THE ROYAL SOCIETY

UNITED KINGDOM

RESEARCH ON GEODESY

1999 – 2002

UNITED KINGDOM RESEARCH ON GEODESY 1999 – 2002

Prepared on behalf of
The Royal Society's International Relations Committee

Submitted to
The International Association of Geodesy
at the XXIII General Assembly of IUGG
Sapporo, Japan, July 2003

Published on behalf of
The Royal Society
by

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and Space Geodesy
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FOREWORD

This report outlines United Kingdom activities in geodesy for the period January 1999 to December 2002. It has been prepared for submission to the International Association of Geodesy (IAG) at its General Assembly in Sapporo, Japan, during the XXIII General Assembly of the International Union of Geodesy and Geophysics (IUGG) in July 2003. 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 five sections 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, and the Royal Society for agreeing to fund its publication.

ALAN H DODSON
Editor and National Correspondent to the IAG
June 2003

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1 SATELLITE LASER RANGING

- **Department of Geomatic Engineering, University College London,** *http://www.ge.ucl.ac.uk/*

SLR system calibration, Herstmonceux: The SLR facility at Herstmonceux uses local calibration targets (LCTs) to determine system range errors for correction of its space observations. Current LCT ranges are based on a survey carried out by OS in 1991. Since the time of the survey the LCT positions have changed and range information has been updated by direct transfer using the laser ranger. The NERC Space Geodesy Facility at Herstmonceux required independent verification of these new calibration values and this was carried out by the Department of Geomatic Engineering at UCL. Leica System 500 GPS receivers were used over very long observation periods to establish a high-precision survey network relating the LCTs to two ITRF reference points and further reference marks in the vicinity of the SLR telescope *(Md Kadzim, 2002)*. Theodolite intersection based on the above reference marks then measured the invariant point of the SLR telescope under rotation and thereby determined its position and distance from the local calibration targets *(Novak, 2002)*. Accuracy is estimated to be better than 0.002m.

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

Satellite laser ranging: The satellite laser ranging system of the NSGF at Herstmonceux has continued in regular operation throughout 1999-2002. 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), one of 9 Services overseen by the International Association of Geodesy (IAG). Currently this global network tracks 22 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. CHAMP, GRACE) - use onboard GPS for precise orbit determination and SLR for orbit determination, stability and validation;
4) Navigation satellites from the GNSS constellations (e.g. 2 of GPS, several GLONASS) - 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.

SGF, in its role as an ILRS Associate Analysis Centre, is collaborating with research groups from some 10 institutes towards an official, regular, ILRS station coordinate and EOP product. During 2002 a related 'Call for Participation' paper was jointly developed and distributed to the ILRS analysis community.

SGF 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.

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. 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.

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.

2 Global Navigation Satellite Systems

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

GNSS: Investigations into sub-daily GPS coordinate solutions affected by un-modelled vertical signals revealed that biases are present in the horizontal coordinates when the ambiguities are not resolved as integer values (*King et al., to be published in 2003*). Biases are greatest in the east coordinate and are 40-50% of the magnitude of the vertical signal for semi-diurnal frequencies. A sensitivity analysis revealed that the ambiguity parameters were absorbing the un-modelled vertical signal and the horizontal expression of this is counter-balanced by biases in the horizontal coordinates. Resolving ambiguities or modelling the vertical signal eliminated the biases.

Sensitivity analyses were carried out on theoretical and proposed GNSS satellite constellations. Precision and reliability changes were investigated for a number of combinations of LEO, MEO and geostationary GNSS satellites, with relevance to the proposed Galileo system *(Rainbow, 2002; Rainbow & Clarke, 2002)*. It is found that a combination of MEO and geostationary satellites offers significantly better precision and reliability than a purely-MEO constellation.

We have investigated the use of small GPS networks for determining tropospheric zenith delay and its consequent application to the correction of tropospheric artefacts in InSAR interferograms *(Wadge et al., 2002)*. Our findings are that in certain cases the tropospheric information obtainable from small networks is of value to removing artefacts in interferograms, especially in mountainous regions where the tropospheric delay is highly correlated with surface elevation.

Low-cost GPS L1 phase receivers have potential for widespread use in vehicle tracking and attitude monitoring, but this field remains in its infancy. We have carried out trials of these receivers using single-epoch positioning and ambiguity resolution algorithms previously developed at the University of Newcastle. Initial results show that freely-floating solutions do not succeed due to poor a priori coordinates and high phase noise, but that solutions constrained with a priori information can have moderate success. We have also investigated the combination of GNSS with inertial and video data using Kalman filtering *(Carroll, 1999)*.

- **Department of Geomatic Engineering, University College London,** *http://www.ge.ucl.ac.uk/*

GPS phase multipath studies: The Department of Geomatic Engineering at UCL has investigated the use of signal to noise ratios output by standard (Costas) GPS receiver phase tracking loops to model multipath errors in double differenced phase measurements. By using non-standard Fourier analysis techniques it was discovered, and reported in Cross, 1999, that in static environments around a 50% improvement in noise levels could be made through such modelling and, more importantly, that the long term error signals were virtually totally removed – resulting in errors with almost white noise characteristics. Methods of assessing multipath, and other aspects of GPS performance, were reported in Edwards et al, 1999. On-going work is concentrating on using output from more sophisticated phase tracking loops to estimate more directly the size of multipath errors.

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

POLARIS: Polaris is a new EC-funded project to develop a software tool that will 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 includes a graphing utility with an interface to an internal GIS application.

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.

GalileoSat: In 2000, the IESSG completed a package of work as part of the ESA funded GalileoSat project led by Alenia in Italy, which studied the technical details of the space and ground segments of the future Galileo system. The IESSG's task, under the leadership of GMV in Spain, and coordinated by Alcatel Space Industries in France, was to study the definition, establishment and maintenance of the coordinate reference frame that would form the basis of all coordinates from Galileo.

GALA: Under a contract to Racal Tracs in the UK, and as part of the Alcatel-led team working on an EC contract, the IESSG studied the scientific market for Galileo services and receivers. The study was part of a much wider work package which investigated all potential markets for Galileo-enabled services, in order to extract user requirements and to estimate the potential revenues from Galileo services. It involved a great many contractors from across Europe, each tasked with studying the market for a particular segment of the market.

The GalileoSat System Simulation Facility project (GSSF): GSSF is a contract funded by the European Space Agency (ESA) to produce an end-to-end software simulation of Europe's planned 'Galileo' satellite navigation system. It will model all of the components of the future system, from the satellites themselves, to the ground segment that will control them and the user receivers that will navigate with their signals.

As part of the VEGA-led team working on the study, the University of Nottingham is acting as a consultant on technical aspects of satellite navigation and specific modelling details. Nottingham's role is to provide definitions of suitable simulation and modelling algorithms, with the necessary algorithm description, pseudo-code where necessary, and test data. One of the future aims of GSSF is to be able to replace software components of the system with real hardware - a so-called hardware-in-the-loop design. For instance, early versions of GSSF will simulate a Galileo user receiver in software, but later versions may wish to replace the software receiver with a prototype hardware version. This requires that the simulation models are as true to life as can practicably be achieved.

Following delivery of the phase one version of the software, the project is making good progress towards a version with high fidelity models of all aspects of the system. It will allow system engineers to investigate a wide range of Galileo issues, from the global performance of the system, to the effect of a small change in a particular hardware component.

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 fifty permanent GPS stations (including the Ordnance Survey active stations), established throughout the British Isles. It has recently gained funding from the Natural Environment Research Council (NERC) to become one of their 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 economics when bidding for research funding.

