UNITED KINGDOM

RESEARCH ON GEODESY

2015 – 2018

Presented to the International Association of Geodesy at the XXVIIth General Assembly of the International Union of Geodesy and Geophysics, Montreal, Canada, July 2019

Prepared on behalf of the Royal Society by the School of Engineering, Newcastle University

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FOREWORD

This report outlines United Kingdom activities in geodesy for the period January 2015 to December 2018. It has been prepared for submission to the International Association of Geodesy (IAG) at its General Assembly in Montreal, Canada, during the XXVIIth General Assembly of the International Union of Geodesy and Geophysics (IUGG) in July 2019.

Following the pattern of previous UK national reports, this document is not divided according to the four commissions of the IAG but is instead presented as a number of interlinked shorter sections. The objective of this is to emphasize the connections that exist between the various disciplines within the continuum of pure and applied geodesy, and to avoid the difficulties that exist in assigning certain activities to particular sections. It has been prepared by the Geospatial Engineering group of the School of Engineering, Newcastle University, from information provided by UK geodesists. The editor wishes to thank all those who have provided this information.

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

Peter Clarke
Professor of Geophysical Geodesy
Newcastle University
Peter.Clarke@newcastle.ac.uk

Editor and Royal Society nominated National Correspondent to the IAG

June 2019

CONTENTS

1. SATELLITE LASER RANGING

NERC Space Geodesy Facility (SGF)

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

SGF is a multi-technique geodetic observatory located at Herstmonceux (East Sussex, UK). The observatory is part of the British Geological Survey, within the Earth hazards and observatories Directorate, and is funded by the Natural Environment Research Council and the UK Ministry of Defence. The techniques in operation at the observatory include a Satellite Laser Ranging (SLR) system; two IGS GNSS receivers; one of the UK Ordnance Survey GeoNet GNSS receivers; three FG5 absolute gravimeters; a broadband seismometer of the BGS British Isles seismic network; as well as other ancillary equipment (e.g. meteorological devices, LIDAR, sun photometer).

SGF is a core station of the International Laser Ranging Service, making daytime and night-time range measurements to geodetic, Earth Observation and GNSS satellites at heights of up to 42000 Km. SGF is the second largest contributor to the long-term series of reference frame solutions continuously provided by SLR since the early 1980s. The current precision of the compressed range data is about 1 mm, and its accuracy is better than 2 mm as assessed by global orbital analysis solutions, with a productivity consistently among the top performers of the network. Several key subsystems of the laser station have been upgraded throughout its history to achieve state of the art performance. Notable among these are the solid state high-repetition rate laser, the event timers, the active hydrogen maser atomic clock, and the single-photon avalanche diode (SPAD) detector. Around one hundred different targets are routinely tracked by the station, a number that has been increasing over the years with the completion of GNSS constellations (Galileo, IRNSS, BeiDou) and the launch of new Earth observation missions. Hardware and software improvements in areas such as system efficiency and aircraft safety enable smooth operation and scheduling of the growing number of targets, maximising productivity without sacrificing the tracking requirements of the scientific and purely geodetic missions. A new ground survey of the observatory was conducted in 2017, providing updated values of the inter-technique tie vectors, as well as the first independently measured distance to the newly installed terrestrial calibration target designed at the observatory, now in routine use.

SGF is one of the (currently) seven official ILRS Analysis Centres (AC). Orbital solutions employing data from the whole network are computed daily with code developed at the observatory. Precise orbits, station coordinates, and Earth orientation parameters are estimated in support of the ILRS contribution towards ITRS realisation and rapid Earth orientation results for the International Earth Rotation Service. Additionally, orbit predictions for selected satellites are computed daily providing redundancy for these products required by the ground network. Short-arc solutions are performed and made available as a quality control check of the observations made when several stations acquire data from the same target simultaneously. The AC engages in research activities in the field of SLR and geodesy. An investigation into the presence of systematic errors in the observations of the network (Appleby, 2016) prompted a change in the ILRS analysis procedures, tested through a major pilot project designed by staff at SGF. The new analysis strategy results in a greater agreement between the network frame scales provided by SLR and VLBI, a long-standing issue plaguing the combination of these space geodetic techniques. Further research focusing on the possible sources of the biases previously uncovered resulted in a complete reassessment of the corrections employed to refer the range observations to the centre of mass of the satellites. A major update of this set of corrections, for all stations of the network since the 1980s, was computed and provided to other ILRS ACs (Rodriguez, 2019).

