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Prepared on behalf of
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by

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FOREWORD

This report outlines United Kingdom activities in geodesy for the period January 2003 to December 2006. It has been prepared for submission to the International Association of Geodesy (IAG) at its General Assembly in Perugia, Italy, during the XXIV General Assembly of the International Union of Geodesy and Geophysics (IUGG) in July 2007. It is issued on behalf of the Royal Society.

Following the pattern set by the previous UK National Geodesy Report this document is presented in an undivided form, i.e. it is not structured to reflect the four commissions of the IAG. The objective of this is to emphasize the linkage between the various disciplines within geodesy and to avoid earlier difficulties in assigning certain activities to particular sections. The document has been prepared within the Institute of Engineering Surveying and Space Geodesy at the University of Nottingham from information provided by UK geodesists.

There have been no significant changes in the structure of geodesy within the UK since the publication of the last report. The Geodesy group within the RAS/GS Joint Association for Geophysics has not however been effective as a means of communication amongst the rather small group of “geodesists” in the UK. Most communication and the dissemination of geodetic information has been facilitated through mail base user groups for “geodesy”, “satellite navigation” and “geomatics”, and through journals. There is not an effective national forum for geodetic matters, and this is a matter of some regret.

The editor wishes to thank Dr David Baker for his work in collating information and for preparing this report.

ALAN H DODSON
Editor and National Correspondent to the IAG
June 2007

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1 SATELLITE LASER RANGING

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Satellite Laser Ranging
The in-house precise orbit determination software *Faust* has been extended to include reduced dynamic computations (Moore and Wang, 2005). This methodology requires dense geographical tracking from systems such as DORIS and permits the recovery of an extended set of constrained 1 cycle per revolution empirical accelerations. The methodology was applied to ENVISAT SLR and DORIS orbits as a contribution to ESA's Precise Orbit Validation Team for ENVISAT. Comparisons using SLR residuals and independent altimetric crossover data showed that the Newcastle orbits were one of the best at that time. The orbits have subsequently been used within studies utilising the transponder sited on the island of Gavdos in the Mediterranean Sea, both to provide a measure of the absolute calibration of ENVISAT and also as a means of transferring inland height data offshore. Other activities associated with SLR include the determination of temporal gravity field variability from the geodetic satellite LAGEOS I, LAGEOS II, Stella, Starlette and Ajisai (Moore et al, 2006).

- **The NERC Space Geodesy Facility (SGF)**
  http://nercslr.nmt.ac.uk/

Satellite laser ranging: The satellite laser ranging system of the SGF at Herstmonceux has continued in regular operation throughout 2003-2006. It is operated, weather permitting, in a flexible manner, 24 hours a day, seven days a week. Given UK weather, SGF is recognised as one of the world's most efficient and productive SLR systems.

The system makes very accurate range measurements to Earth-orbiting satellites by timing the flight of short laser pulses from the telescope to the satellite and back. The target satellites carry retro-reflectors specifically for this purpose, and a range measurement is made about once every second during each satellite pass, with a precision of at best 8mm.

The UK SLR system belongs to a global network of stations coordinated by the International Laser Ranging Service (ILRS, *http://ilrs.gsfc.nasa.gov/*), one of 9 Services overseen by the International Association of Geodesy (IAG). Currently this global network tracks 25 satellites whose scientific missions fall into five broad categories:

1) Dedicated geodetic satellites (e.g. LAGEOS, ETALON) - for research into, and maintenance of scale and origin of, a global geocentric International Terrestrial Reference Frame (ITRF) at mm levels of precision;
2) Altimeter and Synthetic Aperture Radar (SAR) remote sensing EO satellites (e.g. ENVISAT, JASON-1, ERS-2) - tracked to determine accurate orbits and calibrate on-board sensors;
3) Dedicated gravity-field missions (e.g. GRACE, CHAMP) - use onboard GPS for precise orbit determination and SLR for orbit determination, stability and validation;
4) Navigation satellites from the GNSS constellations (i.e. two of GPS, up to three GLONASS and from 2006 GIOVE-A, the first Galileo in-Orbit Validation Element) - tracked to give an independent measurement of the accuracy of their orbit determinations;
5) Experimental satellites - for testing new designs of reflector arrays, etc.

The ILRS sets performance targets, in terms of the precision of the measurements and numbers of passes tracked, for systems to be considered fully operational ILRS stations. Of the 40 stations registered with ILRS, some 15, including SGF, provide the bulk of the high-quality, high volume tracking for precise orbit determination necessary to meet the scientific goals of the satellite missions.

In spring 2006 the SGF system was the first in the world to range to the prototype Galileo In-Orbit Validation Experiment, GIOVE-A, at a height above the Earth of 23,000 km.

SGF, in its role as an ILRS Analysis Centre (AC), computes a weekly four-satellite station coordinate and EOP solution as a contribution towards the combined ILRS weekly product. In a major re-analysis effort, weekly solutions from 1992 to 2006 were computed and contributed to the ILRS submission towards the development by the IERS of ITRF2005 during 2006. The AC is working with other groups to resolve the current scale anomaly in ITRF2005, manifested as a scale difference of about 1ppb between the ILRS and IVS solutions, which may be related to the treatment of the ILRS data. The Facility continues to deliver daily, via its website, an automatic, orbit-based quality check on SLR data from the Herstmonceux system and from the global tracking network. This service enables rapid, independent feedback of SLR data quality and quantity for the benefit of both the SGF and the wider community. The Facility also generates daily orbital predictions of the geodetic satellites, as an official back-up contribution to the ILRS prediction efforts.

In order to maintain the SLR system in a competitive position within the ILRS network, a level of research and development is carried out by the group and with international collaborators.

The SGF has made important discoveries about the characteristics of individual time-of-flight counters used to make the satellite range measurements. During the period a highly-precise and accurate event timer has been built in-house from commercial clock units. Its use essentially eliminates from the range error budget any contribution from the time-of-flight measurement sub-system. In addition, laser range observations made at Herstmonceux from 1993 onwards have been re-calibrated using this event timer, removing a small range-dependent error, of order 8mm, present in the older electronic system. Similar careful experimentation and modelling has led to a greater understanding of the behaviour of the single photon avalanche diode (SPAD) detector, widely used elsewhere in the global network. Unless properly calibrated and operated strictly at single photon levels of return, standard practice at Herstmonceux, SPADs can induce significant bias into the measurements.

The Facility is at an advanced stage of development towards carrying out laser range measurements at kHz rates, a major upgrade from the current 10Hz system. The increased rate will offer improvement in normal point range precision to the single mm level, significantly shorten satellite acquisition times and hence improve productivity and, with the state of the art laser, improve overall system reliability.

SGF and collaborators, within the ILRS Signal Processing Working Group, have made significant progress in the determination of precise values of the corrections required to transfer SLR ranges from the effective reflection points on satellites to their centres of mass, as functions of tracking system characteristics. This work suggests that there remain ambiguities in the appropriate values of the centre of mass corrections at a level of up to 5mm for some of the stations for the LAGEOS primary geodetic satellites. Tabular values of the corrections have been published.

2 GLOBAL NAVIGATION SATELLITE SYSTEMS

- **Imperial College London**
  http://www.geomatics.cv.imperial.ac.uk/

Seamless Positioning in All Conditions and Environments: Satellite positioning via GNSS such as GPS have been adopted in a wide range of applications including multi-modal transport navigation; synchronisation of telecommunications networks; geodetic survey; and asset management systems. However, to access increased accuracy, integrity and availability, the various weaknesses inherent in such systems such as signal attenuation and masking; error modelling and integrity monitoring must be addressed. This project is addressing these weaknesses in order to deliver ‘Centimetres Everywhere’ with the appropriate levels of integrity for different applications. This is to be achieved through research leading to higher sensitivity algorithms for signal acquisition and tracking in harsh environments; exploitation of new signals; sensor error modelling; robust integrity monitoring algorithms; and the combined usage or integration of different sensor and data sources. It is envisaged that the models and algorithms developed will eventually be implemented in a ‘test bed’ whose requirements and architecture will

be specified within this project. The test bed is to be built in a subsequent project. The current vision is that the test bed should provide a benchmark for testing and referencing purposes. As a result, it will adopt as far as possible, an open architecture, to enable individual sensors to be added/removed/replaced as required. The SPACE research team consists of Imperial College London, University of Nottingham, University of Leeds and UCL, and in collaboration with the main companies and government agencies in the field of positioning and navigation.

Determination of the effects of GPS performance and failures on aviation applications: The project was conceived to answer the question - 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 has already been completed having identified the failure modes (or anomalies) and models. Phase 2 has developed improved anomaly protection (or integrity) algorithms used in the assessment of the effect of failures on the navigation performance of an aircraft. The final phase has subsequently developed an end-to-end HAZOP capability to link phases 1 and 2 to operations. The research was carried out for the UK Civil Aviation Authority by Imperial College London, University of Leeds and Helios Technology.

Robust conflict detection and resolution taking into account flight data uncertainty: This EPSRC project is utilising aircraft flight plan, navigation system and pilot flight intent data to develop detailed conflict detection and resolution algorithms that take account of the level of uncertainty associated with the flight plan and intent data, for use especially in more autonomous aircraft operations in flexible airspace. Such algorithms implemented in the flight management system (FMS) of an aircraft, will enhance the safety of operation of civil aircraft. The project will also consider the wider organizational impacts of such position and intent data primarily in terms of their effect on en-route airspace capacity. The algorithms developed will be more robust and reliable than the current ones which do not take account of data uncertainty. As a result, all detection and resolution manoeuvres will be accompanied by a metric of uncertainty to provide a level of protection (integrity) against potential catastrophic failures. The use of such algorithms in aircraft should lead to a safe and efficient air traffic environment in future European airspace. The research is being carried out by Imperial College London and the University of Glasgow in collaboration with Eurocontrol, the UK CAA and ISA software.