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

- *Kinematic data processing*
- *Precise height determination*
- *Atmospheric water vapour studies*
- *Ionospheric studies*
- *Numerical weather prediction*
- *Signal delays due to the atmosphere*

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.

o **Imperial College London,** *http://www.geomatics.cv.ic.ac.uk, http://www.cts.cv.ic.ac.uk*

Performance potential of a combined Galileo/GPS navigation system: **This project was carried out for Alcatel Space by the *London Centre for GNSS Research (LCGR)*:** The LCGR is a joint research initiative by Imperial College London and University College London. The objectives of the research project were to define an integrity monitoring concept for the Global Positioning System (GPS) satellites within the Galileo system, and to quantify the level of *improvement (accuracy and integrity*) to be gained by the adoption of a combined Galileo/GPS navigation system. This was part of a wider study by Alcatel Space aimed at the definition of the Galileo system. The results were used as input to the design of the Galileo system and in international negotiations with the United States of America and other countries.

EGNOS expansion: This project was carried out for the European Space Agency (ESA) to study the requirements for the expansion of the European satellite navigation system, EGNOS (European Geostationary Navigation Overlay Service) to Africa and South America. Imperial College London was a member of a multinational consortium with the responsibility for developing the algorithms and code for modelling navigation system errors required for the expansion studies.

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

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

During 2001 an antenna fault was discovered on the HERS system and since rectification the data quality and consistency has improved dramatically. From 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.

In order to improve the low-elevation sky coverage seen by the GPS/GLONASS system HERP, the antenna will be moved during 2003 from its current location to a superior location close to the principal ground-calibration target used by the SLR system. The move will further strengthen the local links between the GNSS and SLR co-ordinate frames. As part of an ongoing programme of local surveys (a collaboration between SGF and the Geomatics Department at UCL) two MSc students carried out a survey during the summer of 2002. It is likely that the re-sited HERP system will be also be used in support of LEO satellite missions and to monitor the Earth's atmosphere in near real-time, via 1 Hz broadcasting through the Internet.

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 IGS. Two GPS satellites and all GLONASS satellites are fitted with laser retro-reflector arrays and the global network makes precise ranging observations on a regular basis. Because the GLONASS satellites carry large arrays the interpretation of SLR observations is not entirely straightforward. But detailed research has shown that, with an uncertainty of about 2cm, the laser range observations are a good test of the quality of the radial component of the IGS-computed orbits. For the small arrays on GPS satellites there is no such problem of interpretation. The laser data are consistent in showing 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 GLONASS orbits is found to be about 20cm RMS and that of the GPS orbits is about 12cm RMS.

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

GPS time series analysis: Until recently, it was typically assumed that only white noise was present in geodetic time series. However, several data sets of continuous GPS time series have now provided evidence for the presence of time-correlated (coloured) noise. We have shown that the presence of coloured noise can significantly affect the uncertainties of rates estimated from these time series. We derived a set of empirical equations to account for the coloured noise. Our analysis of time series from GPS sites around the world and regional networks have further confirmed the presence of coloured noise in these data sets and that there is a latitude dependence (and hemispheric bias), a time dependence (gradually decreasing) and a spatial correlation in the noise. Regional networks can take advantage of the spatial correlation to reduce the amount of noise present in each time series. Investigation into the role offsets play in the estimation of site velocities has been conducted. Analysis of present GPS data sets reveals that, on average, one offset occurs every ten years, but it may be as often as once every two years. We have derived strategies and equations for dealing with offsets that will both limit the effect they have on site velocities and account for them in the velocity uncertainties.

2a Atmospheric Studies

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

Ionospheric scintillation effects on GPS measurements: The ionosphere is prone to significant disturbances, which are considerably worse during periods of high solar activity, such as the recent solar maximum. Ionospheric scintillation, the most significant manifestation of such disturbances, often takes place in equatorial, and auroral regions such as Northern Europe. Since June 2001 a network of state-of-the-art GPS Ionospheric Scintillation Monitor (the NovAtel/AJ Systems GSV4004) receivers is being used to measure and record GPS phase and amplitude scintillation parameters observed in the UK and in Norway. These specially designed GPS receivers have been co-located with permanently tracking dual-frequency GPS receivers, forming a Northern European monitoring network. This is the core of a 3 year EPSRC (Engineering and Physical Sciences Research Council) funded project, running at the IESSG. The aim is to study the effects of ionospheric scintillation and Total Electron Content (TEC) gradients on GPS applications during the solar maximum, with a focus on accuracy, availability and integrity.

The project stages involve the set up of the network, the development of automated archiving and data analysis strategies, impact assessment of ionospheric scintillation on maritime DGPS and EGNOS users, and on different GPS receiver technologies. In addition to the monitoring network, data obtained from existing International GPS Service (IGS) stations and from the General Lighthouse Authorities (GLA) DGPS reference stations have also been used. Analyses have been carried out on data from periods of known ionospheric activity, but long term systematic studies will also be undertaken. The GPS user errors have been correlated with observed scintillation levels and with available geomagnetic indices during various active periods. Results of the impact assessment exercise, both on the DGPS and EGNOS user, have been published. The study of the impact on different GPS receiver technologies is to be carried out in 2003. On the background of the main objectives of the project resides the idea of forming a long term data base for use by the scientific community and the possible development of warning and/or mitigation mechanisms for the GNSS user community. We have found that amplitude and phase scintillation levels predicted by the WBMOD (Wide Band Model) ionospheric scintillation prediction program present good correlation with GPS user errors and the possibility of mitigating the GPS user errors with the aid of this model is currently under investigation. The scintillation monitor receiver outputs raw scintillation data at a rate of 50Hz, but is also capable of recording only the relevant statistics of these data at every 60 seconds, at different intervals. As a baseline these statistics have been recorded and used in our analysis. However a high rate campaign, with the recording of the 50Hz raw data, is planned for 2003. Please see http://www.nottingham.ac.uk/iessg/isgres38.htm

Meteorology and climate: The IESSG continued its research into the use of GNSS signals for meteorology and climate studies. In particular a collaborative project with the UK Meteorological Office (within the general context of the EC COST Action 716) was initiated, aiming to provide a UK operational capability. Research was particularly focussed on the ability of GNSS network to monitor severe weather events, such as thunderstorms. In addition the Institute continued its research into atmospheric delay estimation from receivers on moving platforms. A collaborative project with the NERC ESSC in Reading investigated GPS delay estimation above and around Mount Etna, Italy, in an attempt to remove atmospheric biases from Interferometric SAR observations.

River level monitoring: The RiGHt project “River Level Monitoring using GPS Heighting” was completed in 2002 by a consortium comprising Science System (Space) Ltd, the Institute of Engineering Surveying and Space Geodesy of the University of Nottingham and the Centre for Ecology and Hydrology. The two phases of the project were both funded by the British National Space Centre (BNSC), under the UK Government’s Space Foresight Programme.

The original RiGHt project, which ran for two years, was successful in demonstrating the feasibility of measuring and monitoring river heights using a GPS equipped buoy in a real-time environment and using satellite communications technology to transfer the data to a central and remote Geographical Information System.

The aim of RiGHt has been to demonstrate innovation in the integration of state-of-the-art technologies such as OTF GPS and low power world-wide satellite communications to solve a real user need. The objectives of the second phase were to address three key developments to the original architecture. Firstly, the use of long-range kinematic GPS techniques was implemented, so as to extend the useful range of the system. Secondly, long-range use requires the adoption of satellite communication techniques to relay the raw data between the buoy, other reference GPS stations and a central computational hub. This has required the use of advanced data compression techniques, to handle the high data rates necessary for raw GPS carrier phase data. The third objective was to integrate the resulting real-time measures of river level into river and flood modelling software, so as to greatly enhance the benefit of the monitoring to the users.

The development of the new RiGHt system was completed by early 2002, and in March a series of land and river based trials were conducted. The RiGHt project has been highly successful. The system may now be deployed in routine monitoring applications or in situations of real emergency. It can provide a very elegant and rapid solution to many users' needs.