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Spatar et al. (2015) examined the sensitivity of SLR solutions to the geocentre coordinates, and showed that the inclusion of Stella, Starlette, Ajisai and LARES (but not Etalon) data in addition to LAGEOS could improve the ability of SLR to sense geocentre motion.

2. GLOBAL NAVIGATION SATELLITE SYSTEMS

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Real-time and kinematic positioning. Webb (2015) used a unique kinematic GPS+GLONASS dataset gathered on a repeated trajectory through nearly 1 km altitude range to test the positioning accuracy of kinematic multi-GNSS; this dataset is available online (Webb et al., 2015).

Systematic Errors. Palamartchouk et al. (2015) examined the use of dual-polarisation GNSS observations for the detection and resulting mitigation of multipath in carrier phase GNSS positioning.

NERC British Isles continuous GNSS Facility (BIGF) and ***Nottingham Geospatial Institute (NGI), The University of Nottingham***

http://www.bigf.ac.uk and *http://www.nottingham.ac.uk/ngi*

PhD students have investigated the following topics:

Multi-Frequency GPS/Galileo Combinations for Quick Precise Point Positioning in Urban Environments (Francesco Basile);

Estimation and Analysis of Multi-GNSS Differential Code Biases (DCBs) using a hardware signal simulator (Muhammad Ammar);

A multiple algorithm approach to the analysis of GNSS time-series for detecting anomalous behaviours, geohazards and meteorological events” (Mohammed Habboub);

Multi-Frequency Multi-Constellation GNSS (Sundoss Al Mahadeen);

Signal Authentication and the Mitigation of Spoofing GNSS Signals (Matthew Alcock);

GNSS PPP (Precise Point Positioning) / INS (Inertial Navigation System) Integrated Techniques (Lei Zhao);

PPP and RTK Algorithm Development (Brian Weaver);

Modelling the multipath-induced signals in Signal-to-Noise Ratio (SNR) of GNSS measurements to determine the vibration of GNSS antenna (Ioulia Peppa).

2a. GNSS – ATMOSPHERIC STUDIES

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Troposphere. Lu et al. (2016) developed a procedure to employ static multi-GNSS to precisely retrieve high-resolution tropospheric gradients. Webb et al. (2016) used a unique kinematic GPS+GLONASS dataset gathered on a repeated trajectory through nearly 1 km altitude range to demonstrate the ability of kinematic multi-GNSS to accurately recover tropospheric zenith wet delay parameters. The dataset is available online (Webb et al., 2015). Yu et al. (2017, 2018a, 2018b) developed a procedure to generate high-resolution tropospheric water vapour models from GPS data and numerical weather models, which could be used in near-real-time to correct InSAR measurements.

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CGPS near real-time processing for meteorology: CGPS near real-time processing for meteorology: As reported in the IUGG reports on UK Research on Geodesy 2007-2010 and 2011-2014, the NGI (formerly the Institute of Engineering Surveying and Space Geodesy or IESSG) at the University of Nottingham has been developing CGPS near real-time (NRT) processing systems for the UK Met Office since 2002, as a 'wrap-around' for Bernese Software versions 5.0 and 5.2. The original system provides hourly updates of 15-minute tropospheric zenith total delay (ZTD) and integrated water vapour (IWV) estimates and, since 2007, these have been included in the EUMETNET (Network of European Meteorological Services) GNSS water vapour programme (E-GVAP) and assimilated in the Met Office's operational numerical weather prediction model. In this regional (European) hourly GPS ZTD/IWV NRT processing system (METO in E-GVAP), the processed network includes about 300 stations and fully covers the British Isles and, with a lower density, most Western European countries. Over the period from 2007 to 2011, the original system was complemented by a global hourly GPS ZTD/IWV NRT processing system (METG in E-GVAP), for which the processed network of about 300 stations includes a sampling of UK and European stations integrated with stations from the global International GNSS Service (IGS) network, and a regional (European) sub-hourly GPS ZTD/IWV NRT processing system (METR in E-GVAP). This was a move from processing data every hour to processing data every 15 minutes, thereby reducing the latency of the output so that the estimates are not just useful for assimilation in numerical weather prediction runs that take place every few hours, but can also be used in relation to severe weather events, such as thunderstorms. From 2011 to 2018, parallel systems to those that run at the UK Met Office were also running as part of the British Isles continuous GNSS Facility (BIGF), based at the University of Nottingham, as a regional (European) hourly GPS ZTD/IWV NRT processing system (BGF2, and IES2 in E-GVAP), a global hourly GPS ZTD/IWV NRT processing system (BGF3), and a regional (European) sub-hourly GPS ZTD/IWV NRT processing system (BGF4), with the derived products of 15-minute tropospheric ZTD and IWV estimates being made available through BIGF for further scientific research, e.g. Ahmed at al. [2016a] and Ahmed at al. [2016b].