Airborne New and Advanced Satellite techniques and Technologies in A System Integrated Approach (ANASTASIA): The aim of ANASTASIA (funded by the EC) is to study on board space based Navigation and Communication technologies that should become available for aircraft between 2010 and 2020. The project will contribute to developing standards, and provide advanced insights into the optimal architectures and technologies for next generation navigation and communication architectures on-board aircraft. The consortium of European industry and research organisations is led by Thales. Imperial is leading the work to develop a navigation architecture and algorithms that exploit multi-constellation, multi-frequency space-based positioning systems, state-of-the art electro-mechanical motion sensors and spatial databases.

Robust navigation algorithms for aircraft precision approach and landing using global satellite navigation systems: This research is investigating ways of using the new signals (in addition to the development of various models for the error sources) proposed as part of the modernization of GPS and the new systems under development including EGNOS (the European Geostationary Navigation Overlay Service) and Galileo to characterize the levels of performance achievable with the carrier phase measurements and to correlate this with aircraft precision approach and landing requirements. Hybridisation with other non-space based sensors such INS (Inertial Navigation Systems) are also being explored. The integration of data from different systems should enable high integrity, continuity of service and availability.

Precise Point Positioning with the GNSS carrier phase measurements: The objective of this project is to improve the performance of Precise Point Positioning (PPP) which is based on the processing of un-differenced pseudorange and carrier phase observations from a single GPS receiver. External products including satellite orbit and satellite clock information are being used to reduce the relevant errors.

Robust statistical framework for monitoring the integrity of space-based navigation systems, and preparing the marketplace for integrity-based services: Integrity monitoring of satellite navigation systems such as the Global Positioning System (GPS) offers a level of protection against potentially hazardous failures or malfunction. Existing integrity monitoring approaches rely heavily on statistical assumptions regarding the characteristics of the residual navigation errors after various error modelling and mitigation schemes have been applied. Some studies have pointed to the fact that in practice, residual navigation errors although not very different from normal laws, may neither have normal tails nor zero mean. Furthermore, there has been insufficient data to demonstrate the nature of the distribution. This project is testing the assumption that residual navigation errors come from a normally distributed population with zero mean. Real GPS data from around the world are being used to test the statistical assumptions underpinning current methods with the objective of specifying a new and robust statistical framework that takes into account the spatio-temporal characteristics associated with the residual navigation errors. The research will follow this by studying the potential user services to be supported by systems employing the new statistical framework.

- **IESSG, The University of Nottingham**
  http://www.nottingham.ac.uk/iessg/

IRC2G : Development of a Multi-constellation Augmentation Service Based on EGNOS and Galileo Simulation: In a project funded by the European GNSS Supervisory Authority (GSA, formerly the Galileo Joint Undertaking), the Finnish Geodetic Institute, the IESSG and the Chinese Academy of Surveying and Mapping prototyped a multi-constellation augmentation service based on EGNOS and a Galileo simulation. The project covered the prototype development of an SBAS message generator to generate the SBAS messages for both GPS and Galileo; a simulator for simulating the Galileo-related errors, raw measurements and ephemeris; an Internet broadcaster for disseminating the augmentation signals over the wireless Internet, and a Pocket PC-based user terminal for demonstrating the integrated GPS/Galileo augmented service.

GGPhi : A Low-Cost, Low-Power Galileo/GPS Carrier Phase Positioning System: GGPhi is another project funded by the European GNSS Supervisory Authority. It was led by the CAA Institute of Satellite Navigation at the University of Leeds, who were in charge of the design of the remote sensor and the control unit. The IESSG was working on the positioning algorithms; and the Informatics Development Institute in Ireland studied the networking aspects. The GGPhi concept aims at making carrier phase precision positioning attainable for those applications that are constrained by environmental and cost issues, such as landslide monitoring and other environmental applications, where power and communications infrastructure may not exist, and where there is a significant risk of the loss of the receivers. To this purpose a measurement system composed of a number of remote wirelessly-connected Galileo/GPS measurement units supported by a control unit, in charge of the measurement scheduling, GNSS-aiding and data processing, is being designed.

The Potential Impact of GNSS/INS Integration on Maritime Navigation: The General Lighthouse Authorities of the UK & Ireland commissioned an assessment of the impact that the integration of Global Navigation Satellite Systems (GNSS) with Inertial Navigation Systems (INS) would have on the aids to navigation (AtoN) services currently provided, and those to be provided in the future. There is concern about the vulnerability of GNSS, and the provision of complementary and backup systems is seen to be of great importance. The integration of INS could provide an independent and self-contained navigation system, for a limited time period, invulnerable to external intentional or unintentional interference, or the influences of changes in national policies.

The study included an analysis of the potential use of GNSS-INS in three of the four phases of a vessel's voyage: coastal, port approach and docking. The project consisted of a technology assessment, looking at the different inertial technologies that might be suitable for each phase. This was followed by a technology proving stage, evaluating suitable equipment using simulation and field trials to prove that the claimed performance could be achieved in practice. The final

stage of the project was to assess the effects of the availability of such systems on existing and planned aids to navigation services.

SISTER : Satcomms In Support of Transport on European Roads: SISTER is a Framework 6 Integrated Project in which the potential benefits of the provision of satellite communications to support a wide variety of intelligent transport services are being investigated. It is intended that a mobile satellite communications system will be used alongside a variety of short and medium range terrestrial communications systems, and that the complexity of selecting the most appropriate communications technology would be handled automatically. SISTER involves some 20 partners from across Europe, and is led by Avanti Communications in London. The IESSG's role is to develop and test the provision of RTK reference data streams over a continental area via Satcomms.

The British Isles GPS archive Facility (BIGF), *http://www.bigf.ac.uk:* BIGF, operating since 1998, is the long term repository for continuous GPS data recorded by a network of over 120 permanent GPS stations (including the Ordnance Survey of Great Britain and Ordnance Survey of Northern Ireland active stations), established throughout the British Isles. In 2002 BIGF gained funding from the Natural Environment Research Council (NERC) to become one of its prestigious facilities. BIGF is hosted by the IESSG, known globally as a centre for postgraduate teaching and research in the field of satellite positioning. It therefore provides an appropriate venue for a central archive of such data.

By archiving GPS data on a long term basis, BIGF preserves long term signatures buried in the data, also enabling cost economies when bidding for research funding.

BIGF facilitates research by non-commercial scientific users for use in scientific applications, recent examples include:

- *Atmospheric water vapour studies*
- *Coastal erosion*
- *Hydro-ecological modelling*
- *Ionospheric studies for VLBI*
- *Kinematic data processing*
- *Numerical weather prediction*
- *Precise height determination*
- *Signal delays due to the atmosphere*
- *Vertical offshore reference frames*

The aim of BIGF is to *enable access* and to *broaden the range* of disciplines using the archive. Access to the archive is enabled firstly by submitting an online form at the BIGF website, with data delivery by secure ftp.

The Future Real-time Location and Navigation study, FURLONG: This study, funded by the British National Space Centre under the S@tcom programme, involved the simulation and processing of Galileo and the Modernised GPS observations, in order to assess the precision and reliability of future real-time positioning services. The work was undertaken by the Institute in partnership with SciSys Space and Defence Ltd and the Centre for Ecology and Hydrology, both being leading UK organisations in this field.

Furlong aimed to demonstrate that future navigation and communication systems can be integrated successfully to provide high precision and reliable location-based services, and to determine the parameters which must be met for successful operation. This was achieved through a series of sophisticated linked simulations, including the application of complex and detailed environmental models to realistically model signal obscuration, multipath and degradation, covering the current and future GNSS signals and communication systems.

The resulting toolbox of simulation and analysis tools was used to emulate the performance of a number of proposed real-time positioning services. The results highlighted the fact that to achieve a high-level positioning accuracy the availability of a good communications link is critical,

regardless of the GNSS systems used. FURLONG will thus provide a key foundation on which industry can build services.

GalileoSat System Simulation Facility (GSSF): Since 2000, the IESSG has been involved in the ESA-funded project to produce an end-to-end software simulation of Galileo - the GalileoSat System Simulation Facility (GSSF). As part of the VEGA-led team working on the study, the IESSG is acting as a consultant on technical aspects of satellite navigation and specific simulation modelling details, and is responsible for the correct implementation of all navigation-related algorithms. Part of this role involves the provision of definitions of suitable simulation and modelling algorithms, with the necessary algorithm description, pseudo-code where necessary, and test data. In addition, the IESSG is responsible for the formal validation of the software.

POLARIS: Polaris is an EC FP5-funded project to develop a software tool to provide a link between the Galileo System design and users of the system. Polaris analyses the Navigation Performance of Galileo, and allows users to test the performance when augmented by various other sensors, such as odometers, compasses, and even GPS. Polaris will help identify new GNSS services, optimise the Galileo system from a user point of view, and optimise the Galileo Service Definition. Polaris will be a powerful means of illustrating the role of Galileo and showing users its potential benefits. The Polaris team is led by GMV in Spain. The IESSG leads the work package on the User Application Subsystem, and is responsible for modelling the environment and trajectory of specific applications, and for providing detailed modelling algorithms for the additional sensors.

- The NERC Space Geodesy Facility (SGF), http://nercslr.nmt.ac.uk/

GNSS: SGF manages two IGS systems at Herstmonceux; HERS, currently an Ashtech Z12 system, operating since 1996 and HERT, a joint GPS/GLONASS dual frequency Z18 receiver.