2b Engineering Applications

- **Department of Geomatic Engineering, University College London,** *http://www.ge.ucl.ac.uk/*

GPS attitude determination: Several GPS attitude studies have been undertaken in the Department of Geomatic Engineering at UCL. One involved integration of several sensors, including a multi-antenna and multi-receiver GPS-based system, to provide both attitude and position for airborne remote sensing operations. It was applied to data collected on board the UK Natural Environment Research Council's Airborne Remote Sensing Facility aircraft (Sheridan et al 2002, and Sheridan and Cross, 2000). Another project involved the design and testing of an attitude determination algorithm for a low orbiting spacecraft using GPS signals as the sole observable *(Jameson et al, 2001, and Cross and Ziebart, 2002)*. The algorithm was designed to run in real-time at a rate of 10Hz on-board the spacecraft, using only minimal chip and memory resources. Principal features of the algorithm design were: rearrangement of the conventional double difference GPS phase observation equations in terms of the Euler angles alone (thus reducing the number of solve-for parameters to three), numerical differentiation of the model equations, no requirement for a Kalman Filter, a novel single epoch ambiguity resolution technique and the facility to trap and fix cycle slips. Testing was effected by developing an independent observation simulator.

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

Combined use of virtual scale models and space geodesy: Late in 2001 the Institute was awarded a ROPA (Rewarding Our Potential) grant from the Engineering and Physical Sciences Research Council to develop blue sky research on an area that exploits the existing expertise of the IESSG in high precision GPS positioning and an equally specialised know-how, existing at the University's MRL (Mixed Reality Laboratory), in augmented reality. The aim is to investigate and develop a means to give engineers, and the community affected by civil engineering work, information that is often difficult to visualize via computer screens or 2D plans. At the end of 2002 a prototype system had been developed, in which the user works in a collaborative environment where it is possible to see virtual and real features of a test-bed area seamlessly in real time. With this information, the users of the system can assess and discuss how the environment will be affected by the engineering work, enabling a vision of the future and the possible solution of problems that could appear during construction, further enabling the pursuit of cost reduction and improvements in efficiency.

Augmented reality for sub-surface visualisation: The IESSG in collaboration with the School of Chemical, Environmental and Mining Engineering were sponsored by the Department of Trade and Industry to develop a GPS based Augmented Reality system. Ten external organisations were also involved in the research. Augmented Reality is the science of superimposing Virtual

Reality data onto the real world, in real time. Applications developed during field trials include superposition of buried pipe and cable information, mining and geology information onto real world views.

Bridge deformation monitoring with GPS: The overall of the project is the creation of a system that employs computational simulation with GPS to monitor the health of bridges without the need for onsite inspection. The main research interest is GPS and making it more effective for the specific aim of bridge deflection monitoring. GPS has been proved in the past to be an efficient tool for this monitoring, but research is still being conducted into mitigating the associated error sources and providing more accurate deformation information. In the past expensive dual frequency receivers have been used with good results, but one of the aims of this project is to use cheaper single frequency receivers. The aim is the creation of a more affordable monitoring system. Displacements that deviate from the normal design configurations will redistribute stresses and strains amongst the other bridge components, which will in turn affect the load carrying capacity of the whole bridge. A system that can spot abnormal movement or changes in frequency of the bridge can be used to flag faults that could lead to catastrophic failure.

Since starting research the author's main interests have been accelerating the ambiguity resolution in single frequency receivers, so that cheaper receivers can be used for this application; using a total station for dynamic bridge monitoring and comparing the results to GPS; and introducing pseudolites (pseudo-satellites) to improve the reliability, integrity and accuracy of the solution. A number of bridge trials have taken place, the results of these have been processed and analysed.

Detection of abandoned mineshafts: This is a collaborative research project with British Geological Survey supported by the EPSRC, involving the development of a vehicle-towed capacitively coupled form of resistivity detector, to be used in searching for abandoned mineshafts. Unlike many geophysical sensors this system can take measurements whilst moving, enabling high rates of data capture, but requiring highly accurate positioning, which can only be provided by RTK GPS. To minimise costs a single frequency GPS receiver can be used.

The Institute has now developed the real-time navigation, triggering and positioning element of the geophysical equipment, which has been field tested on buried objects at the BGS and over known mineshafts at Bonstal moor.

Construction plant control and guidance using RTK GPS: Work in this area continues through a project part funded by Trimble Navigation Europe Ltd. The research work includes a full scale trial where a GPS system guided and controlled a bulldozer whilst clearing and levelling an area of ground. The project aims to assess the strengths and weaknesses of using GPS in plant guidance and examines its current and future roles in the construction industry. Testing was carried using a Trimble provided SiteVision GPS plant guidance/control system, including quality assessment of individual system components and assessment of performance as a whole in a full scale trial.

GPS signals used in plant control applications, in precision grading for example that requires carrier phase measurements, suffer from multiple error sources, in particular signal multipath, causing measurement error of up to 5 cm. Whilst many techniques exist to mitigate pseudorange measurement multipath, or carrier phase multipath in static applications, the issue of carrier phase multipath for a dynamic receiver has not been adequately investigated. Part of this project therefore, involves research into the efficiency of various methods of identifying and mitigating carrier phase multipath in real-time for dynamic applications, and furthermore how GPS can be augmented in difficult signal reception environments using inertial sensors, and other positioning systems.

- **Imperial College London,** *http://www.geomatics.cv.ic.ac.uk, http://www.cts.cv.ic.ac.uk*

Transport Telematics - Local area augmentation system for fleet management: This project was funded by Logica (UK) Limited to specify an architecture for a local area navigation system for fleet management in urban areas. The architecture proposed consisted of the use of Medium Frequency (MF) signals generated from terrestrial MF signal generators (similar to those used for LORAN-C) to augment the signals from the space based navigation systems such as GPS, GLONASS and Galileo.

Transport Telematics - Space-based dynamic positioning in built-up environments: This is an ongoing project on high accuracy and high integrity dynamic positioning in urban areas to support road transport navigation. Part of this has been the contribution of Imperial College London to the review of the Countdown Bus Information System operated by Transport for London (TfL). The project assessed the capability of stand-alone and augmented space-based navigation systems to support the navigation functionality of the Countdown system. Currently, the system uses roadside beacons and distance information from odometer to determine the location of buses. Research is continuing to investigate data fusion techniques involving the integration of GNSS with low-cost MEMS technology sensors to enable required navigation performance in built-up areas.

Transport Telematics - The development and demonstration of a vehicle performance and emissions monitoring system: This is a *Foresight Vehicle LINK* project awarded to a consortium including Imperial College London, Sira Technologies Ltd and Saturn Technologies Ltd, to develop a real-time vehicle performance and emission monitoring system (VPEMS). It will be completed in 2003 with funds from the UK government and industry. The project is developing further and applying state-of-the art technologies to create and demonstrate the capabilities of an accurate, reliable and cost effective VPEMS. The system is to be fitted on vehicles to monitor driver/vehicle performance and the level of concentration and emissions inside the vehicle and at the exhaust respectively. Real-time sensing of spatially and temporally referenced vehicle performance and emission data will enable, for example, the monitoring of environmental compliance, identification of polluters and effective management of maintenance of vehicles. Such data will also facilitate research on the major drivers of vehicular pollution and the corresponding health impacts. A special advisory committee consisting of colleagues from industry and government agencies is facilitating the development and exploitation activities.

Transport Telematics - Measures of road traffic congestion: This project is exploring the extent to which existing data sources including GNSS, could be used to improve on the methods for measuring traffic congestion. The project is divided into two phases, one to survey existing data sources and the other to investigate how the data could be used to provide a reliable and relevant measure or measures of traffic congestion. Issues of coverage (spatial and temporal) and data quality are important particularly if data from different sources is to be required.