These research projects have also been conducted during the period:

PEARL (Precise position Estimation for Applications in Real-time of Brazilian Latitudes) project funded by the European Business Innovation Centre Network through European Commission (EC)/H2020 INCOBRA project;

- TREASURE (Training Research and Applications network to Support the Ultimate Real time high accuracy EGNSS solution) Innovative Training Network funded by EC/H2020 MSCA actions;
- Ionospheric Prediction Service (IPS) project funded by EC/H2020;
- Ionospheric Research for Biomass in South America (IRIS), project funded by European Space Agency (ESA);
- Monitoring Ionosphere over South America to support high precision applications (MImOSA2), project funded by ESA.

PhD students have also investigated the following topics:

- Precise Point Positioning (PPP): GPS vs. GLONASS and GPS+GLONASS with an alternative strategy for Tropospheric Zenith Total Delay (ZTD) Estimation (Jareer Jaber Mohammed);
- Improved Receiver Tracking Models for Scintillation Monitoring (Melania Susi);
- Urban Heat Island Monitoring Using a Dynamic GNSS Sensor Network (Jorge Mendez Astudillo);
- Ionospheric Scintillation Sensitive Tracking Models and Mitigation Tools (Kai Guo).

2b. GNSS – ENGINEERING APPLICATIONS

NERC British Isles continuous GNSS Facility (BIGF) and ***Nottingham Geospatial Institute (NGI), The University of Nottingham***

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GeoSHM (GNSS and EO for Structural Health Monitoring of Bridges) projects include a Feasibility Study (FS) which was completed in 2015 and a demonstration which was finished in April 2019. These two high profile projects both sponsored by the European Space Agency were chosen by the sponsor three times as showcase projects. In the GeoSHM demonstration the consortium led by the University of Nottingham have taken into account the technical and administrative issues identified from the FS stage in order to formulate the objectives that truly reflect the real end-user requirements through extensive engagements with essential stakeholders, mainly in the UK, the US and China. During the GeoSHM demonstration an innovative GeoSHM-Lite has been designed and installed on the Forth Road Bridge which is used as Testbed Bridge. An effective GeoSHM Analyst Tool to extract essential real-time information regarding the bridge health condition was also developed. The GeoSHM system is now under the full deployments to the bridges, mainly in China where more than half of world large bridges are based.

PhD students have also investigated the following topics:

- Detection and Localisation of Structural Deformation Using Terrestrial Laser Scanning and Generalised Procrustes Analysis (Hasan Jaafar);
- Assessment of the accuracy and the contribution of multi-GNSS in structural monitoring (Hussein Msaewe);
- Investigation of the potential of low-cost multi-GNSS receivers for structural health monitoring (Chenyu Xue).

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Sadeq et al. (2016) used RTK GNSS to validate high-resolution digital surface models (DSMs) in an urban area (Glasgow), and demonstrated the superiority of a Bayesian probabilistic approach to merging DSMs derived from different sources of high-resolution satellite imagery. Li et al. (2016a) performed a similar validation exercise on medium-resolution global digital elevation models (DEMs) available in mainland China, and showed that significant negative biases exist here for all such global DEMs. Grayson et al. (2018) investigated the use of GPS kinematic Precise Point Positioning (PPP) of a drone as an alternative to the traditional survey of ground control points; Guo et al. (2018) carried out a related methodological study into the improved performance of multi-GNSS PPP compared with GPS-only PPP, with precision agriculture applications in mind.

2c. GNSS – OCEANOGRAPHIC STUDIES

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http://research.ncl.ac.uk/geodesy/

GNSS wave glider. Morales Maqueda et al. (2016) have applied Precise Point Positioning techniques to GPS data from a wave glider, and shown that it is able to detect short-wavelength variations in water surface topography and the geoid.