In order to improve the low-elevation sky coverage seen by the HERS GPS/GLONASS system, the antenna was moved during 2003 from its original location close to HERS to a superior location close to the principal ground-calibration target used by the SLR system. At this stable site the renamed HERT receiver is approximately 100m from the SLR system. This move has further strengthened the local links between the GNSS and SLR co-ordinate frames and enabled a degree of site stability monitoring via a daily automatic differential GPS baseline solution between HERS and HERT, as part of a developing new capability within the group to analyse GNSS data. The solutions reveal an annual signal in the baseline of amplitude less than 2mm, and further investigations continue, including analyses of the laser and emerging on-site absolute gravity data. In a continuing collaboration between SGF and the Geomatics Department at UCL, an MSc student carried out a local GPS and Total Station survey during the summer of 2003 in order to re-determine the distances between the laser telescope and the calibration targets, at distances of between 100 and 400m. The derived value of the distance to the principal calibration target is within 1mm of the original OS-derived distance.

Since 2001 the GNSS observations are rigorously checked on site for consistency and quality and then delivered in accordance with the IGS guidelines; the GPS and GPS/GLONASS data both hourly and daily are delivered in standard RINEX format to IGS data centres and to the British Isles GPS Facility, BIGF. In addition, one-second data from the HERT system are archived on site in RINEX format to be available on request, with the same system HERT also streaming GPS and GLONASS navigation data into the Internet for re-broadcast in support of the emerging and important EUREF-IP and IGS Real-time Projects.

Evaluation of potential systematic bias in GNSS orbital solutions (SGF): The high accuracy of SLR measurements can be exploited to test the accuracy of operational orbital ephemerides of GNSS satellites, as determined by the IGS Analysis Centres. Two GPS satellites and all GLONASS satellites are fitted with laser retro-reflector arrays and the global laser ranging network makes precise ranging observations to the two GPS and three of the GLONASS vehicles on a regular basis. Most of the GLONASS satellites launched this decade carry smaller arrays than those from the 1990s and early 2000s, making the interpretation of SLR observations much more straightforward. For the small arrays on GPS satellites there had not been a problem of

interpretation. However, the laser data remain consistent in suggesting that the IGS orbits are too large; ranges determined from the IGS orbits place the satellites about 5cm further away from the centre of the Earth than the SLR observations imply. The radial scatter in IGS GLONASS orbits is found to be about 5cm RMS and that of the two GPS orbits about 2cm RMS.

2a Atmospheric Studies

- **Institute of Engineering Surveying and Space Geodesy**
  http://www.nottingham.ac.uk/iessg

Ionospheric Scintillation Research at the IESSG: The IESSG continued research work on ionospheric scintillation effects on GNSS. Within the scope of a project started on 2001, an array of GPS Ionospheric Scintillation and TEC Monitor (GISTM) receivers was in place in the UK and Norway until the end of 2003. At the end of 2006 one of these receivers was logging high rate (50Hz) scintillation data in Nottingham and another in Dourbes, Belgium, the latter under collaboration with the Royal Meteorological Institute of Belgium (RMI). Of particular interest to the IESSG studies have been the analyses of effects on different GPS positioning techniques and on the performance of the European Geostationary Navigation Overlay System (EGNOS) in a scenario of strong scintillation. Investigations were carried out on positioning errors when using different techniques, such as C/A code based point positioning and Differential GPS, as well as carrier phase based positioning, with results widely publicised. Comprehensive statistical analyses were undertaken, aiming to characterise ionospheric scintillation occurrence over Northern Europe and impact on GNSS users. Statistics of occurrence of high levels of phase scintillation (given by the widely used $\sigma\phi$ index) showed that, on a day of enhanced geomagnetic activity at northern European latitudes, for nearly 3% of the time, two satellites may be affected simultaneously, demonstrating that if this enhanced activity leads to receiver loss of lock on these satellites the impact on system availability can be significant, in particular for safety critical applications. The IESSG has participated of COST296 MIERS (Mitigation of Ionospheric Effects on Radio Systems) and has established collaborative links with a number of institutions. Joint work with the University of Leeds has been carried out in 2006 on the use of GPS ionospheric scintillation indices as input to receiver tracking models, aiming to use the latter to assess receiver tracking performance under scintillation conditions. Collaboration with colleagues at the National Institute for Geophysics and Volcanology (INGV, Italy) has focused in particular on forecasting of scintillation occurrence, whereas joint studies with Sao Paulo State University (UNESP, Brazil) have concentrated on mitigation of effects on GPS positioning accuracy using an improved stochastic model.

Meteorology and climate – GPS Near real-time processing: Over the period 2003-2006, the IESSG developed a GPS near real-time (NRT) system for the hourly estimation of tropospheric delays. The development was carried out for the UK Met Office, which announced at the end of 2006 that the ZTD estimates had started to be assimilated in their operational numerical weather prediction model. The processed network now fully covers the British Isles and, with a lower density, most of Western European countries, which represents in total more than 200 stations being processed. Further planned developments will bring the hourly system to a fifteen minute based processing to reduce the latency of the output. Research has also been carried out into the use of GPS NRT data for better understanding severe weather events, such as thunderstorms.

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Atmospheric Studies: Troposphere: An extensive validation of GPS-based estimates of integrated water vapour across the Australian region was carried out in collaboration with the Australian Bureau of Meteorology Research Centre, as a first step to assessing the potential for using GPS-based water vapour estimates in Australian numerical weather prediction models (Glowacki et al, 2006). The average relative accuracies of GPS-based integrated water vapour estimates compared with co-located radiosondes were found to be 8.8%, whereas respective errors of 10.7% and 18.0% were obtained on comparison with analyses and 6-hour predictions

from the Australian Bureau of Meteorology's operational global numerical weather prediction system for the year 2000. This indicates the potential of GPS integrated water vapour estimates to substantially reduce such errors if assimilated. Diurnal variations in integrated water vapour time series were also shown for the first time across the Australian region.

Atmospheric Studies: Ionosphere: An ionospheric tomography derived from the L1 and L2 GPS carriers has been investigated as a means of reducing errors in positioning a kinematic rover from a network of regional base stations with known positions. The methodology seeks to estimate the parameters of the ionospheric model, station tropospheric corrections and any ambiguities that have not been fixed in the Kalman filter with spatial and temporal constraints applied to the tomography. The use of L1 and L2 rather than the ionosphere free combination has the potential for enhanced accuracy although the procedure requires a reasonably accurate a priori ionospheric model such as that derived for the previous day.

2b Engineering Applications

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Engineering Applications: In 2003 Newcastle University was successful in its bid to the Sixth Framework Programme PRIORITY 1.1.6.3, Global Change and Ecosystems. As part of the 47 partner consortium LESSLOSS, Newcastle has developed a low cost dual frequency GPS monitoring station. At only one third of the cost of a commercial dual frequency GPS receiver the Newcastle ALPS (Autonomous Logging and Processing System) can be deployed in greater network densities allowing increased spatial resolution of landslide monitoring. The ALPS system has been tested extensively against commercial receivers and is currently undergoing field trials as the School's BIONICS (Biological and engineering impacts of climate change on slopes) testing site located at Nafferton Farm, Northumberland. This testing site comprises fully instrumented man made embankment with climate parameter controls e.g. rainfall event/return periods. Information available from the ALPS system is helping landslide modellers gain deeper insight into earth movement processes and failure triggers.

Systematic Errors: Extensive studies of the propagation of un-modelled periodic ground displacements into GPS coordinate estimates and time series used in geophysical studies are detailed in Penna and Stewart (2003) and Stewart et al (2005). It has been demonstrated that un-modelled 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.

Sidereal-repeating (predominantly multipath) error has been studied by Ragheb et al (2006), 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.

- **Proudman Oceanographic Laboratory**
  http://www.pol.ac.uk

Global Navigation Satellite Systems: We have continued our research into the stochastic properties of geodetic time series. Twelve years of DORIS data have been analysed to understand the nature of the noise in the weekly station coordinate time-series. The data set was found to have noise characteristics similar to that found in CGPS time series, that is, a combination of white noise plus flicker noise. The white noise shows a dependence on site latitude and the number of DORIS-equipped satellites used in the solution. We found a rate

uncertainty of 1 mm/year after 12 years in the vertical which is comparable to that achieved by GPS. However the results show that it takes DORIS twice as long to reach 1 mm/year than GPS in the horizontal component.

- **Institute of Engineering Surveying and Space Geodesy**
  http://www.nottingham.ac.uk/iessg

Precise Point Positioning: Since 2003, the IESSG has carried out research related to the precise point positioning (PPP) technique using the Bernese GPS software versions 4.2 and 5.0. In recent years, this technique has become a popular technique for many geodetic monitoring applications at the millimetre level. To date, PPP has mainly been associated with the GIPSY OASIS II software developed at the Jet Propulsion Laboratory (JPL). However, other scientific GPS software packages, such as the Bernese GPS software (BSW) versions 4.2, and especially, 5.0 developed at the Astronomical Institute at the University of Berne (AIUB), are also capable of analyzing un-differenced GPS measurements. It can be shown that globally transformed Bernese PPP coordinate solutions are nearly equivalent to those from JPL produced using GIPSY OASIS II and SOPAC produced using GAMIT/GLOBK. Furthermore, coordinate time series from Bernese PPP have station velocity estimates which agree at the <1mm/yr for horizontal and <2mm/yr for vertical components. It was confirmed that using GPS products from the CODE IGS analysis centre rather than from the IGS combination process improves results.

CGPS station performance monitoring: Since 2003, the IESSG has developed several quality control tools based on TEQC for the monitoring of CGPS station performance and to investigate multipath and radio frequency interference problems at particular CGPS stations. These tools are used to routinely monitor the performance of all CGPS station data included in BIGF and the ESEAS CGPS archive at the Norwegian Mapping Authority. Furthermore, these tools have enabled investigations of multipath and radio frequency interference effects at several CGPS stations in the UK, namely ABER, ABYW, MORP and NSTG. As part of BIGF further work is being carried out on this topic, which is also in-line with international developments.