GPS integrity and air traffic service hazard assessment: The objective of the first phase of this project was to study the strengths and weaknesses of the global positioning system (GPS) of satellites as a navigation tool for civil aircraft. The study quantified the level of integrity (safety) afforded by GPS both at system and user levels, related this to civil aircraft navigation requirements and finally, proposed techniques for improving the performance of GPS to meet the requirements. The next phase of the project will carry out a hazard assessment of GNSS-based air traffic services.

Integrated high precision kinematic positioning using GPS and EGNOS observations: This project has developed algorithms and software to assess the performance achievable when combining range and carrier phase measurements from different satellite navigation systems, GPS and Geostationary Earth Orbiting (GEO) satellite data within the EGNOS system. Additional satellite systems are required to augment GPS in order to increase the performance (accuracy, integrity and availability). The results showed a major improvement in real-time kinematic positioning when GPS data is combined with EGNOS data.

***Structural stability monitoring using satellite positioning systems and GIS*:** The objective of this project is to specify and demonstrate a system architecture for structural deformation

monitoring based on satellite positioning and geographical information systems technologies, and to develop methods for using this data to understand structural behaviour. The work requires a multi-disciplinary approach combining advanced satellite positioning and geographical information systems technologies with background in structural analysis and assessment as well as external input from practicing engineering firms.

Earthquake risk assessment using remote sensing: A consortium consisting of Imperial College London and European industry was awarded a contract by the European Space Agency (ESA) under the Long Term Development of Earth Observation Market initiative. The project is developing and validating the technique of Permanent Scatterer Interforemetry Synthetic Aperture Radar (PSInSAR) for the purpose of deriving high precision maps of ground displacements over time. Imperial College London is contributing expertise in positioning with GPS to validate the new PSInSAR concept.

Air Traffic Control and Management - Assessment of the impact of future air traffic management technologies and procedures on airspace capacity: With global demand for air transport doubling every 10-15 years, the total number of flights in Western Europe is forecast double between 2000 and 2010. Current air traffic management (ATM) procedures and technology cannot cope. There are increasing safety risks, with growing numbers of recorded 'near misses', and ever increasing costs of delay due to congestion. The technological challenge is to increase airspace capacity without compromising safety, environmental and economic requirements. An on-going project supported by the EPSRC and the Royal Society is exploring the impact of new technologies (in particular satellite navigation systems) and management procedures on airspace capacity. The involvement of the ATM industry is crucial to the success of this project. Eurocontrol and QinetiQ are collaborators on the project.

Air Traffic Control and Management - Cross-sectional time-series analysis using simulated controller workload data: This project is funded by Eurocontrol to carry out further research on understanding airspace capacity's dependence on controller workload. A cross-sectional time-series analysis using simulated controller workload data will be carried out.

3 NATIONAL AND CONTINENTAL NETWORKS

- **IESSG, The University of Nottingham,** *http://www.nottingham.ac.uk/iessg/*
  Ordnance Survey of Northern Ireland, *http://www.osni.gov.uk/*
  Ordnance Survey Ireland, *http://www.osi.ie/*
  Commissioners of Irish Lights, *http://www.cil.ie*

IRENET: The active GPS network for Ireland is the result of collaboration between Ordnance Survey Ireland (OSi), the Commissioners of Irish Lights (CIL), and the Ordnance Survey of Northern Ireland (OSNI) and comprises of sixteen stations distributed around the island. During the first half of 2002 an extensive GPS measurement campaign was undertaken to connect the sixteen GPS network stations to the European GPS co-ordinate reference framework (EUREF). The IESSG processed the GPS data to determine accurate ETRS89 coordinates for the 16 active GPS stations, which will become the realisation of ETRS89 in Ireland. In addition to this, assessments of the station velocities and movements of the 11 IRENET95 Zero Order passive stations and the 3 EUVN97 passive stations were made. The ETRS89 coordinates of a network of 29 FMB and tide gauge passive station were also determined, relative to the active network stations.

- **International Institution for History of Surveying & Measurement (A body within FIG).**

Struve geodetic arc and its extension: Since 1994 the History of Surveying Group within FIG, with the support of IAG and IAU, has been working on a project to get a selection of the remaining surveys stations on the Arc recognised as an UNESCO World Heritage Monument.

The Arc was observed between 1816 and 1855 and contained 265 station points. In today's geography it passes through ten countries :- Norway, Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Belarus, Ukraine and Moldova.

It has been a considerable challenge to get ten countries to each produce all the necessary field work and documentation but all is gradually coming together.

The aim is to finish with between 35 and 40 points preserved and suitably marked. Submissions to UNESCO can only be made once a year and it is hoped to submit the case for the Arc in February 2004. The National Land Survey of Finland has kindly agreed to collect, collate and print all the necessary documentation.

Following on from this project efforts are now being directed to verifying a link from the southern end of the Struve Arc (Izmail on the Black Sea) via Romania, Bulgaria and Greece to Crete then across the Mediterranean to Egypt and thence through the Arc of 30th Meridian to South Africa.

If successful, it is hoped to apply a similar World Heritage Monument exercise to this triangulation and thus form a monument from North Cape to Cape Aghulas - a distance of some 11 450 km or almost 105 degrees.

If any readers are aware of information relating to a connection from Izmail to Crete. either circa 1868 or later, we would be very interested to hear about it. Please contact J R Smith, Honorary Secretary to the Institution, at *101765.332@compuserve.com*

- **Ordnance Survey of Great Britain,** *http://www.ordsvy.gov.uk*

New official extension to the EUREF for Great Britain, EUREF GB 2001: The purpose of the EUREF GB 2001 campaign was to compute new ETRS89 coordinates for all the stations in the Ordnance Survey Active GPS Network. Although GB had an existing network of EUREF stations (EUREF GB92), this was based upon ground marked stations only and did not include any Continuously Operating GPS Receivers (COGRs). The EUREF GB 2001 campaign was based upon two weeks of observations at the 30 permanent GPS stations which comprise the Active GPS Network, four additional stations and six fiducial IGS stations in Europe. The coordinates were computed following the latest recommended methods of the EUREF Technical Working Group. 20 stations from the campaign were proposed and officially ratified at the EUREF 2002 symposium as an improvement and extension of EUREF89.

Ordnance Survey National GPS network, *http://www.gps.gov.uk:* Launched in 2000, the website gives online users free access to: the Ordnance Survey Active GPS Network RINEX data server; the passive GPS station database; online coordinate converter (utilising the OSTN02 / OSGM02 transformations) and information resource.

The Active GPS network consists of 30 permanent geodetic GPS receivers installed throughout Great Britain, such that most locations are within 75 km of at least one Ordnance Survey active station, and major urban areas are served by several. All Ordnance Survey active stations record dual-frequency GPS data 24 hours a day at a 15 second epoch rate. The network control centre at Ordnance Survey headquarters in Southampton receives a one hour packet of GPS data from each active station once per hour around the clock, and adds this to the RINEX data server for immediate access by users.
The 900 passive GPS network station coordinates were updated following a complete readjustment of the entire network known as OSGPS2002. OSGPS2002 incorporates many extra observations and also extends the passive network into the Scottish Islands, the Scilly Isles and the Isle of Man. The expected coordinate errors at a passive station are now improved to 0.055 m horizontal (95%) and 0.066 m vertical (95%). Hundreds of observations between passive and active stations have been included in OSGPS2002 meaning that the two networks are now in closer sympathy.

Definitive national grid transformation OSTN02: OSTN02 is a transformation model which not only models the relationship between ETRS89 and OSGB36 but actually redefines OSGB36 in

terms of ETRS89. Since the introduction of the Ordnance Survey National GPS Network and the ratification of the Active stations as the official realisation of ETRS89 in Great Britain (EUREF GB 2001), the national geodetic coordinate frame has been defined in ETRS89. Prior to this, OSGB36 National Grid was realised by the coordinates of the old terrestrial Retriangulation. Because OSGB36 only exists on land, OSTN02 has been limited to within 10km offshore. OSTN02 is a grid look up type model and achieves an accuracy of 0.1m rms when comparing coordinates of lower order (third and fourth order) control achieved through GPS plus OSTN02 and existing archive OSGB36 coordinates.