3. NATIONAL AND CONTINENTAL NETWORKS

NERC Space Geodesy Facility (SGF)

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

The two IGS stations HERS and HERT remain in continuous operation. The HERS Septentrio Timing receiver has been upgraded to a multi constellation version and is now submitting RINEX version 3 data to IGS and EUREF data centres. It also continues to be driven by the active hydrogen maser and contributes to the IGS clock products. The Ordnance Survey GeoNet system HERO, installed by the OS in 2009 close to the SOLA trig pillar has also been recently upgraded to a Septentrio multi constellation receiver. Following on from our detailed site stability study, we have continued to maintain a time series of local height variations through the digital levelling project, which confirms the site is stable vertically at the sub-mm level. Our independent GNSS analysis work using Gamit is ongoing and collaboration with the BIGF facility processing and products team is planned for this year.

NERC British Isles continuous GNSS Facility (BIGF) and ***Nottingham Geospatial Institute (NGI), The University of Nottingham***

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British Isles continuous GNSS Facility (BIGF): From 1998 to 2018, the British Isles continuous GNSS Facility (BIGF) was funded by the UK's Natural Environment Research Council (NERC) and based at the University of Nottingham. Since 2018, BIGF is still based at the University of Nottingham but is now funded by the UK Research and Innovation (UKRI) through the British Geological Survey (BGS). It is a unique and secure repository of archived GNSS (Global Navigation Satellite Systems: GPS, Glonass (GLO), Galileo (GAL), Beidou (BDS)) data, dating back as far as 1997. All data are in RINEX (Receiver INdependent EXchange format) files, which are quality-assured and accompanied by metadata, and also form the basis of derived products; in the form of homogenous time series of parameters including station coordinates and tropospheric integrated water vapour, to facilitate scientific users who are interested in these parameters but do not want to carry out their own high-level processing of GNSS data. BIGF serves all of these data, metadata and derived products to the complete user-spectrum - nationally and internationally across academia, government, and business, with impact on research and development, policy and the wider societal good. Data are currently sourced from a network of about 160 continuously recording GNSS (CGNSS) stations, sited throughout the British Isles. Such data have always been, and continue to be, provided to BIGF free-of-charge by a number of collaborators that own, operate and manage the CGNSS stations in the British Isles but who do not archive their data beyond about the last 45 days. These collaborators include the three national Ordnance Surveys (Great Britain (OSGB), Ireland (OSi) and Northern Ireland (OSNI)), the University of Nottingham, the Environment Agency Thames region, the Hersmonceux Observatory, the UK Met Office, Newcastle University and the University of Hertfordshire. As of March 2018, the archive comprised ~780k station-days (~2,136 station-years) of 30 second GPS, and GPS+GLO, data, and ~346k station-days (~947 station-years) of 1Hz GPS+GLO data. Of the current, about 160 CGNSS stations, this includes three stations (HERS, HERT, MORP) that are part of the International GNSS Service (IGS), and twenty stations (ADAR, ARIS, CASB, CHIO, DARE, EDIN, ENIS, FOYL, HERS, HERT, INVR, LERI, MORP, NEWL, PMTH, SCIL, SHOE, SNEO, SWAS, TLL1) that are part of the EUREF Permanent Network (EPN). In addition, ten stations at tide gauges (ABER, DVTG, LWTG, LIVE, LOWE, NEWL, NSTG/NSLG, PMTG, SHEE, SWTG) have been included in the IGS TIGA Project [Hunegnaw et al., 2016], and all stations are included in the EUMETNET (Network of European Meteorological Services) GNSS water vapour programme (E-GVAP). Cumulative demand on the archive from April 1998 to March 2018 was ~17,363 station-days (~47,537 station-years), to about 1,000 discrete projects, comprising of ~9,336k stations-days (~25,561 station-years) of 30 second data, ~76k station-days (~208 station-years) of 1Hz data and ~7,951 station-days (~21,769 station-years) of derived products, with the 1Hz data and the derived products having been available since 2011. Details of the use of the derived products by BIGF in associated scientific research are given in sections 2a, 12 and 13.

A PhD student has also investigated the following topic: Comparison of Transformation Procedures for the Nigerian Geodetic Network (Abimbola Ayeni).

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Newcastle University has continued to contribute to the International GNSS Service as an Associate Analysis Centre, providing daily and weekly global coordinate combinations in parallel with the official IGS product. We continue to operate IGS sites 'MORP' (Morpeth, England) and 'ROTH' (Rothera, Antarctica) and TIGA site 'NSLG' (North Shields Tide Gauge, England). MORP and NSLG both contribute to the NERC 'BIG F' data repository www.bigf.ac.uk; the former is also part of the EUREF Permanent Network. Parker et al. (2017) reviewed the requirements and operational considerations for GNSS and InSAR monitoring of vertical land motions at tide gauges.

