain accumulation across the North Anatolian Fault (NAF) have used SAR data acquired from only a single line-of-sight (LOS) direction, leading to large uncertainties on model parameters and necessitating several modelling assumptions to be made. We have measured interseismic deformation across the NAF using both ascending and descending SAR data for the first time. By using SAR data from the two look directions, we have been able to reduce the range of uncertainties in slip rate and locking depth from previous studies by 60%, and by assuming no vertical motion across the fault, we estimate both fault-normal and fault-parallel motion. These results support other evidence for predominantly horizontal strike-slip motion on the NAF. Our data are consistent with a slip rate of 20–26 mm/yr below a locking depth of 13.5–25 km for the NAF.

We studied a series of recent earthquakes in the Zagros fold-and-thrust belt in southern Iran, one of the world's most seismically-active mountain ranges. Using InSAR, we showed that these earthquakes were buried within the thick sedimentary cover, which had previously been considered to be aseimsmic, deforming purely by folding. On the other hand, smaller aftershocks - detected using portable seismometers deployed by Iranian collaborators - were concentrated in the basement below the cover, and were thus vertically separated from the mainshocks. The full thickness of the seismogenic layer failed to rupture during the main earthquakes, and the lower part of this layer poses a considerable seismic hazard for the future. Results reported in papers in EPSL and GJI.

Satellite radar measurements of deformation at Costa Rica's most active volcano, Arenal, show that part of its western flank is moving downslope at a rate of about 7 centimetres per year. Interferograms from between 2005 and 2009 show that movement is at angle of about 55 degrees below the horizontal plane and is steady in rate. We interpret this deformation as slip along a shallow plane driven by the weight of young lavas effused from the volcano since its reactivation in 1968. Our observations contribute to assessment of particular hazards around Arenal itself and, more generally, to our understanding of edifice stability at young stratovolcanoes.

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Modelling the glacial isostatic adjustment (GIA) of the British Isles. Since 2003, the IESSG has been collaborating with the Department of Geography, and the Department of Earth Sciences, at Durham University. This research is related to modelling the glacial isostatic adjustment (GIA) of the British Isles and, most recently, in Bradley et al. (2009), we compared estimates of crustal velocities within Great Britain based on CGPS measurements (Teferle et al. 2009) to predictions from a model of GIA. These comparisons showed that the observed and predicted values for vertical motion are highly correlated, indicating that GIA is the dominant geodynamic process contributing to this field; whereas motion of the Eurasian plate dominates the horizontal motion component. In Bradley et al. (2009), a recently published model of the British–Irish ice sheet to predict vertical crustal motion for a large number of spherically symmetric Earth viscosity models was adopted, and it was shown that the adopted ice model is capable of producing a high-quality fit to the observations. Furthermore, the CGPS estimates of vertical motion provided a useful constraint on the average value of viscosity within the upper mantle; although values of model lithospheric thickness and lower mantle viscosity were less well resolved. Ultimately, a suite of predictions based on an alternative ice model were carried out and indicated that the vertical motion data were relatively insensitive to uncertainties in the ice loading history and so the constraints on upper mantle viscosity were robust.

Map of current vertical land movements in the UK. A preliminary map of current vertical land movements in the UK was published in Teferle et al. (2009) and used in Bradley et al. (2009). In 2008/9 the IESSG were awarded a small grant from the Natural Environment Research Council (NERC) to create a map of current vertical land movements in the UK based on an optimal combination of absolute gravity (AG) and continuous GPS (CGPS), as part of the Oceans 2025 programme and the NERC Strategic Ocean Funding Initiative (SOFI). For this: new coordinate time series were produced in ITRF2005 from a high level CGPS processing, resulting in 3 to 12 years of daily position estimates for 127 CGPS stations in the UK; new estimates of vertical station velocity and their uncertainty were produced for the 127 CGPS stations from an analysis of their time series and, in terms of precision, the uncertainties were in the range of ±0.2 to 1.1mm/yr (1-sigma), whereas, in terms of accuracy, a comparison with AG vertical station velocities was carried out at two co-located sites (Lerwick and Newlyn) and, as seen previously, it was found that the CGPS vertical station velocities were too positive, this time by about 1.1mm/yr; a rigorous assessment of the suitability of all 127 CGPS stations for the purpose of providing reliable estimates of vertical land movements was then carried out, with 71 of the 127 excluded due to unacceptably large (greater than 0.5mm/yr) velocity uncertainties, mainly related to their time series being less than 6 years in length, and a further 10 being excluded based on a detailed consideration of local environment, monument type and foundation, and local site geology, suggesting that they may have experienced vertical motion that is not due to glacio-isostatic adjustment or natural compaction; the optimal combination of AG and CGPS was considered to be achieved by aligning the 'over positive' CGPS to the more realistic AG vertical station velocities, using the two co-located sites. The map of current vertical land movements created was seen to be generally consistent with maps of long term vertical land movements based on geological and geophysical studies, which have vertical land movements in the UK of the order of 1 to 2 mm/yr, with Scotland rising and the South of England subsiding, so that Great Britain is effectively 'tilting'. Furthermore, consistent with the maps of long term vertical land movements, the new map also shows the highest uplift centred around the area of Scotland with maximum ice at the last glacial maximum and a zero line running roughly between Liverpool and Newcastle. However, the map of current vertical land movements has a limit of 1.5 mm/yr of vertical land movement and a detailed comparison between the geodetic (current) and geological (long-term) estimates gives differences (geodetic minus geological) of between 0.7 and -1.3 mm/yr, with the geodetic estimates showing less uplift in Scotland, and less subsidence in South-West England. The results and outputs were used in the UK Climate Projections (UKCP09) reports, where vertical land movements are combined with model predictions of future changes in sea level to better assess future changes in sea level with respect to the land. The research also acted as a proof-of-concept study, with the processing strategy and scripts developed, the results obtained and the experience gained from the processing and analysis all being transferred to the NERC British Isles continuous GNSS Facility (BIGF) who will be responsible for the future refinement of the map.