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

Control networks: Work has continued to establish more geodetic control in the Antarctic Region areas of South Georgia, South Sandwich Islands, Antarctic Peninsula, South Orkney and South Shetland Islands as well as the Atlantic Island of Tristan da Cunha. Most data has been post-processed with IGS stations resulting in ITRF coordinates.

4 INTEGRATED SYSTEMS AND INERTIAL NAVIGATION SYSTEMS

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

GPS integrated with remote sensing: GPS is being used in combination with terrestrial laser scanning and ground based photogrammetry for monitoring cliff erosion and slumping.

Integration of GPS / INS: The IESSG at the University of Nottingham have developed a sophisticated software package which enables the close and effective integration of RTK GPS with Inertial Measurement Units (IMU). An Adaptive Kalman Filter is used to jointly process the pseudo-range and carrier phase GPS measurements with the accelerometer and gyro readings. The IMU data greatly enhances the ability of the software to detect and repair cycle slips in the phase data and also greatly accelerate the ambiguity resolution. In a complementary manner the GPS data enables a far more rapid alignment of the IMU sensors and the containment of the biases and drifts of the sensors. The package has been tested with data from the IESSG Navigation Simulator and also real data from marine trials of the integrated system. Further work is now continuing to develop the software so that it may be exploited throughout a range of applications areas.

Low-Cost Navigator (LCN): The University of Nottingham is part of a team led by Thales working on the integration of GNSS and inertial sensors into a low cost package that is able to provide precise navigation in difficult environments. The University's role is to assist the design process by testing future components in a simulation environment. To achieve this, the University has developed a capability to simulate inertial components (gyros, accelerometers) as part of its GNSS simulator, in an integrated environment. Detailed models of the performance of the inertial components have been developed, so that synthetic GNSS data and inertial data can be produced from a common platform. A trajectory generator allows synthetic data to be produced from a combined GNSS/Inertial platform which is moving in a precisely controlled way. Data from this tool has been validated using an analysis filter from another consortium member, as well as with in-house analysis tools.

5 SATELLITE ALTIMETRY

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

Satellite altimetry: We have continued with ongoing studies into the stability of altimetric range measurements using absolute and relative calibration techniques. An absolute calibration of TOPEX/Poseidon (*Dong et al, 2002*) and of ERS-2 (*Dong et al, to be published in 2003*) altimeter biases have been undertaken using UK tide gauges equipped with GPS. The tide gauge reading is extrapolated to sub-satellite points using a local geoid while the ocean tide numerical model has been replaced by estimation of the tide-difference parameters from the TOPEX data itself. The methodology is general and can be applied to other locations and is currently being used for Jason-1.

Relative calibration studies have been undertaken for TOPEX/Poseidon using the global network of tide gauges and for ERS-2 using dual crossovers with TOPEX/Poseidon (*Moore, 2001*). Intra-calibrations of TOPEX/Poseidon have revealed differences between Side A and Side B of the altimeter and a clear annual signature. A time series of the ERS-2 bias, as derived from dual crossover data, shows evidence of a small drift in the altimetric range with the sea-state bias a potential source of error.

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

Over the past four years, research in the E.A.P.R.S. laboratory at De Montfort University has concentrated on the analysis, interpretation, and development of novel applications of satellite radar altimeter data. By interpreting the complex echo shapes obtained over non-ocean surfaces, a global database of over 1000 million orthometric heights has been generated from the ERS-1/ERS-2 altimeters, with additional data from Topex/Poseidon and., recently, Envisat RA-2.

One focus of research has been the investigation of existing Global Digital Elevation Models, both to determine the extent of errors by comparison with a globally distributed, independently derived height dataset, and to provide information on the effects of these errors on current global and regional gravity field models. Following on from this research, which confirmed the presence of very significant, regional scale height and terrain errors in current GDEMs, a new GDEM – ACE (Altimeter Corrected Elevations) was generated, by merging the best available ground truth with altimeter derived heights. Over 40% of the earth's land heights have been significantly altered in this radically different GDEM, which is now increasingly used, in applications as diverse as DTM 2002, and as the AATSR GDEM for Envisat.

In allied work, the potential for analysis and correction of regional DEMs was pursued, over Australia, in conjunction with Curtin University, Perth, and for SAR generated models, with the European Space Agency. Currently, the SRTM dataset is being assessed as the model is progressively released into the public domain: initial results over North America appear promising.

A new focus over the past four years has been the analysis of data over inland water. Initially working over river systems, the potential of retracked altimeter data to retrieve global information over inland water has been demonstrated.. Detailed river height data have been retrieved, and decadal time series have been analysed. Recently, this work has been extended to an analysis of global lake systems, and it has been shown that valid height data can be extracted from the complex altimeter echoes from ERS-1/2 for over three quarters of the earth's major lakes, and for one quarter of these lakes by retracking Topex data, allowing the derivation of global lake climatology. These time series are now being and analysed for climate-related information. With the ability of the new altimeter missions, Envisat and Jason-1, to release processed data quickly, this work is now being extended to near-real-time monitoring of inland water. Recognising the potential of this technique, a new high level hydrology product is being designed in collaboration with the European Space Agency. This will be available from 2004 for Envisat data.

Envisat CAL/VAL: One key activity during this period has been the involvement in the Calibration/Validation Team for the Envisat RA-2, both in investigation of the performance over land surfaces, and in analysis of the backscatter over natural land targets. Cross-calibration has been carried out with ERS-1 and ERS-2 ice and ocean mode backscatter, and Topex data are now being studied. The outcome of the Envisat Cal/Val activity shows that the RA-2 is retrieving data even over the extreme terrain of the Andes and Himalayas mountains. Of particular interest is the retrieval of the first ever altimeter heights from lake Titicaca, high in the Andes, demonstrating the potential for height generation and for monitoring of inland water even in extreme terrain.

SSG 3.184 Use of remote sensing for monitoring heights and depths: The E.A.P.R.S. lab has played a key role in the work of this IAG Special Study Group (chaired by Professor Berry) over the past four years, with a range of collaborative research projects with group members, and with development of new datasets such as the ACE GDEM.

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

Satellite altimetry: POL has continued to employ data sets from TOPEX/POSEIDON and ERS-1/2, and now JASON-1. Projects have included the use of altimeter data for ocean circulation studies, and research into the use of UK tide gauge equipped with GPS to provide an ongoing altimeter calibration system. A particular topic is the interaction of mean flows with eddies and Rossby waves. In the Southern Ocean it has been shown that the mean eastward flow overcomes the intrinsic westward propagation of Rossby waves to produce the world's only large region of eastward propagation of sea level anomalies, apart from the equator. The eddies in the Southern Ocean have been shown to remove eastward momentum from, or to produce a torque on, eastward jets. this is unlike the situation in many ocean models, suggesting a greater role for interactions with bottom topography than hitherto accounted for. The interaction between mean flows and transients has also permitted verification of the existence of zonal jets in the Coral Sea, predicted from model analyses. A comparison of seasonal cycles in the northern North Atlantic, as measured by altimetry and surface drifters, has also been undertaken, showing that the two datasets are consistent and complementary, and elucidating the flow pattern in this region which is important for the global thermohaline circulation.

Altimetry has also been compared with Antarctic tide gauge measurements (see the POL entry under *Mean Sea Level studies*).

6 SYNTHETIC APERTURE RADAR

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

Phase ambiguity determination: A technique has been developed that resolves SAR phase integer ambiguity from single InSAR pairs. The method requires only very coarse, sparse ground control and has major implications for differential techniques and the derivation of atmospheric delay residuals.