National Oceanography Centre

http://noc.ac.uk/

NOC has maintained the **National Tidal and Sea Level Facility (NTSLF)**, *http://www.ntslf.org/* and the **Permanent Service for Mean Sea Level (PSMSL)**, *http://www.psmsl.org/* . For details of related work please see Woodworth & Hibbert (2015), Hibbert et al (2015, Bradshaw et al (2016), and Teferle et al (2016).

Ordnance Survey of Great Britain

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

Ordnance Survey's national RTK GPS network OS Net has been developed since 2003 and covers the whole of Great Britain with 115 stations. Current European permanent network (EPN) submissions from OS Net are hourly data from: ADAR, ARIS, CHIO, DARE, EDIN, INVR, LERI, PLYM, PMTH, SCIL, SHOE, SNEO and SWAS.

Stations DARE, INVR, and SHOE also provide real time data (RTCM 3) to the EPN. Real time data from other OS Net stations is not possible due to conflict with OS Net partner's commercial operations.

A recent receiver hardware refresh has enabled multi constellation operation across the entire network. A server hardware refresh is now (June 2019) in progress and when complete both RINEX v2 (GPS+GLO) files and RINEX v3 (GPS+GLO+GAL+BDS) files will be submitted to the EPN. The new receivers are mainly two different makes and are mixed evenly across the whole network to mitigate against total network failure in the (rare) event of a major problem effecting one type of receiver.

The definitive ETRS89 – OSGB36 national grid transformation OSTN02 has been updated to OSTN15. The update takes into account the small changes in OS Net coordinates caused by the adoption of the ETRF97 frame realised by the EUREF IE/UK 2009 GNSS campaign and to minimise the resulting impact on the OSGB36 realisation. The expected RMS change in OSGB36 coordinates between previous OS Net coordinates (based on EUREF GB 2001 GNSS campaign) + OSTN02 and new OS Net coordinates + OSTN15 is less than 1cm in both east and north. Full details are in Greaves et al (2016).

Similar to the update of the definitive ETRS89 – OSGB36 national grid transformation, the companion height corrector surface OSGM02 has been updated to OSGM15. The update to ETRS89 that required the OSTN02 transformation to be updated to OSTN15 would by itself have also required a small update to the OSGM02 model. However, in Great Britain the OSGM02 gravimetric model also required improvement in its fitting to the local mean sea level based height datums in the Scilly Isles, north-west Scotland and also on the Scottish islands especially the Outer Hebrides. The data in the west of Ireland also required improvement post OSGM02. Additional gravity data from the GRACE (Gravity Recovery And Climate Experiment) satellite mission was available to be incorporated into the underlying gravimetric model bringing further improvements in resolution.

The change resulted in a systematic shift of RMS 0.025m in the realisation of Ordnance Datum Newlyn (ODN) on mainland GB and larger shifts on the Scilly Isles, Outer Hebrides and parts of north west Scotland. Full details are in Greaves et al (2016) and https://www.ordnancesurvey.co.uk/docs/gps/updated-transformations-uk-ireland-geoid-model.pdf.

4. INTEGRATED SYSTEMS AND INERTIAL NAVIGATION SYSTEMS

NERC British Isles continuous GNSS Facility (BIGF) and ***Nottingham Geospatial Institute (NGI), The University of Nottingham***

http://www.bigf.ac.uk and *http://www.nottingham.ac.uk/ngi*

PhD students have investigated the following topics:

Indoor Collaborative Positioning based on a Multi-sensor and Multi-user System (Hao Jing);
Automotive Applications of High Precision GNSS (Scott Stephenson);
A Novel Avionics Based GNSS Integrity Augmentation System for Manned and Unmanned Aircraft (Roberto Sabatini);
Integration of ARAIM Technique for Integrity Performance Prediction, Procedures Development and Pre-Flight Operations (Simone Paternostro);
Towards Seamless Pedestrian Navigation (Pekka Peltola);
Advanced Navigation Architecture for low cost UAVs (Hery Mwenegoha);
GNSS PPP (Precise Point Positioning) / INS (Inertial Navigation System) Integrated Techniques (Lei Zhao);
GPS/UWB Cooperative Positioning for V2X Application (Yang Gao);