Mapping the Underworld - [www.mappingtheunderworld.ac.uk] is a 4-year research project worth over £1m, ending in 2008, with the main aim to evaluate and combine novel location ideas with existing methods, to give a single multi-modal capability to locate, identify and assess the condition assets. Partners include: academics from Bath, Birmingham, Leeds, Nottingham, Oxford, Sheffield and Southampton, with expertise in ground penetrating radar, acoustics, quasi-static field, soil/asset interaction and in-pipe sensor technology; together with industry, most notably the UK Water Industry Research (UKWIR).

VISTA or Visualising Integrated Information on Buried Assets to Reduce Street-work - is another major collaborative research project involving the Universities of Nottingham and Leeds, as well as UKWIR and 18 other organizations, including professional organizations, utility, excavation and survey companies.

The Institute was one of the pioneers in applying augmented reality (AR) as a means to visualize sub-surface assets. VISTA focuses on enhancing and integrating existing asset metadata with a real-time precise location capability, which will enable the seamless display of the real above ground environment and synthetic below ground assets, in an AR display unit.

3 NATIONAL AND CONTINENTAL NETWORKS

- **Ordnance Survey of Great Britain**
  http://www.ordnancesurvey.co.uk

Ordnance Survey's national RTK GPS network OS Net(tm) has been developed since 2003 and currently covers the majority of GB with 101 (as of June 2007) stations. To increase the coverage and improve error modelling some stations from Ireland and Northern Ireland have been added. Expansion into the north west of Scotland to complete the coverage of GB is planned to

be completed by the end of 2007. The full network is planned to consist of approximately 110 stations.

OS Net is managed via the GPSNet(tm) 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 two partners - Leica (SmartNet service) and Trimble (VRS Now(tm) service). Partners take the raw GPS 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.

Starting in 2008 a complete upgrade of all the station hardware is planned. Receivers will be upgraded to GNSS and antennas will be upgraded to be GNSS compatible including Galileo signals.

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

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Newcastle University IGS Global Network Associate Analysis Centre: Newcastle University has maintained an International GNSS Service (IGS) Associate Analysis centre (GNAAC) since 1995, producing weekly coordinate solutions for the global IGS network polyhedron. Essential to this activity is the Solution Independent Exchange Format (SINEX) which Newcastle took an active role in developing. GNAAC activity has continued submitting SINEX beyond the initial IERS pilot project and along with the other IGS GNAAC's form an integral part of the official coordinate analysis produced at NRCAN by Remi Ferland, between 2003 and 2006 the GNAAC has been coordinated by Konstantin Nurutdinov and David Lavallée. GNAAC by-products have been key to much of the scientific work undertaken at Newcastle.

No Net Rotation Reference Frame determination: Kreemer et al [2006] have determined a new No Net Rotation (NNR) reference model of the Earth's horizontal surface velocity from ~5700 geodetic velocities. The most important implication of this work is for the International Terrestrial Reference Frame (ITRF), since by convention the ITRF is a NNR. The sensitivity of the new NNR frame is tested according to data input and model assumptions: these differences are ~0.6 mm/yr, and much smaller than the differences with the current ITRF of 3.1 mm/yr, so it is concluded that the ITRF does not satisfy the NNR condition. This work also highlights the sensitivity of NNR determination to the realisation of the ITRF origin.

Geocenter motion determination: Lavallée et al. [2006] present a new precise method for determining geocenter motion from GPS. This unified approach utilizes constraints on elastic properties of the Earth to allow precise GPS baseline determination and improve the determination of the GPS geocenter despite orbit modelling imprecision. The application of this approach to GPS improves consistency among different GPS solutions, agreement with SLR geocenter motion estimates and those from surface mass loading models. This unified approach has been developed from work on surface mass loading which has been undertaken at Newcastle (see below). This work has implications for the ITRF since geocenter motion is not included in the current ITRF realisation because of past disagreements between different techniques; this is a well known shortcoming of the current ITRF realisation which needs to be addressed in the near future.

IGS/EPN and TIGA stations (MORP and NSTG): Since 1996, the University of Newcastle has operated a permanent GPS site near Morpeth (MORP), about 30 km north of Newcastle upon Tyne, and carried out episodic and semi-permanent GPS observations at the 100-year-old tide gauge at North Shields (NSTG). In association with the University of Nottingham, NSTG has operated continuously since 2001. In late 2002, MORP was accepted into the IGS and European Permanent Network (EPN), contributing daily and near-real-time data. The entire back-catalogue of GPS data for MORP and NSTG has been submitted to the TIGA archive in support of sea-level change measurements.

A new monument has recently been installed at the Cockle Park Farm site where MORP is located, about 7m from the existing monument. As with the existing MORP site, MORG (proposed name only) is monumented on a ~3m high slab of quarried stone to provide a robust connection between the local bedrock and the antenna. We have installed a GPS/GLONASS receiver at the site and will soon request it be included in the IGS/EPN networks along with MORP with daily data transmission envisaged. We expect to upgrade the receiver to GPS/GLONASS/Galileo once suitable receivers are available.

- **IESSG, The University of Nottingham**
  http://www.nottingham.ac.uk/iessg/

University of Nottingham European Sea Level Service (ESEAS) CGPS Analysis Centre: Between November 2003 and November 2005, the IESSG has been one of six ESEAS CGPS analysis centres, processing data from over 30 CGPS stations located at or close to tide gauges in Europe. For this purpose the IESSG used the precise point positioning (PPP) capability in the Bernese GPS software version 5.0. On a daily basis, stations of the ESEAS CGPS network along with the global IGS reference station network are processed using PPP followed by the transformation of all PPP solutions into the International Terrestrial Reference Frame (ITRF). The parameters for this transformation are determined from the daily PPP solutions of the IGS stations and their official epochal ITRF coordinates. Although the EC funded project has finished, the IESSG together with the Norwegian Mapping Authority continue their engagements as ESEAS CGPS ACs.

University of Nottingham European Sea Level Service (ESEAS) CGPS Time Series Analysis Centre: Between November 2003 and November 2005, the IESSG has been one of two ESEAS CGPS coordinate time series analysis centres and was responsible for coordinating and implementing the ESEAS coordinate time series analysis strategy. The implementation involved the analysis of fifteen different coordinate time series solutions from six different ESEAS CGPS analysis centres and the TIGA analysis centre at the University of La Rochelle. The results have been presented in the ESEAS – Research Infrastructure Final Report.

A Network Real-time Kinematic GPS (NRTK GPS) Test-bed Facility, established by the University of Nottingham and Leica Geosystem Ltd (UK): Whilst the Ordnance Survey was developing a national wide NRTK GNSS infrastructure, OS Net, in the last two years, an effort to establish a Nottingham/Leica NRTK GPS facility was initiated jointly by The University of Nottingham and Leica Geosystems (UK) in May 2005. The network was designed to consist of 16 permanent GPS reference stations and a few more temporary reference stations. It is the only network GPS reference station facility in the UK for a pure scientific research purpose.

The network itself covers an area of 20,000 km2 in the centre of the UK. Each of the 16 GPS sites is occupied with a Leica GRX1200 GPS receiver and an AT504 choke ring antenna. The 8 sites owned by the University of Nottingham are roughly situated on the eastern side of the network and the rest 8 existing sites owned by Leica are mostly on the western part of the network as shown in Figure 2. The maximum, minimum and average inter-station separations are 102 km, 30 km, and 60 km, respectively. The design of this network layout intends to investigate the impact of different inter-station distances/atmospheric models on the positioning accuracy as well as the quality metrics of NRTK GNSS. Eventually, this network will act as a testbed for various outdoor UbiPos activities. It has taken about more than half a year in total for the authors in finding the property owners with right geographical locations, and who are willing to accommodate a GPS receiver and install a GPS antenna on their properties virtually for free. Consequent site inspection was carried out, mainly to investigate the site multipath level and the potential RF interference by the surroundings.

Except for a reference station network, the facility also contains two other basic components: a control centre and the user groups. The control centre consists of a data server which is running Leica network processing and data management software, GPS Spider. Through the Internet, each site is connected to the data server either directly or indirectly. The real-time data received from each reference site are in a form of either passive data set (a data product passed by Leica

Geosystems from its GPS reference sites) through an indirect connection or active data streams from Nottingham sites through a direct connection. At the moment, the user groups are authorised mobile GPS receivers, including those of facility owners and the site property owners whose activities in using this network can be justified as scientific research. The following items summarise the main applications of this test-bed facility:

- Support teaching, training and research activities at broad areas, for example location based services, real-time crustal/structural deformation monitoring, weather forecasting, etc,
- Support UbiPos activities and field trials through integrated sensor systems,
- A test-bed for several recently awarded EC Galileo projects,
- A test-bed for Future Intelligent Transport Systems and Services (ITS).

4 INTEGRATED SYSTEMS AND INERTIAL NAVIGATION SYSTEMS

- **Imperial College London**
  http://www.geomatics.cv.imperial.ac.uk/

Improved integrity algorithms for integrated GPS/INS systems in the presence of slowly growing errors: This project addressed integrated GPS/INS architectures, the corresponding failure modes and the sensor level integrity algorithms used to protect users from such failure modes. An exhaustive literature review was conducted to identify the various failure modes. These were then grouped into classes based on their characteristics and a mathematical (failure) model specified for each class. For the analysis of failures, a simulation of a typical aircraft trajectory was developed, including the capability to generate raw measurements from GPS and the INS. The simulated GPS and INS measurements for the aircraft were used to evaluate the performance of the current integrity algorithms. Their performances were assessed for the most difficult case of failures; slowly growing errors (SGE), and shown to be inadequate (i.e. a considerable period of time is required for detection). A new algorithm was subsequently developed based on the detection of the growth rate of a typical test statistic (assuming a single failure at a time). Results showed that the new algorithm detects slowly growing ramp-type errors faster than the current methods, with a forty percent improvement in the time it takes to detect the worst case SGE. The algorithm was then extended to include detection of multiple SGEs for which a new tightly coupled method referred to as the “piggyback architecture” was proposed. This method provides the novel capability of detecting all failures including those affecting the INS. The proposed algorithms are validated with real GPS and INS data. In this way, the integrity performance of the integrated system is enhanced against the worst case failures with a detection time that is beneficial for the achievement of stringent time-to-alert requirements. A practical implementation would then comprise of the use of the rate detector algorithm alongside the current methods or the piggy back architecture.