7 SATELLITE ORBIT AND GRAVITY FIELD DETERMINATION

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

Satellite orbit and gravity field determination: Precise orbit determinations have been undertaken for the altimetric satellites ERS-2 and TOPEX/Poseidon and their follow-on missions ENVISAT and Jason-1. Orbital analysis has also been used to develop a tailored gravity field for the ERS orbit *(Moore, 2001)* while dual and single satellite crossovers provide a measure of both the orbital accuracy and a mechanism for investigation of the relative altimetric bias. Work in this area has contributed to ESA's Orbit Validation Team (OVT) and Cross Calibration Validation Team for ENVISAT. Our in-house software FAUST has been extended to permit a reduced-dynamic solution which has proved superior to the standard dynamic methodology for ENVISAT.

Effort has been devoted to orbital analysis and gravity field recovery from the CHAMP mission. GPS tracking has been used within a reduced dynamic formulism of the GIPSY/OASIS II software to produce positioning for study of the gravity field and for participation in the IGS LEO Pilot Project (*Moore et al, to be published in 2003*). Errors affecting gravity field recovery from CHAMP have been investigated *(Moore et al, to be published in 2003*) with the conclusion that orbital positioning is the critical source of error with accelerometry contributing at a lower level. Attitude error is not significant.

- **Department of Geomatic Engineering, University College London,** *http://www.ge.ucl.ac.uk/*

Analytical non-conservative force modelling for near-Earth satellites: There is an on-going study in the Department of Geomatic Engineering at UCL to develop generalised methods of modelling the solar non-conservative force field (including effects due to solar radiation pressure, anisotropic thermal re-radiation and Earthshine/thermal emission effects). The techniques that are being developed *(Ziebart and Dare, 2001 and Ziebart et al, 2002)* can cope with highly complex spacecraft structures, and there is no requirement to simplify either the spacecraft structural data, or the derived models. They are applicable at the stages of mission design, operation or scientific analysis, and are designed to be applicable principally to low earth orbiters and medium earth orbit navigation satellites. Models for GLONASS and JASON-1 have been published and the techniques are currently being applied to GPS Block IIR, and a number of other earth observation missions.

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

Satellite orbit determination: POL has continued to operate a Precise Range and Range-Rate (PRARE) ground-station at Ascension Island as part of the global tracking network for ERS-2.

Space gravity: POL has been closely involved in the Science Working Teams for the GRACE and GOCE gravity missions. At the time of writing, GRACE is providing the first data sets of temporal changes in the Earth's gravity field, and a UK consortium including POL, Newcastle and Reading Universities has been assembled to analyse the data. POL has produced a global barotropic ocean model to help remove the effect of high frequency mass movement which will alias the GRACE retrievals. The model has been tested against deep ocean pressure measurements, and compared favourably with a higher resolution, baroclinic model for these high frequency effects. A massively parallel version of the model which incorporates Greens functions to take account of ocean loading and self attraction is currently being tested.

In 1999 GOCE was accepted by the European space Agency for launch in 2006, and planning has since continued apace. GOCE will provide a definitive snapshot of the gravity field and geoid for oceanographic and geodetic studies. Attention has also begun to be addressed to the scientific needs of the generation of space gravity satellites which will follow GRACE and GOCE.

8 GRAVITY SURVEYS

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

Absolute gravity: POL is using the FG5 absolute gravimeter FG5-103 to make measurements of vertical crustal movements near UK tide gauges with long mean sea level records. This is part of a UK program to use GPS and absolute gravity measurements to separate climate related changes in mean sea levels from the vertical crustal component in relative sea levels. Absolute gravity near 3 of the United Kingdom's (UK) core tide gauges was repeatedly measured using an FG5 gravimeter over a period of 3-4 years to determine vertical land movements at those gauges. The absolute gravity sites were established at Newlyn and Aberdeen in 1995 and in Lerwick in 1996. Assuming a height change of 1 mm causes a change in gravity of 0.2 microgal we see vertical land movements of 1.0 ±1.4 mm/yr at Newlyn, - 3.8 ± 1.6 mm/yr at Lerwick and 0.9 ± 3.1 mm/yr at Aberdeen. These land movements are, within the error estimates, in agreement with land movement predicted by a model of post-glacial rebound/subsidence. To ensure that our absolute gravimeter is giving accurate results with an accuracy equivalent to the highest international standards it has been regularly inter-compared with other absolute gravimeters at sites in USA (1999) and France (2001, ICAG2001) and was verified to be in agreement at the 2 microgal level.

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

OSGM02 model: The UK Hydrographic Office has provided offshore gravity data in support of the OSGM02 geoid model.

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

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

Ocean tide loading: We are currently conducting research into the effects of ocean tide loading in the UK. GPS data collected at permanent sites around the UK are being analysed with the GIPSY/OASIS II software, estimating harmonic terms along with the site coordinates and other parameters. Ongoing research will compare these measurements with estimates from numerical tide models and absolute gravity. A similar project is also underway for the Antarctic continent where large uncertainties exist in numerical tide models, particularly under and near to the ice shelves.

IGS GNAAC: The IGS supports the use of GPS by the provision of high quality orbits, Earth rotation parameters and coordinate time series. Newcastle University is a global network associate analysis centre (GNAAC) of the IGS. As such we play a key role in this service by integrating weekly coordinate and Earth Orientation Parameter (EOP) solutions from IGS analysis centres into a common reference frame, for all GPS tracking sites that are a part of the IGS. The TANYA software used for this has been developed at Newcastle, as well as software for online checking of data file compliance to the SINEX format. Global station coordinate and EOP estimates from satellite laser ranging measurements are also being combined as part of the ILRS Pilot Project. The results from these combinations are also of great importance for global plate kinematics studies (*Lavallée, 2000*).

The coordinate time series from the GNAAC has allowed the experimental discovery of a degree-1 global deformation due to seasonal hydrological movements (*Blewitt et al., 2001*) and further developments in the areas of self-consistent loading theory, ocean/continent water distribution, and sea-level change (*Blewitt & Clarke, to be published in 2003*). These data are also currently

being used to validate surface deformations inferred from measurements and models of the time-varying gravity field.

- **Grant Institute, The University of Edinburgh,**
  http://www.glg.ed.ac.uk/gi/

Theory (Geoid and Vertical Reference Systems):

1. *Hipkin, (to be published in 2003)* describes a new and much simpler way to compute the geoid from gravity data available on the surface of an *ellipsoidal* Earth. The conventional ellipsoidal modification of Stokes integral over a local cap misses up to 98% of the ellipsoidal effect - contributions up to 0.6 m - but is also an unnecessary procedure. We only need to compute a correctly ellipsoidal version of the free air anomaly from a global gravity model like EGM96 when using it in a remove-restore algorithm.

2. *Hipkin (2002a)* argues that the geoid can no longer be defined adequately by its relation to mean sea level but that a conventional global datum should be set by giving the total geopotential on the geoid W_0 the same value as the reference potential on the ellipsoid, U_0. If this conventional datum is adopted and the 1983 IAG resolution about zero-frequency tides is implemented by all, no parameter changes to the Geodetic Reference System 1980 are needed.

3. The theory and practice of a modern vertical reference system with a global datum and no monuments is discussed in *Hipkin (to be published in 2003).* The essence of the European Vertical Reference System 2000 adheres to this model but its frame is inconsistent by retaining NAP as a definitive datum rather than a provisional 'working hypothesis'.

Theory (Geodynamics):

1. An analysis *(Hipkin, 2001a,b)* of the statistical properties of data distributed randomly over a sphere concluded that the definitions of the 'power spectrum' adopted in the geodetic and geomagnetic communities are both wrong. Because of the error, a first order property of the Earth's gravity field had been overlooked. With the new analysis, it is shown that the complexity of Earth structure must increase by one or two orders of magnitude between the uppermost mantle and the core, in contrast to the 'empty mantle' models derived from some seismic tomography studies. It is also shown that Moritz' empirical covariance function C_3 is a necessary result of randomly distributed density anomalies over the Bjerhammer sphere but that his alternative C_2 has no such basis in statistical physics.