5. SATELLITE ALTIMETRY

Centre for Polar Observation and Modelling, University of Leeds

A.Shepherd@leeds.ac.uk

CPOM’s work addresses the key knowledge gaps of quantifying and predicting changes in Earth’s land and sea ice cover. These issues are of high societal importance because they reflect and drive high-impact changes in the global climate system and understanding them is a central goal of our science program. We use radar altimetry data from the ERS-1/2, Envisat, CryoSat-2, AltiKa and Sentinel-3 satellites to measure land ice, sea ice and ocean surface elevation, together with their changes through time. These measurements are used to study a range of geophysical parameters across Earth’s polar regions, including sea ice thickness and volume change, ice sheet mass balance, ice sheet grounding line location, ice shelf basal melting and ocean circulation. CPOM also leads many technical studies relating to satellite altimeter performance and the development of new mission concepts, most notably activities related to CryoSat-2, Sentinel-3 and the candidate mission CRISTAL. Since 2015, CPOM has published 29 papers that make use of satellite altimetry datasets, covering the development of new mission and processing concepts through to the interpretation of climate and geophysical signals. These papers include community assessments of Antarctic ice mass loss, the first continental-scale estimates of Antarctic grounding line migration, new high-resolution estimates of Greenland ice sheet mass loss, new measurements of Arctic ocean circulation, and Near Real Time observations of changing Artic sea ice volume. CPOM also runs sea ice and land ice data systems and services, which deliver products to support scientific research and operational services in Near Real Time. The sea ice service, for example, receives an average of 454 data downloads per month and has registered 26,609 unique users (21% from the UK) since it was launched in 2015. User institutions include the UK Met Office and the US Naval Research Laboratory, who have assimilated these measurements to improve their model predictions of summer sea ice extent.

School of Geographical Sciences, University of Bristol

http://www.bristol.ac.uk/geography

Antarctic grounding lines from Cryosat (ANGeLIC) Dawson and Bamber (2017) developed a new technique for mapping the grounding line of Antarctic ice shelves using a combination of standard and swath elevation data from the CryoSat-2 radar altimeter. The mapped grounding line was in good agreement with previous observations from differential SAR interferometry and from ICESat repeat track altimetry.

National Oceanography Centre

http://noc.ac.uk/

For details please see Bouffard et al (2018), Calafat et al (2017), Liu et al (2018), Passaro et al (2018), Roemmich et al (2017), Williams et al (2015), and Woodworth & Menendez (2015).

School of Engineering, Newcastle University

http://research.ncl.ac.uk/geodesy/

Moore et al. (2018) have derived a new method for the analysis of Cryosat altimetry data as a means of gauging inland water levels and river flow.

6. SYNTHETIC APERTURE RADAR

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http://research.ncl.ac.uk/geodesy/

Li et al. (2016b) provided a review of the opportunities afforded by the new Sentinel-1 satellites, in particular the reduction in ground track repeat time that will take place once the constellation is complete. Tomás & Li (2017) provided a review of the suite of Earth Observation data including InSAR, which could be applied to monitoring efforts and scientific investigations into geohazards, as part of a special issue of Remote Sensing that they co-edited. Dai et al. (2016) used Sentinel-1 InSAR to monitoring the Daguangbao mega-landslide in China, whereas Chen et al. (2016) used InSAR to study groundwater extraction subsidence in Beijing. Zhou et al. (2016) also used InSAR imagery, to observe peat subsidence related to carbon emissions in Indonesia.

Long et al. (2018) and Wang et al. (2018a, 2018b) have developed a number of novel data analysis methods for ground-based synthetic aperture radar (GB-SAR) deformation monitoring. Luo et al. (2019) have derived a new range split spectrum method that permits satellite InSAR measurements of ground deformation in the presence of high strains.

Zhuang et al. (2016) used InSAR in support of studies of loess redistribution and landslides following the 1920 Haiyun (NW China earthquake). Clement et al. (2018) have developed an SAR-based method for the characterisation of flooding.

Nottingham Geospatial Institute (NGI), The University of Nottingham

http://www.bigf.ac.uk and *http://www.nottingham.ac.uk/ngi*

PhD students have investigated the following topics:

The development of InSAR data to see through shallow soil cover (Ahmed Athab);
The application of PS-InSAR to monitoring the health of peatlands (Lubna Al-Shammari);
The application of PS-InSAR to monitoring landslides in Nigeria (Udeme Nkanga);
The application of PS-InSAR to the monitoring of former coal fields in the UK (David Gee);
The application of PS-InSAR to the monitoring of coal fields in China (Zhengyuan Qin); and
The application of PS-InSAR, GRACE and GOCE to monitoring groundwater (Vivek Agarwal).