Reliable map-matching algorithms for land transport applications: A range of transport telematics applications and services require continuous and accurate positioning information of the vehicles travelling on the road network. Two types of information are essential for such telematics applications and services. These are the determination of the vehicle position and the determination of the physical location of the vehicle on the road network. The most common devices used for vehicle positioning are based on GPS, Dead-Reckoning (DR) sensors, Map Matching (MM) and microwave beacons. The use of these devices either in isolation or combination depends on the Required Navigation Performance (RNP) parameter specifications (accuracy, integrity, continuity and availability). Furthermore, the capability to identify the physical location of a vehicle is a key requirement in transport telematics applications. In order to achieve the RNP, system and sensor complementarity, such as in the case of the integration of GPS, DR and digital map data could be used to enhance geometric positioning capability. MM not only enables the physical location of the vehicle to be identified but also improves the positioning capability if a good digital map is available. This research has developed novel map-matching algorithms that exploit all available information (quantitative and qualitative). Fuzzy logic techniques are used to address some of the vague qualitative information available.

Free network mobile people and product location for enhanced personal and property security: The project has demonstrated the feasibility of a low-cost system capable of providing continuous tracking of people and property in all environments. The objective was to develop a system to locate ad-hoc networks of mobile users and equipment using current or near future wireless radio enabled equipment. The 'nodes' of the network could be people with suitably equipped mobile phones (or simple tags) or equipment (such as PCs, printers) with wireless radio connections. The location network can expand and contract 'organically' so that no central control points are required. In this way 'bottle-necks' in the system are avoided when there are many users and location can be performed very quickly. This EPSRC project was carried out by Imperial and University of Leeds in collaboration with New Forrest Communications Ltd, the Police Scientific Development Branch and the Forensic Science Services.

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Accurate and precise GNSS positioning of aircraft over long baselines: As part of a NERC-funded to investigate ice volume changes in Svalbard using airborne LiDAR, we have been developing the *Track* kinematic GPS processing software (part of GAMIT/GLOBK). *Track* implements a Kalman Filter to estimate site positions and tropospheric zenith delay parameters using multi-rover and multi-base stations. We have implemented into *Track* ocean tide loading displacement corrections, antenna phase centre models and enhanced tropospheric estimation strategies in order to improve the precision and accuracy of the final positions. We have demonstrated ~5-7cm RMS agreement with long-baseline (~2500 km) tests and against Oscar Colombo's *IT* software for real flight data.

- **IESSG, The University of Nottingham**
  http://www.nottingham.ac.uk/iessg/

GPS / IMU integration software: The Institute has developed Kinpos, with funding from the University. This is a sophisticated software package that enables the close and effective integration of RTK GPS with output from an Inertial Measurement Unit (IMU). A Kalman filter is used to jointly process pseudorange and carrier phase GPS measurements with accelerometer and gyro readings. The IMU greatly enhances the ability of the algorithms to detect and repair cycle slips in the phase data and also greatly accelerates ambiguity resolution. In a complementary manner, the GPS data enables a rapid alignment of the IMU and containment of the biases and drifts of the inertial sensors. The software has been tested in a broad range of land, sea and airborne applications, using a variety of grades of inertial sensor, and has now been developed to enable future commercialisation activities.

The SPACE project: Seamless Positioning in All Conditions and Environments (SPACE) is a 3-year joint research project, funded by the Pinpoint Faraday Partnership, drawing for the first time on the combined expertise of the 4 leading UK institutions in the area of GNSS and positioning technologies: the Institute, University of Leeds, University College London and Imperial College, together with the most important industrial organisations in the field. This £1.5M project is backed by EPSRC and industry - BAe Systems, the Civil Aviation Authority, Leica Geosystems, the Ordnance Survey of Great Britain, Nottingham Scientific, QinetiQ, Thales Group and EADS Astrium.

The SPACE remit is to address the scientific and technical boundaries of high quality GNSS-based positioning in all environments, including dense urban and indoor locations, where GNSS positioning has previously not been accurate, reliable or even possible. The project addresses issues such as multipath mitigation, sensor level integrity, filter design, sensor integration and GNSS hardware design. The aim is to develop a research test-bed facility that will provide high accuracy positioning everywhere. The test-bed will be used as a reference platform for users to benchmark their positioning systems, and enable implementation and testing of third party algorithms.

A number of PhD studentships and collaborative academic-industry research projects have been initiated and funded under Pinpoint; the most successful University group being the Institute with 5 CASE Studentships, in collaboration with Ordnance Survey, Leica, Applanix, QinetiQ and EADS Astrium.

5 SATELLITE ALTIMETRY

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

TOPEX/Poseidon, Jason-1 and ERS-2 radiometer calibrations: Sea-level change studies from altimetric satellites are reliant on the stability of the sea-surface heights determined from the on-board altimeters. Key here is the accuracy and stability of the wet tropospheric delay correction as measured by the on-board microwave radiometers. Since 2003, Newcastle University has undertaken a series of studies investigating the accuracies of the various on-board radiometer instruments for both NASA's and ESA's altimetric satellite missions. Precise GPS processing has been successfully employed to both detect and correct for the gain anomaly fall experienced by ERS-2 radiometer in 1996 and subsequent drift in the 23.8 GHz channel. Similarly a high degree of consistency between GPS estimated wet tropospheric delay and Jason-1 microwave radiometer has also been observed. Furthermore, the apparent jump in the Jason-1 radiometer (cycles 26-34) is also detectable using GPS. For TOPEX/Poseidon, studies show the radiometer displays a dominant drift of around +0.2 K/yr in the 18 GHz channel during the first 7 years of flight which subsequently stabilizes. Recent work focuses on the calibration of radiometer on-board ENVISAT and the use of UK's co-located tide gauge and GPS database for further investigation of ENVISAT's altimeter performance.

Altimeter calibrations using tide gauges: Newcastle, often in collaboration with the Proudman Oceanographic Laboratory (POL) and Nottingham University, has undertake absolute and relative calibrations of altimeters onboard satellites For absolute calibrations the tide gauges in the UK network that have been connected to the reference frame by GPS and levelling are used to recover the mis-closure between the altimetric and tide gauge time series, the so-called altimeter bias. Absolute bias studies have included TOPEX/Poseidon, Jason-1 and ENVISAT. (e.g. Woodworth et al., 2004).

Drift in the altimetric range measurements associated with the wet tropospheric radiometric correction has been investigated for ERS-2, TOPEX/Poseidon, Jason-1 and most recently ENVISAT by comparing the radiometric correction against that estimated from a global network of GPS stations (Edwards et al, 2004; Edwards and Moore, 2006). In addition investigation of the coldest ocean brightness temperatures (TB) and the hottest brightness temperatures over the Amazon and Congo deficiencies permits investigation into the drift within the multiple radiometric channels. From these drifts corrections to the TBs have been derived either from the GPS data or by utilising the GPS data as independent verification.

- **Earth and Planetary Remote Sensing Laboratory, De Montfort University**
  http://www.cse.dmu.ac.uk/EAPRS/

Over the past four years, research has focussed on the analysis and interpretation of radar altimeter data over all surfaces, including both geophysical and engineering issues, together with synergistic applications.

Mapping/DEM Validation: The global mapping work leading to the release of the ACE-1 Global Digital Elevation Model (GDEM) has continued, with a series of both regional and global studies. As the sophistication of deconstructing and retracking the component parts of the complex echoes typically returned from the Earth's surfaces continues to advance, the scope of this work has greatly increased, as has the network of international collaborative research with institutes on four continents. With the availability of data from the EnviSat RA-2 to augment previous coverage of mountainous regions, a global analysis and validation of the SRTM dataset has now been

completed. Work has commenced on the considerable task of fusing the huge in-house dataset of multi-mission altimeter derived heights (from ERS-1, ERS-2, TOPEX, Jason-1 and EnviSat) to enhance and error correct the SRTM dataset and produce a new fused GDEM, ACE2, in collaboration with the European Space Agency (ESA).

The newest of the IAG Centres forming the International Gravity Field Service, the IDEMS centre (International Digital Elevation Model Service), has successfully been initiated at the EAPRS Lab at De Montfort University, with the task of providing both data and information on Digital Elevation Models to the geodetic community worldwide. As part of this work, it is planned to release the ACE2 model, together with associated information, to the geodetic community via the IDEMS website as soon as it is completed (within the next 18 months). More information on the IDEMS centre may be found at: http://www.cse.dmu.ac.uk/EAPRS/iag/

Inland water monitoring: One research area undergoing rapid growth is the successful retrieval of inland water heights globally from the series of satellite altimeter missions. This work has now enabled a Near Real Time pilot service at ESA ESRIN, disseminating EnviSat RA-2 derived heights to the global community within 3-5 days of measurement to informing water management decisions. A network of collaborating institutes has been set up across Africa to inform the future development of the NRT service. This work links to the ESA TIGER programme, and the World Meteorological Organisation WHYCOS programme. Analysis of the huge database of historical data is continuing, both to quantify changes in the global resource and to identify patterns of climate change and anthropogenic requirements. These data are also being fused with data from the GRACE mission, in a series of collaborative studies to identify and quantify surface and subsurface hydrological signals in the GRACE gravity data.