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Assimilation of geoids within ocean circulation models. The best estimate of ocean dynamic topography should come from combining satellite geodetic data, altimeter data, along with in situ ocean data e.g. from density profiles or surface drifter measurements. However in situ ocean data are not uniformly sampled in space and time and therefore time-mean in situ information is hard to generate directly. The best way to combine these sources of information should be through data assimilation in a time evolving ocean model. We are collaborating with the Met Office in the development of explicit representation of a Mean dynamic topography along with its error covariances, in the operational ocean assimilation system run daily at the Met Office. This methodology is already used as part of the operational suite, Lea et al (2008), Haines et al (2011a). We are currently working to ensure that new GOCE geoid products along with their error covariances can be included within the operational framework, Haines et al (2011b). This work was supported by the GOCINA and GOCINO EU programs, and the NERC Data Assimilation Research Centre Knudsen et al (2007). Ongoing collaborations are supported by the NCEO.

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Combination of geodetic measurements. Comparing and combining different geodetic measurements is made more difficult by the fact that they sample processes differently. For example, sea level measurements from tide gauges differ from those of altimetry due to the effects of local crustal deformation in the former and uncertainties in reference frame determination of the latter. Assuming that regional measurements were primarily due to the Earth's response the the last ice age, Hill et al., 2010, developed a technique that allowed different measurements (tide gauge, GPS, and GRACE geoid rates) to be self-consistently assimilated into prior model predictions of glacial isostatic adjustment (GIA). The updated GIA prediction is similar to earlier model results, but also includes uncertainty estimates. The technique allows the impact of the each of the data types on the final solution to be investigated and compared.

Non-tidal Ocean Loading: Research was carried out in a joint project with Newcastle University on the measurement of non-tidal ocean loading in the vertical using data from 17 continuous GPS stations around the North Sea. We found that displacements due to non-tidal ocean loading are comparable in size to atmospheric loading and the combined correction reduces the RMS of the vertical displacement time series by around 20-30%.

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Glacio-isostatic adjustment. As part of COST Action ES0701, led by Dr Matt King at Newcastle, Spada et al. (2011) undertook a benchmark study of GIA codes for the first time. Immediately following the 2010 IGS Workshop, Newcastle hosted a one-day ES0701 symposium on vertical rates of land motion relating to improved estimates of glacio-isostatic adjustment and sea level. King et al. (2010) reviewed the state-of-the-art in modelling and GPS observations of GIA, particularly for Greenland and Antarctica and with a focus on GPS vertical velocities.

Cryospheric applications. Work in this area (King et al., 2009; Shepherd et al., 2009; Truffer et al., 2009; Winberry et al., 2009; Brunt et al., 2010; King et al., 2010) concentrates on the response of glaciers and ice sheets to seasonal and long-term climate change, and tidal forcing. Two linked studies (Das et al., 2008; Joughin et al., 2008) using GPS in kinematic precise point positioning mode demonstrated localised acceleration of ice sheet flow during the drainage of a supra-glacial lake, implying that meltwater lubrication has at least a localised effect on flow speed. However, it appears that the influence of meltwater on outlet glacier speed is more limited.

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Vertical tectonic signals from integrated InSAR and GPS observations: Southern Walker Lane and Sierra Nevada: Improving our knowledge of crustal strain and mountain uplift is critical to improving our understanding of the history and dynamics at work in the continental lithosphere, and to quantifying seismic and other geohazard, In some cases key questions remain unanswered. For example, for the Sierra Nevada of the western United States, the rate and timing of uplift of the range have been the subject of vigorous debate. Estimates of the age of the modern topography based on geologic and geochronological data vary by over one order of magnitude, from less than 3 to as old as 60 million years. Scientists from the University of Nevada, Reno and the University of Glasgow used 18 years of InSAR and 11 years of GPS data to construct integrated maps of secular Earth surface motion across the southern Walker Lane and Sierra Nevada. The degree of internal consistency between InSAR and GPS velocity maps is 0.5 mm/yr, and represents the current limit of precision that can be achieved with InSAR line-of-sight (LOS) maps of crustal deformation. From a difference between InSAR LOS velocity and predictions from a horizontal strain rate map we inferred a rate of secular vertical motion of the southern Sierra Nevada of approximately 2 mm/yr, in agreement with models that call for a relatively young modern Sierra Nevada elevation, whose age is ~3 Ma or less. This work was highlighted in the January 14 2011 issue of Science (Kerr, 2011) and the 2011 NERC NCEO Science Highlights Brochure.

14. VERTICAL DATUMS

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NOCL has begun work with the Technical University of Munich and other groups in a European Space Agency study of the utility of a worldwide vertical datum derived from GOCE data.

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