Centre for Polar Observation and Modelling, University of Leeds

A.Shepherd@leeds.ac.uk

CPOM use Synthetic Aperture Radar (SAR) data from European satellites including Sentinel-1, ERS-1/2 and Envisat, to measure ice velocity, calving front position, fracture propagation on ice shelves, and grounding line position. Six peer reviewed publications have been published since 2012 using the SAR datasets, with many more conference presentations and posters. CPOM runs a Near Real Time (NRT) ice sheet outlet glacier velocity service to deliver SAR datasets to the scientific community, for use in university teaching and as a tool to facilitate schools outreach projects. The ice velocity service delivers gridded maps and transects of ice speed across 6 major outlet glaciers in Antarctica and Greenland, from Sentinel-1 data acquired since 2014. High resolution radar amplitude images are also provided and this data has been used to measure calving front location and ice berg calving events. The CPOM ice velocity service was the first in the world to systematically deliver ice speed measurements online and it now receives an average of 162 users per month with a total of 5,353 active users since the service launched in 2016. In addition to publications, the CPOM velocity data is used by award winning UK Space Agency school outreach programmes, and in undergraduate teaching. Dr Hogg, at the University of Leeds, is responsible for the development and maintenance of the CPOM ice velocity service. The SAR land ice velocity datasets are complimentary to the CPOM ice sheet modelling activity, led by the Prof Payne at the University of Bristol, which uses ice speed as an input dataset.

7. SATELLITE ORBIT AND GRAVITY FIELD DETERMINATION

[No activities reported]

8. GRAVITY SURVEYS

[No activities reported]

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

NERC Space Geodesy Facility (SGF)

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

Monthly or weekly measurements of the local acceleration due to gravity continue to be recorded at the SGF, resulting in a time line of measurements currently spanning 12 years. Following a successful overseas campaign in 2016 the SGF upgraded FG5#222 (on loan from NOC) to the state of the art control and electronics modules, dispensing with the unreliable electronics and computer. Following this 3 days of measurements were recorded at the Newlyn gravity site, as well as at a new site in the BGS magnetic observatory in Hartland, Devon. The SGF will conduct testing at the site in Hartland during 2019, with a view to providing a location in the UK for small scale comparison of gravimeters. The FG5 absolute gravimeter FG5-222 and FG5-103 were transferred from NOC to BGS in January 2019, making the SGF home to the UK's absolute gravimetry resources.

10. GEOID DETERMINATION

[No activities reported]

11. DEFORMATION MONITORING

Nottingham Geospatial Institute (NGI), The University of Nottingham

http://www.bigf.ac.uk and *http://www.nottingham.ac.uk/ngi*

Research at Nottingham has focussed on the use of interferometric synthetic aperture radar (InSAR) for an array of applications. Specifically, this includes the application of the novel Intermittent Small Baseline Subset (ISBAS) technique for monitoring land surface motion associated with groundwater abstraction (Sowter et al., 2016), gas production (Gee et al., 2016), coal mining (Gee et al., 2018) and peat condition (Alshammari et al., 2018; Marshall et al., 2018). Further developments were also made to extend the capability of the ISBAS method from regional to national deformation monitoring (Novellino et al., 2017; Sowter et al., 2018).

A PhD student has also investigated the following topic: Integration of Global Navigation Satellite System (GNSS) and Interferometric Synthetic Aperture Radar (InSAR) for Deformation Analysis in Malaysia (Muhammad Bin Che Amat).

School of Engineering, Newcastle University

http://research.ncl.ac.uk/geodesy/

Peppa et al. (2016, 2017, 2019) fused GNSS and inertial sensor observations to position an unmanned aerial vehicle used for landslide detection and monitoring at Hollin Hill, northern England.

British Geological Survey (BGS) - Earth and Planetary Observation and Monitoring

https://www.bgs.ac.uk/research/earthHazards/epom/home.html

Deformation monitoring is a key activity of the British Geological Survey as surface motion can be a key indicator of many natural and anthropogenic processes including landsliding, underground mining and groundwater abstraction. All of these can have significant impacts on lives and livelihoods.