Engineering Issues and Future Mission Support: The ongoing research into the use of the RA-2 Individual Echoes, together with the University of Southampton, Science Systems and ESA, is providing valuable information on future altimeter design in addition to informing a range of geodetic disciplines. The EAPRS Lab is also currently running a series of studies towards future missions with geodetic implications; SMOS, CryoSat-2, EarthCare, Jason-2 and Sentinel-3.

- **Proudman Oceanographic Laboratory**
  http://www.pol.ac.uk

Satellite altimetry: Research at POL specific to altimetry has focused on methods for ongoing calibration of altimetric sea surface heights in terms of sea levels measured by tide gauges close to the altimeter ground track. Papers have been published on calibration of TOPX/Poseidon, Jason-1 and ERS-2 which have made use of selected UK tide gauges and local geoid models. Methods developed elsewhere (e.g. at University of South Florida), which calibrate altimeter data sets with the use of the global tide gauge data set, have benefited from the provision of data from POL-operated gauges in the UK and South Atlantic. Altimetry is ceasing to be a specialist activity and altimeter sea level data sets are increasing being used with tide gauge data in combined analyses. Nevertheless, there is a consensus in the altimeter community that the establishment of an International Altimeter Service (IAS) would be desirable, an initiative in which POL has taken a lead together with Ohio State University and DGFI, Munich.

6 SYTHETIC APERTURE RADAR

- **IESSG, The University of Nottingham**
  http://www.nottingham.ac.uk/iessg/

Persistent Scatterer Interferometric SAR (PSInSAR): Since 2003, the IESSG has developed its own PSInSAR software and used it for the analysis of ENVISAT acquisitions over London and Nottingham. The IESSG has also, in collaboration with the British Geological Survey, started work on the use of trihedral radar reflectors for *ground control* of PSInSAR results and the combination of PSInSAR and GPS techniques for modelling of atmospheric delays. However, it is usually difficult to tie-in PSInSAR measurements to traditional ground surveying methods, such as

GPS or levelling from the remote sensing data alone. If trihedral corner reflectors are used, these can be precisely surveyed. The optimisation of reflector networks will depend on a number of factors such as the relationship between the GPS antenna and reflector, the relative geometry of the reflector network, establishing reflector alignment in azimuth and elevation, site selection, site stability and how the reflectors are secured at the site.

7 SATELLITE ORBIT AND GRAVITY FIELD DETERMINATION

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Satellite Orbit and Gravity Field Determination: In principle, precise orbit determinations can be enhanced by utilising temporal variability in the lower order and degree gravitational harmonics as estimated from geophysical models of atmospheric pressure, ocean circulation and hydrology. In the first attempt of this kind, the validity of this approach, with current level of accuracy from geophysical models, was undertaken using the estimated geo-centre motion from LAGEOS I and LAGEOS II (Moore and Wang, 2003). A different methodology has utilised variation in the degree 2 order zero and order 1 harmonics inferred from Earth rotation parameters and polar motion. The methodology requires modelling of the motion term in the excitation functions from atmospheric and ocean models. The residual mass variation has been shown to be useful in precise orbit determinations for the degree two zonal harmonic.

Recovery of temporal variation in the lower order and degree harmonics has utilised geodetic satellites and the gravity field determination satellite, CHAMP. In Moore et al. (2005) a singular value decomposition approach identified the variability within lumped harmonic combinations that was observable with CHAMP. The combination of CHAMP and SLR ranging results from the geodetic satellites was seen to be an improvement over just SLR ranging for a 4 by 4 field by comparison against geophysical models. Other studies have compared mass redistribution form SLR to geodetic satellites and deformation studies from GPS against the GRACE monthly gravity field solutions.

Parallel to the aliasing study within the GRACE gravity field solutions due to Antarctic tidal mis-modelling a comprehensive analysis of the effect of high temporal mass redistribution due to the atmosphere, oceans and global hydrology was undertaken. The simulations showed that aliasing of the global cycles is probable but the magnitude of the aliasing is currently below the errors in the GRACE signatures.

Tidal aliasing into GRACE-derived ice mass balance estimates for Antarctica: Mis-modelled ocean tides alias into GRACE gravity field time series. Solar-related semi-diurnal constituents S2 and K2 are the most problematic as they alias to approximately 162 days and 7 year periods, respectively. Ocean tide models are not error free and especially so in Antarctica (King and Padman, 2005; King et al., 2005). Using TPXO6.2 as a “truth” we have investigated the effect of using CSR4 or FES2004 in the GRACE gravity field reductions at CSR or GFZ. Important spurious secular trends appear over ~3years which bias published ice mass balance estimates.

8 GRAVITY SURVEYS

- **Earth and Planetary Remote Sensing Laboratory, De Montfort University**
  http://www.cse.dmu.ac.uk/EAPRS/

Global Ocean Retracking: As part of the international research effort to create a new Global Gravity Field model (EGM07), the entire ERS-1 Geodetic Mission dataset has been retracked at full resolution over the global ocean. Using a suite of tailored algorithms, and exploiting the knowledge gained from global land and inland water retracking, this approach has successfully generated data to within 1 km of coasts, and substantially enhanced the previous information content over the Arctic and Antarctic oceans, allowing the generation of significantly improved

geoid information in these regions to augment DNSC06. Work is now proceeding to generate new Mean Sea Surfaces using this approach, and to inform a series of regional studies with collaborating institutes.

- **NERC Space Geodesy Facility (SGF)**
  http://nercslr.nmt.ac.uk/

Absolute gravimetry: Regular weekly operations of the newly-installed FG5 absolute gravimeter began in October 2006. The baseline observational programme is a 30-hour session centred on mid-GPS week, resulting in a weekly series of average gravity values of precision about 1-2 μgal, equivalent to a vertical precision of around 3mm. This is a joint programme with the Proudman Oceanographic Laboratory and UCL and will strengthen UK work in this field as well as providing what is hoped will be a stable series of gravity measurements to complement the high precision SLR and GNSS measurements from Herstmonceux. A long series of gravity measurements will strengthen in particular the interpretation of the long series of SLR and GNSS height solutions from the site.

- **Proudman Oceanographic Laboratory**
  http://www.pol.ac.uk

Gravity surveys: POL 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). During this period we have also purchased a second absolute gravimeter (FG5-222) to compliment the work done with FG5-103. To ensure that our AG measurements represent true land movement our machines have been regularly inter-compared with other absolute gravimeters at sites in the USA and Luxembourg. We, in conjunction with colleagues in Europe, have studied the error budget of AG measurements (together with superconducting gravimeter data) in order to obtain realistic uncertainty estimates for the estimated rates of land movement.

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

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Validation of Antarctic ocean tide models: Ocean tide models at the Poles are less well constrained by observations between 66N/S where Topex observations are available. The Antarctic is especially data poor in terms of direct observation of ocean tides from other sources. To address this King and Padman (2005) assembled a comprehensive database of tide gauge, bottom pressure recorder, GPS and gravity observations of ocean tides, including for the major ice shelf regions. Comparison with recent ocean tide models revealed 5-7 cm RMS errors per constituent for the four major constituents (TPXO6.2), 40% lower than the next best model (FES2004). This compares to 1-2 cm in the oceans where Topex data are available.

Ocean tide loading displacements: Allinson et al. (2004) investigated the performance of 'direct' estimation of ocean tide loading displacements from GPS by parameterising eight diurnal and semidiurnal constituents in daily precise point positioning solutions. Results showed that that parameter estimates began to stabilise with ~90 days of data and were at that point within ~10% of the values computed using 1000 days of data. King et al. (2005) applied this approach to the Antarctic, showing that, of the models tested, that TPXO6.2 was the most accurate. Significant residual remains for K1 and K2 and the K2 terms suggested satellite-specific range errors. King (2005) compared the harmonic approach to a kinematic precise point positioning solution for the South Pole site AMUN showing generally sub-mm agreements between the two techniques. A time-dependency to the K2 estimates was also demonstrated and attempts were made to mitigate its effects on the other parameters. Thomas et al. (2006) compared GPS (ambiguity fixed and

free) and VLBI harmonic estimates at 25 sites globally. While the two sets of estimates were not statistically separable, the GPS estimates were notably closer to the models values for the lunar constituents. K1 estimates from VLBI were in worse agreement with the models than the GPS estimates.

- **Proudman Oceanographic Laboratory**
  http://www.pol.ac.uk

Earth Tides and loading: POL has completed and published a major study into the interpretation of tidal gravity measurements from the global network of superconducting gravimeters which form the Global Geodynamics Project (GGP). Observational results from a few high quality LaCoste and Romberg gravimeters with electrostatic feedback were also included in this work. Ocean tide loading and attraction at the tidal gravity stations were computed using 10 of the latest global ocean tide models. One notable result was that the POL measurements with a Lacoste and Romberg ET gravimeter in Wuhan, China, clearly show that the FES series of global ocean tide models have significant errors in the East China Sea and the Yellow Sea. The global tidal gravity measurements, after corrections for ocean tide loading, were used to determine the global tidal gravimetric factors to 0.1% and hence to constrain the range of available anelastic models of the Earth's body tides.

Research was carried out in a joint project with the University of Newcastle on the measurement of UK ocean tide loading vertical and horizontal displacements using data from the network of continuous GPS stations. Comparisons with ocean tide loading models showed that the tidal loading displacements can be determined to better than 1mm using the GPS data.

The POL storm surge model was used to compute the vertical and horizontal loading displacements and the associated changes in gravity during storm surge events on the north-west European shelf. The model results were validated using continuous gravity data from the superconducting gravimeter at Membach, Belgium, which is 200km inland from the North Sea. The loading deformations from storm surge events were shown to affect a wide area of north-west Europe and the gravity changes will also be aliased into the monthly gravity fields produced by the GRACE satellite gravity mission. This work shows the importance of using global barotropic ocean models for correcting GRACE and other geodetic measurements for variations in mass and loading over periods from hours to several days.