2. A further application of the pink noise model *(Hipkin, 2002b)* shows its superiority over Kaula's rule as a statistical model of the Earth's gravity field. The systematic deviations of EGM96 from the power law relation of Kaula's rule argue against a 'criticality' as a mechanism for internal density hereogeneities. A nine parameter pink noise model predicts all 120000 free parameters of EGM96 with residuals that are indistinguishable from the normal distribution.

3. An extension of the pink noise model to the gravity fields of the other terrestrial planets *(Hipkin, to be published in 2003)* revealed a quite unexpected identity in the rheological properties of the lithospheres of the Earth and Venus, despite their very different thermal and tectonic regimes. The analysis for the Earth gave a central depth of 49 km and a load-bearing capacity $10^{4.65}$ Pa, compared with 51 km and $10^{4.56}$ Pa for Venus. In addition, the larger load-bearing capacity of Venus at 500 km depth is not reached inside the Earth until depths two or three times greater, consistent with the hypothesis the re-circulation of volatiles into the Earth's upper mantle by plate tectonics weakens it substantially compared with Venus, where subduction does not occur.

4. Forsyth's model for interpreting isostatic admittance data in terms of a combination of bottom and top loading has been generalised (Banks et al, 2001) to include internal loading. We

describe am objective way to combine admittance and coherence information that puts unique bounds on rheological properties.

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

Earth tides and ocean tide loading: *Major progress has been made with the interpretation of* tidal gravity measurements taken by various groups around the world using continuously recording superconducting gravimeters at a network of global sites as part of the 6 year (1997-2003) Global Geodynamics Project (GGP). In addition, measurements made by POL in the 1980s in Europe, China and Brazil using LaCoste and Romberg ET spring gravimeters with electrostatic feedback proved to be of great value in this work. Ocean tide loading model computations were made for the gravimeter sites using 10 new ocean tide models. It was shown that a few of the superconducting gravimeters have significant calibration errors and are therefore not suitable for testing the latest body tide and ocean tide models. The relatively large number of high quality observations from both superconducting and spring gravimeters in Europe, together with the very small ocean tide loading at diurnal periods in this area, provide a valuable opportunity for testing the models of the Earth's body tide. It was shown that the observed amplitudes are consistent with the latest body tide models and that there is a phase lag of order 0.02° in the diurnal gravity body tide (after correction for ocean tide loading). This is first time that this very small phase lag (due to the Earth's inelasticity) has been observed in tidal gravity measurements.

The global tidal gravity observations were used to test the 10 different ocean tide models. Some of the ocean tide models give anomalous results in various parts of the world. For example, the 4 French global finite element ocean tide models give anomalous results in the western Pacific (China, Japan and Australia). Tidal gravity observations from Spitzbergen provided a valuable opportunity to test the global ocean tide models in the Arctic Ocean, where the models cannot be constrained by Topex/Poseidon altimetry data. It was shown that in this area the latest of the French global finite element ocean tide models is in very close agreement with the tidal gravity measurements and that the agreement is better than that obtained using regional ocean tide models.

10 GEOID DETERMINATION

- **Department of Geomatic Engineering, University College London**
  http://www.ge.ucl.ac.uk/

Geoid determination: Work has been carried out at by the Department of Geomatic Engineering at UCL on geoid determination at local and regional scales. At the local scale, a geoid model was constructed for engineering purposes and compared with OSGM91 (*Iliffe et al, 2000).* More recently, UCL formed a consortium with KMS and the University of Copenhagen in Denmark to compute OSGM02, a new geoid model for the British Isles *(Forsberg et al, 2002)*. Full results are to be published shortly.

- **Grant Institute, The University of Edinburgh,**
  http://www.glg.ed.ac.uk/gi

Practical geoid computation and interpretation:

1. A new geoid EDIN2000 *(Hipkin et al, to be published in 2003)* has been computed covering the British Isles and adjacent parts of the north west European shelf, specifically for the purpose of determining dynamic sea surface topography over the oceanic parts of the area (Haines *et al*, 2003). Comparisons are made with GPS and levelling, and with oceanographic and gravimetric determinations of dynamic sea surface topography. After decades of controversy, we finally confirm the suspected large systematic error in British levelling, but also find a small local defect in all current geoid models (EGG97, EDIN2000 and OSGM02)

near the Newlyn datum. Probably for the first time globally, we have been able to use the combination of a gravimetric geoid and satellite altimetry to determine realistic geostrophic currents in an oceanic region. We find a three-year mean speed of 0.32 m s^{-1} for the shelf edge current carrying 'Gulf Stream' water into the Norwegian Sea, with a noise level elsewhere generally below 0.05 m s^{-1}.

2. There is a very significant improvement in the quality of the geoid computed from marine gravity data when the datum and trend of along-track gravity profiles are adjusted to minimise cross-over errors. But we also found that simple interpolation of point values to estimate gravity at the point where two tracks crossed aliases random noise into long-wavelength geoid errors. Consequently a new algorithm has been developed for network adjustment of marine gravity data. It is capable of handling very large numbers of irregularly distributed ship tracks. A pilot study covering all data in the North Sea was presented at IGGeC *(Hipkin, 2002c)* but the method is now being applied to a compilation of 13000 ship tracks covering the whole of the northern North Atlantic as part of the GOCINA project *(Knudsen et al, to be published in 2003).*

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

GPS heighting of fundamental benchmarks for geoid determination: In early 1999, the Ordnance Survey of Great Britain (OSGB) carried out GPS observations at a network of 188 fundamental benchmarks (FBMs), in order to compile a high quality GPS/levelling data set with which to evaluate geoid models for the UK. The data was observed as a series of relatively short, 4 hour observation sessions, with each FBM station being observed for two sessions. The IESSG were responsible for the processing and analysis of the GPS data in order to compute ellipsoidal heights in the ETRS89 e1989.0 coordinate reference system. The results showed that by using 4 hours of data collected with a single GPS receiver and data from active stations that form part of the National GPS Network of Great Britain, it was possible to determine ellipsoidal heights to a precision and accuracy of about 1.5cm. The ellipsoidal heights were used in the computation of the OSGM02.

- **Ordnance Survey of Great Britain,** *http://www.ordsvy.gov.uk*
  Ordnance Survey Ireland, *http://www.osi.ie/*
  Ordnance Survey of Northern Ireland, *http://www.osni.gov.uk/*

Geoid Model OSGM02: Commissioned by the Ordnance Surveys of Great Britain, Ireland and Northern Ireland, the Ordnance Survey Geoid Model 2002 (OSGM02) utilizes all available gravity, terrain and GPS / levelling data and covers the area 45.5° N – 61.5° and 11.5°E – 3.5° W (approximately 1445 km x 980 km. A quasi-geoid was constructed and, subsequently, converted to geoidal heights. This gravimetric geoid was then fitted to GPS / levelling data. To accommodate different vertical datums, the GPS fitting has been computed in patches corresponding to the various datums in use (i.e. Newlyn, Belfast, Malin Head and various island datums) and is limited to within 10 km offshore. The final post-fit standard error of the fitted geoid is 2 cm for mainland Great Britain and Northern Ireland, slightly poorer in the other areas.

A scientific version of the gravimetric geoid, not fitted to the levelling datums, will be made available upon request.

11 DEFORMATION MONITORING

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

Tectonic deformation monitoring: We have continued our geodetic investigation of present-day tectonic deformation throughout Greece and the Aegean Sea, assimilating new GPS campaign measurements with previous data (*SING Working Group, 2001*). More recently, we have taken part in large-scale GPS campaigns in mainland Italy and their comparison with historical terrestrial surveys (*Hunstad et al., to be published in 2003*).

Permanent surface displacement due to an individual earthquake is non-linearly related to the earthquake source parameters. This has implications both for the estimation of source parameters from the inversion of geodetic data, and for realistic assessment of the error budget. We have applied robust non-linear inversion methods to recent earthquakes (*e.g. Wright et al., 1999*) to recover realistic source parameters with minimal use of *a priori* information. Recent and continuing work shows that the spatial correlation of geodetic errors is highly significant for error estimation, particularly when using synthetic aperture radar (SAR) interferometry (InSAR).

We have carried out tests of rapid-static, kinematic and real-time-kinematic GPS methods for use in volcano deformation monitoring on Mt Etna, Sicily (*Page, 2000*). Ongoing work includes the use of small-scale GPS networks to mitigate tropospheric errors in InSAR and kinematic GPS, for use in volcano monitoring projects and investigations into the effects of tropospheric estimation in mountainous areas and are developing models to allow improved estimation for RTK heighting in mountainous terrain.

Local/industrial deformation and subsidence monitoring: Since 1996 we have been investigating the use of high precision GPS geodesy to monitor platform subsidence rates at several North Sea oil platforms operated by Shell Petroleum and Exploration (UK). The precise point positioning (PPP) strategy is employed as implemented in the GIPSY/OASIS II software developed by JPL. Further research includes investigation of the source of non-secular signals present in these and related time series.

Over the past two years ground subsidence due to oil and mineral extraction has been measured at a number of locations. In the North-East of England, ongoing subsidence due to past coal mining has been monitored using a newly developed low-cost 'all-in-a-box' single-frequency GPS system (*Gledan and Edwards, 2001*). Coastal erosion in North Yorkshire has also been monitored using GPS and InSAR in conjunction with photogrammetric techniques (*Buckley, to be published in 2003*).

- **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. In a pilot study completed in 1999, 2.25 years of CGPS data and nine sets of episodic GPS measurements were measured at a network of three CGPS stations and twenty-two monitoring stations in the Thames region. The pilot study rationalised the understanding of current changes in ground level in the Thames region. Specifically, over the 2.25 year monitoring period, it was shown that seasonal changes of up to 50 mm occurred where London Clay is at the surface, but such movements were not apparent where London Clay is overlaid by other deposits.

12 MEAN SEA LEVEL STUDIES

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

Mean sea level studies: GPS observations at NSTG (see above), along with repeated precise levelling, have been used to calibrate long-term tide gauge measurements of sea-level change. NSTG has a long (100-year) history of tidal observations and is close to a nodal line of post-glacial rebound, making it a key site in climate change studies. However, our GPS and levelling results confirm that the tide gauge structure has significant vertical movement with respect to the nearby bedrock which has no significant geocentric motion (*Sanli, 1999; Sanli & Blewitt, 2001*).

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.

- **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/

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 report "United Kingdom Research on Geodesy 1995-1998", several more episodic GPS stations have been upgraded to operate as continuous GPS stations (CGPS) giving at total of seven CGPS@TG stations in the UK. Further stations are currently being planned for the near future to be located on some remote Scottish Islands. A total of thirteen episodic GPS campaigns have now been carried out since 1991, with those in 2002 and 2003 incorporating a quasi-continuous observation strategy for TG sites offering secure operation on a temporary basis. Data from several CGPS@TG stations are now 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 GPS analysis centre.

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.

Stochastic characterisation of the CGPS coordinate time series in the UK: The coordinate time series of 21 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 5 years and the data have been archived in the British Isles GPS archive Facility. 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 two empirical methods 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. It was demonstrated that the best stochastic model describing the coordinate time series consists of a combination of white and coloured noise. Using estimates for each noise component it is possible to compute more realistic station velocity uncertainties.

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

Sea level studies: MSL data from the global network have continued to be collected at POL by the Permanent Service for Mean Sea Level (PSMSL) of the International Council for Science (ICSU). The PSMSL is one of the main organisers of the Global Sea Level Observing System (GLOSS) of the Intergovernmental Oceanographic Commission (IOC). MSL studies have included research into long term changes of UK, European and global MSL, of which the IPCC Third Assessment Report in 2001 was a special focus. Sea level change investigations have also taken place within programmes of the EU and DEFRA, and as part of Programme 1 of the POL Science Plan 2001-6.

Research highlights have included determination of the regional trends in MSL through the 20th century, together with the magnitude of MSL 'accelerations' from the 18th to 20th centuries obtained from 'data archaeology' of some of the first UK sea level information. The role of the North Atlantic Oscillation on UK MSL and wave climate has been investigated at POL through Tyndall Centre collaborations.

MSL information from tide gauges have been demonstrated to be essential to the monitoring of ocean circulation in many ocean areas (e.g. through straits and at high latitudes), often in combination with altimeter information.

POL has continued the long (now 15 year) time series of ocean bottom pressure measurements in Drake Passage, along with tide gauge measurements at Rothera and (in conjunction with the Ukraine) at Vernadsky. An analysis, in conjunction with other tide gauge records from around Antarctica obtained by various international groups as a contribution to GLOSS, has confirmed the model prediction that sea level fluctuations are highly coherent around Antarctica, and are correlated with the atmospheric Southern Hemisphere Annular Mode. The spatial pattern of this coherent mode has been mapped in conjunction with satellite altimeter data. Other relationships between tide gauge data, bottom pressure, bottom temperature, and El Nino, and the sudden change in J2 described in 2002 from satellite orbital computations, are under investigation.

13 GEOPHYSICAL AND OCEANOGRAPHIC APPLICATIONS OF GNSS

- **British Antarctic Survey;** *http://www.nerc-bas.ac.uk*

The British Antarctic Survey has been involved in the compilation of three major mapping products:

1. BEDMAP - A gridded compilation of bedrock topography of Antarctica, compiled using a wide variety of international sources (*Lythe et al., 2000*). For more information see http://www.nerc-bas.ac.uk/public/aedc/bedmap/bedmap.html

2. ADMAP - A gridded compilation of magnetic anomaly data for Antarctica, compiled using a wide variety of international sources (*Golynsky et al., 2001*). For more information see http://www.antarctica.ac.uk/mdms/cgi-bin/view.pl?pd_pkey=94224675324251

3. The Antarctic Digital Database version 4 - Vector topographic data for the entire continent of Antarctica, managed on behalf of the Scientific Committee on Antarctic Research by British Antarctic Survey. Downloadable from http://www.nerc-bas.ac.uk/magic/add_home.html (A*DD Consortium, 2000*). Latest version is version 4.0, released in August 2002. Version 4.1 due for release in summer 2003.

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

Glaciological application of GPS: We have pioneered a technique that produces highly precise kinematic estimates of horizontal and vertical ice motion using Precise Point Positioning (*King & Aoki, to be published in 2003*). Horizontal coordinate estimates are precise at the 20-30mm level, while vertical coordinates are precise at the 50mm level. Such high precision is obtainable since ice motion is normally slow and constant and hence tight constraints can be applied to the site random walk. This technique has been utilised in research into non-linear horizontal ice stream and ice shelf motion in Antarctica and vertical tidal measurements on several ice shelves. Further work has been done on the Inverse Barometer Effect over the ice shelves. These results have had a significant impact on the modelling of the Antarctic ocean tides and led to the discovery of stick-slip motion in the mouth of Whillans Ice Stream (*Doake et al., 2002*).

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

Integrated Coastal Zone Mapping ICZM® Project: The UKHO has been actively involved with the Ordnance Survey and British Geological Survey on this project. Particular focus is now on the assimilation of vertical datums and further research continues on this subject.

14 LAW OF THE SEA

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

Law of the Sea: The UKHO is actively involved with ABLOS, the joint IHO/IAG/IOC Advisory Board on the Law of the Sea. The UKHO provided the Chairman from 1999 – 2001.

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