10 GEOID DETERMINATION

- **Proudman Oceanographic Laboratory**
  http://www.pol.ac.uk

Geoid Determination: POL has worked closely with scientists at Edinburgh University in the development of geoid models for the UK (e.g. EDIN2000). POL has also been involved for many years in proposals for space gravity missions (e.g. membership of the Mission Advisory Group of the ESA Gravity Field and Steady-State Ocean Circulation Explorer, GOCE). GOCE is planned for launch in 2007. POL also remains a member of the US/German Gravity Recovery And Climate Experiment (GRACE) Science Working Team. During the past few years, a number of papers have been published concerning the use of space gravity data to benefit studies of ocean circulation, coastal processes, climate and sea level change.

11 DEFORMATION MONITORING

- **IESSG, The University of Nottingham**
  http://www.nottingham.ac.uk/iessg/

Monitoring changes in regional ground level in the Thames Estuary and Greater London: Small ground movements can have major strategic or economic significance in certain regions of the world. For example, in low lying river estuaries and coastal regions susceptible to flooding. One such region where small ground movements are exhibited is the Thames Estuary and Greater London, warranting the construction of tidal defences, such as the Thames Barrier. In 1996, the UK Environment Agency initiated a project involving the IESSG and the British Geological Survey. The objective was to develop a generic strategy for monitoring changes in regional ground level using GPS and the ITRS, and providing an interpretation of such changes in terms of local and regional geology. The strategy developed was based around the use of a small number of continuous GPS stations, acting as reference stations for a dense network of monitoring stations, observed using episodic GPS measurements every three months. During the period 2003 to 2006 further work funded by the Environment Agency resulted in a collaboration between IESSG, the British Geological Survey and Nigel Press Associates.

Structural Health Monitoring of Bridges: Researchers at the IESSG in the University of Nottingham have conducted a series of trials using state-of-the-art dual frequency GPS receivers, to monitor the movements of a number of long suspension bridges and other structures in the UK. In particular several trials were conducted on the Humber Bridge under both a controlled loading environment and ambient vibration to monitor the bridge deflection. The viability of GPS technology to monitor the displacements of the Humber Bridge subjected to known loading conditions was verified. The initial research of the IESSG was focused on the viability of GPS technology to monitor both long-term bridge settlements and dynamic response to external loads. The latest work is on the development of a systematic approach for the sensor integration, sensor configuration and field test arrangement, data collection, algorithm and software development, quality control, advanced signal processing and multipath mitigation techniques, data analysis and dynamic response identification, and result visualisation.

12 MEAN SEA LEVEL STUDIES

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Mean Sea Level Studies: Unification of vertical datums between the UK and Baltic countries has been undertaken by connecting mean-sea level at tide gauges around the UK with those in the Baltic. The geodetic coordinates of mean-sea level have been converted into geopotential space to yield measures of the geopotential constant W0 and its time derivative. The time derivative is corrected for local vertical motion at the gauges by using GPS.

- **Proudman Oceanographic Laboratory**
  http://www.pol.ac.uk

Mean Sea Level Studies: Sea level studies at POL in recent years have been focused around two main themes. One concerns trends (linear and non-linear) and accelerations in global and regional mean sea level. The second is concerned with the use of sea level data to investigate ocean and climate processes. These include the role of Southern Ocean winds (parameterised by the Southern Annular Mode) in controlling transports in the Antarctic Circumpolar Current; the mechanisms which lead to coherent modes of sea level variability in the Arctic; tropical processes (e.g. ENSO, Indian Ocean Dipole) which determine large-scale patterns of sea level change in the central Atlantic; and the relationships between changes in the North Atlantic Oscillation and those in mean and extreme sea levels around the UK.

Long term changes in sea level are nowadays of great interest to policy makers and the general public. POL research was included in a major World Climate Research Programme (WCRP) conference on sea level rise and variability in June 2006, and has been contributed to the Fourth Scientific Assessment of the Intergovernmental Panel on Climate Change (IPCC). A special report on the vulnerability of the Maldive Islands to sea level rise in coming decades was completed.

Short term, extremely damaging, changes in sea level, also became of renewed urgent interest, following the Sumatra tsunami and the Hurricane Katrina storm surge. POL has since been involved in several national (Defra) and European (TRANSFER FP6) programmes on tsunami modelling and improved warning systems. This research has included the development of new tide gauge systems (e.g. radar gauges) together with advanced data telemetry methods. A new 'baseline' tide gauge design has since been employed for installation of new gauges in Africa as part of the OdinAfrica programme. POL continues to be actively involved in tidal research, with a major recent study on tidal asymmetry. 'Quasi-tidal variations' such as the 5-day mode in global sea level have also been investigated further.

POL has continued to play a major role in international sea level organisation, by providing the Permanent Service for Mean Sea Level (PSMSL) data base, and important organisational contributions to the IOC Global Sea Level Observing System (GLOSS). It took a lead in the construction of an international sea level proposal under the International Polar Year (IPY) and has supported the development of the IAG Global Geodetic Observing System (GGOS).

- **IESSG, The University of Nottingham**
  http://www.nottingham.ac.uk/iessg/

European Sea Level Observing System (EOSS) and European Sea Level Service (ESEAS): In 1996, European Commission Cost Action 40: EOSS (European Sea Level Observing System) was started. Dr Bingley from the IESSG was UK national delegate to EOSS and was an active member of working group 1 of EOSS, which was specifically concerned with precise height determination at tide gauges. One result of Cost Action 40 was the proposal to establish a European Sea Level Service (ESEAS). Work on the development of ESEAS was started in July 2001 to bring together a major fraction of the previously scattered sea level observing and research resources in Europe into a coordinated research organisation, in order to study sea level variations at inter-annual and century time scales and assess potential future changes in sea level and extreme sea levels. This work was greatly assisted by the award of a three-year European Commission grant through Framework V. The so-called ESEAS-Research Infrastructure (ESEAS-RI) project started in November 2002. The ESEAS-RI project involves twenty-one partners from thirteen countries. It comprises five work packages:

- WP1: Quality control of sea level observations.
- WP2: Absolute sea level variations.
- WP3: Decadal to inter-decadal sea level variations.
- WP4: Improving the sea level observing system.
- WP5: Project management.

The Institute is contributing to work packages WP1, WP4 and WP5, and is leading work package WP2. Work package WP2 will develop the appropriate processing and analysis strategy for the use of continuous GPS (CGPS) at sites close to tide gauges in order to obtain reliable estimates of vertical land movements, and to assess their contribution to changes in relative sea level. The map shows the proposed network of ESEAS Observing Sites, with red dots showing tide gauges that are not co-located with GPS and blue dots showing tide gauges that are co-located with CGPS. Observations from all CGPS stations co-located with ESEAS Observing Sites will be processed and analysed. These sites cover several areas of Europe with types of coasts being affected by different physical processes (e.g. tectonic activity, post-glacial rebound, sedimentary compaction, anthropogenic effects). For further details on ESEAS and EOSS see http://www.eseas.org/. The ESEAS-RI project finished in November 2005 and its results can be found in the ESEAS-RI Final Report.

Monitoring of vertical land movements at tide gauge sites in the UK: Sea level observations at tide gauge sites are corrupted by local, regional or continental vertical land movements. In order to derive estimates of absolute sea level changes, relative tide gauge mean sea level observations must be corrected for these deformations. This can be carried out by referencing tide gauge benchmarks (TGBMs) to a global reference frame using GPS. The tide gauge (TG) measurements can then be de-coupled from changes in ground level and estimates for the change in absolute sea level obtained. The application of GPS to monitor vertical land movements at selected sites of the UK National Tide Gauge network has been on going at the IESSG since 1990. The work has been funded by the Department for Environment, Fisheries and Rural Affairs (Defra) through their long term commission with the Proudman Oceanographic Laboratory (POL). The developments at the IESSG have closely followed the recommendations of the "Carter reports" in 1989 and 1994 and the IGS/PSMSL workshop in 1997. Since the reports "United Kingdom Research on Geodesy 1995-1998" and "United Kingdom Research on Geodesy 1999-2002", several more episodic GPS stations have been upgraded to operate as continuous GPS stations (CGPS) giving at total of ten CGPS@TG stations in the UK. Further stations are currently being planned for the near future to be located in Scotland, England and Wales. Data from several CGPS@TG stations are being submitted to the IGS Tide Gauge Benchmark Monitoring Pilot Project (TIGA PP) and to the European Sea Level Service (ESEAS), for which the IESSG operates as one ESEAS CGPS analysis centre (see above).

Development and evaluation of the dual-CGPS station concept for monitoring vertical station motions at tide gauge sites: Vertical station velocities and their associated uncertainties derived from continuous GPS (CGPS) height time series can be used to de-couple secular mean sea level (MSL) trends from vertical land movements at tide gauge sites. In order to precisely describe the often local character of these vertical displacements, the observing CGPS antenna should preferably be as close as possible to the tide gauge itself. This sometimes proves to be difficult, as tide gauges are conveniently situated for tidal observations in port or harbour environments, which can be far from optimal for permanent CGPS installations and observations. In this dual-CGPS station concept, one CGPS station is established at the tide gauge, in order to monitor the local vertical land movements, and a second CGPS station is established on stable rock, further inland within a few kilometres of the tide gauge. The tide gauge CGPS station enables the relative mean sea level to be corrected and an estimate for absolute mean sea level to be obtained. The second CGPS station complements this and helps to describe the underlying geophysical vertical land movements. The dual-CGPS station concept is based on the approach that systematic effects common to both stations, e.g. common periodic signals, can be removed by differencing. The coordinate difference time series derived from the dual-CGPS station analysis show a similar day-to-day scatter as the single baseline time series obtained from the single baseline analysis between the station pair. The findings from the evaluation of the dual-CGPS station concept support the investigations into vertical land movements. Furthermore, the dual-CGPS station concept enables a range of additional methods to be applied for analysis, such as adaptive filtering. With the introduction of more CGPS@TG stations during the period 2003-2006, it was possible to form a new dual-CGPS station pair between stations LERW and LWTG. Investigations in the use of several Ordnance Survey of Great Britain Active GPS Network stations to from further dual-CGPS stations pairs are underway.

Stochastic characterisation of the CGPS coordinate time series in the UK: Since the "United Kingdom Research on Geodesy 1999-2002" report further work on stochastic characterisation of CGPS coordinate time series was carried out. The coordinate time series of 40 CGPS stations in the UK have been analysed for their stochastic properties. The coordinate time series have an observation time span of between 1 and 9 years and the data have been archived in BIGF. The assumption that CGPS measurements would improve estimates of station velocities by a factor of $(1/\sqrt{N})$, with N being the number of measurements, by having more measurements than when observing episodically, has been shown to be unrealistic. Station velocity uncertainties in CGPS coordinate time series have been shown to be too optimistic, if the day-to-day scatter in daily coordinate solutions is wrongly assumed to be time independent (white noise). The stochastic characterisation of the CGPS coordinate time series was carried out using the empirical method of Williams [2003] and the maximum likelihood estimation (MLE) with integer and fractional spectral indices. The results from these methods agree well and confirmed that the noise in the UK CGPS coordinate time series obtained from the analysis at the IESSG, is not purely white but

contains a combination of white and flicker noise. Using estimates for each noise component it is possible to compute more realistic station velocity uncertainties.

Vertical land and sea level changes in the Canary Islands: Since 2006, the IESSG in collaboration with the Instituto de Astronomía y Geodesia (CSIC-UCM), Facultad de C.C. Matemáticas, Universidad Complutense de Madrid has investigated vertical land and sea level changes in the Canary Islands. These islands, located in the Atlantic Ocean on a latitude between 28° and 29° North, between 100 and 500 km off the African west coast, are an archipelago with ongoing active volcanism. Due to these processes the affected islands are assumed to undergo vertical land movements at different spatial and temporal scales. The location of the Canary Islands in the Atlantic Ocean is interesting for both sea level studies using tide gauge and satellite altimetry data, but these studies are ultimately hindered by the lack of detailed information on local, short and long-term vertical land movements.

Currently there are five active tide gauges located in the Canary Islands in the Permanent Service for Mean Sea Level (PSMSL) revised local reference (RLR) database, all indicating a sea level rise, but at different levels. There are four continuous GPS stations with sufficient observation time span, belonging to the European Reference Frame Permanent GPS Network (EPN), the International GNSS Service (IGS) network, the European Sea Level Service (ESEAS) network and the Instituto de Astronomía y Geodesia (CSIC-UCM), Facultad de C.C. Matemáticas, Universidad Complutense de Madrid.

13 GEOPHYSICAL, GLACIOLOGICAL AND OCEANOGRAPHIC APPLICATIONS OF GNSS

- **School of Civil Engineering and Geosciences, Newcastle University**
  http://www.ceg.ncl.ac.uk/

Geophysical, Glaciological and Oceanographic Applications of GNSS: Monitoring Tectonic Deformation: Studies have been undertaken to monitor plate boundary deformation in the Central and Eastern Mediterranean regions using GNSS applications. One such study processed data from more than 100 permanent GPS sites across Central Europe using the precise point positioning technique and obtained rigorous estimates of site velocities and their confidence limits via simultaneous estimation of the secular velocity, annual and semi-annual harmonic displacements, and power-law characteristics of the coordinate time series noise. Plate rotation rates were derived and the compatibility of site velocities within the Adriatic region with Eurasian, African and local (microplate) motions were tested. On a regional scale, campaign GPS data was reprocessed for the Hellenic region of Greece and represented in a common reference frame. Geodetic strain was estimated and compared to seismic strain rates derived from earthquake catalogues to determine seismic hazard potential.

GNSS applied to Glacier Dynamics: Several studies have examined glacier and ice shelf dynamics using GNSS applications, mainly using the kinematic precise point positioning technique. In their *Science* paper, Bindschadler et al. (2003) reported on the discovery of stick-slip motion of a major Antarctic ice stream (Whillians Ice Stream) modulated by the ocean tides. Joughin et al. (2005) reported on the ongoing slow down of this same ice stream using historic and recent GPS-derived velocities.

GPS validation of GRACE gravity fields: King et al. (2006) compared surface displacements computed from GRACE gravity fields with GPS radial displacements (in a CM frame) at several dozen sites globally. A range of GRACE averaging radii were tested and it was shown that the optimum fit to the CSR Release 01 GRACE fields was for an averaging radii of half-width 500km over land (R=0.55) and >=2000 km over the oceans (R=0.3).

Investigation of the Inverse barometer effect over ice shelves: Padman et al. (2003) compared measured atmospheric pressure to observed ice shelf elevation changes from GPS data. They showed that an IBE correction is justified for frequencies covering the ‘‘weather band’’, 0.03-0.5 cpd (cycles per day). The IBE correction reduces the standard deviation of the weather-

band signal of height change from ~9 cm to ~3 cm. With this correction, the largest remaining high-frequency error signal in ice elevation change is the inaccuracy of the present generation of Antarctic tide models, estimated to be of order 10 cm for most of Antarctica.

Surface Mass Loading: Newcastle University pioneered the inversion of geodetic measurements for surface mass loading parameters in 2001. Since that time Newcastle has had a number of ongoing projects in this area. Gross et al. [2004] compared degree 2 spherical harmonics of the surface mass load estimated from GPS inversions and Earth rotation demonstrating a strong correlation which further validated the inversion approach. This work has also focussed on the theoretical aspects of inversion [Blewitt et al., 2003; Blewitt et al., 2005] and the implementation of self consistent, mass conserving land-masked basis functions finely tuned to the task. Clarke et al [2005] used this work to show shortcomings in surface mass loading models that do not conserve mass. Ongoing projects include the integration of the inversion technique with GRACE and SLR observations.

Global Strain Rate Map Project: Newcastle University has provided the core reference frame solution for the Global Strain Rate Map project [Holt et al., 2003; http://gsrm.unavco.org] since 2000 and the latest realisation [Kreemer et al. 2006] is the most up to date and comprehensive global strain rate, geodetic velocity field and Euler vector model available today, computed from over 5700 velocities. This model has applications in global plate tectonics modelling, crustal block and fault modelling, seismology and earthquake hazard, terrestrial reference frames and geothermal energy to name a few.

- **IESSG, The University of Nottingham**
  http://www.nottingham.ac.uk/iessg/

Plate Motions and Crustal Deformations in Saudi Arabia*:* Since 2003, the General Directorate of Military Survey (GDMS), through collaboration with the IESSG, densified the GPS network in Saudi Arabia, covering nearly two thirds of the tectonic plate and enabling both measurements its motions and crustal deformations. As current investigations of the motions of the Arabian and its neighbouring plates are primarily based on GPS measurements obtained in the surrounding areas of the Arabian plate, with few stations actually located on the Arabian plate itself in the Kingdom of Saudi Arabia, this network will advance the knowledge of the dynamics of the Arabian plate and its intra-plate deformations.

Modelling the glacial isostatic adjustment (GIA) of the British Isles: Since 2003, the IESSG has been collaborating with the Departments of Geography and Earth Sciences at Durham University by providing estimates of three-dimensional crustal motions from CGPS stations in the British Isles as constraints in recently developed GIA models. Large scale present-day deformation within the British Isles is dominated by the GIA process. Model predictions demonstrate that the GIA-induced deformation includes a significant component from both the local British-Irish ice sheets as well as the more distant Fennoscandian and Laurentide ice sheets. For example, the associated tangential component of the GIA signal is predicted to be a uniform motion in a northwesterly direction which is mainly attributed to the Laurentide ice sheet.

All previous studies, which used the high quality relative sea level (RSL) data set for the British Isles to constrain GIA models for this region, have been unsuccessful in obtaining high-quality fits to the entirety of these data due to the large spatial variations of the GIA signal itself and the highly non-monotonic nature of the RSL data. Furthermore, the model predictions display a strong sensitivity to local ice and Earth model parameters as well as the melt history of the remaining (globally distributed) ice sheets, resulting in a high degree of non-uniqueness. This is a major obstacle in arriving at a robust model solution for this region.

14 VERTICAL DATUMS

- **United Kingdom Hydrographic Office (UKHO),**
  http://www.ukho.gov.uk

Vertical Offshore Reference Frame – VORF: The aim is to refer vertical height/depth data to a consistent reference frame, in this case ETRF89, in the area of the UK continental shelf. At sea data is referred conventionally to Chart Datum – which approximates to the tidal level of approximately Lowest Astronomical Tide. Chart Datum is not a seamless reference surface, it varies from location to location. It is established based on local water level measurements at discrete locations but its surface offshore is often less well known. Key elements of the challenge lie in developing a methodology for relating Chart Datum to the ellipsoid underlying the global datums used in GPS data acquisition. This will result in not only an accurate representation of Chart Datum, and its relationship with all other relevant surfaces, but also a system that runs efficiently whilst handling the vast amount of data acquired by modern survey instruments.

The VORF project is a fundamental step in allowing UKHO to assimilate data from suppliers and customers in vertical reference frames other than the currently used Chart Datum. It will also aid high accuracy surveying with GPS and LIDAR to determine the tidally-defined shorelines such as Mean Sea Level (MSL), storm surge modelling, sea level rise studies, ecosystem studies, coastal zone management and proactive disaster mitigation planning. Additionally, further developments in global positioning and 3-D navigation may require the presentation of hydrographic information on reference frames other than Chart Datum.

UCL delivered the VORF Demonstrator software and trained UKHO staff in December 2006. The project has now been extended to improve the accuracies in a number of areas which are known to be weak due to data deficiencies and to refine some of the modelling.

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