For the 2015-2018 period, a particular focus has been the characterization of the mine water rebound process in the South Wales Coalfield and in The North East region of England, the shrink-swell phenomena associated to clay deposits in the Greater London area and the ground stability analysis over areas of potential subsurface energy source or storage, e.g., UKGEOS (https://www.ukgeos.ac.uk/?utm_source=BGS&utm_medium=referral) and the BGS/BEIS Baseline Monitoring Project.

It has become widely acknowledged that baseline monitoring is required ahead of any shale gas or oil development in the UK. A number of reports have recognised its importance including those by the Royal Society and Royal Academy of Engineering, Public Health England, CIWEM and the UK Shale Gas Task Force. Measuring the baseline enables the environment to be characterised before any industrial development takes place so that if any changes occur as a result of it they can be detected. BGS is conducting an independent environmental baseline monitoring programme in the Vale of Pickering, North Yorkshire and The Fylde, Lancashire. Utilising InSAR we are monitoring ground deformation to assess ground motion.

Part of our work is also addressed overseas, as part of the BGS Official Development Assistance programme (https://www.bgs.ac.uk/research/international/oda/home.html), building resilience to landslides in Ethiopia and groundwater extraction in Hanoi (Vietnam).

COMET, School of Earth and Environment, Leeds University

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

COMET scientists at the University of Leeds are at the forefront of using Satellite Radar Interferometry (InSAR) to monitor ground deformation. Efforts have gained significant momentum since the launch of ESA's Sentinel-1A satellite in 2014, followed by Sentinel-1B in 2016, which has made mass processing over large areas feasible for the first time.

Acknowledging the potential of InSAR for volcano monitoring (Spaans & Hooper, 2016) and active tectonics and earthquakes (Elliott et al, 2016), over the last 5 years we have built systems to automate the production of interferograms, with results made available to the community via the COMET-LiCS Sentinel-1 InSAR portal (https://comet.nerc.ac.uk/COMET-LiCS-portal/). We are now on track to produce high-resolution strain rate maps for the entire Alpine-Himalayan Belt and East African Rift within the next two years.

At the same time, we have worked to refine the techniques, through for example the development of atmospheric corrections (Bekaert et al, 2015a, 2015b, 2016), and new algorithms which accurately extract deformation of the ground from time series of satellite radar images (StaMPS) (https://homepages.see.leeds.ac.uk/~earahoo/stamps/).

We have applied InSAR in the response to and investigation of earthquakes (Hussain et al, 2016a; Hamling et al, 2017; Floyd et al, 2016), tectonic strain (Hussain et al, 2016b, Wang etal, 2019) and volcanic eruptions (Gonzalez et al, 2015; Spaans & Hooper, 2018). Work is also now focusing on developing methods to automatically detect and monitor signals of ground deformation around volcanoes (Gaddes, 2018).

12. MEAN SEA LEVEL STUDIES

NERC British Isles continuous GNSS Facility (BIGF) and *Nottingham Geospatial Institute (NGI), The University of Nottingham*

http://www.bigf.ac.uk and *http://www.nottingham.ac.uk/ngi*

Monitoring of vertical land movements at tide gauge sites in the UK: As reported in the IUGG reports on UK Research on Geodesy 2007-2010 and 1011-2014, the application of CGPS to the monitoring of vertical land movements at sites of the UK National Tide Gauge network has been on-going at the NGI (formerly the Institute of Engineering Surveying and Space Geodesy or IESSG) at the University of Nottingham, in collaboration with the NERC National Oceanography Centre (NOC), Liverpool (formerly Proudman Oceanographic Laboratory), since 1997. Since 2009, this research has been an integral part of the British Isles continuous GNSS Facility (BIGF), based at the University of Nottingham. The most recent estimates of changes in mean sea level (decoupled from vertical land movements and changes in land level) around the coast of Great Britain over the past few decades/past century were created by BIGF based on a CGPS re-processing of data from 1997 to 2015:273 with Bernese Software version 5.2 [connecting the BIGF network to the IGB08 via a global network of reference stations, and using C13 (CODE repro2/repro_2013) re-analysed satellite orbit and earth orientation parameter products; mitigation of 1st and higher order (2nd and 3rd order and ray bending) ionospheric effects; a-priori modelling of troposphere effects using VMF1G and mitigation using zenith path delay and gradient parameters; I08.ATX models for antenna phase centre variations; and models for Solid Earth tides, ocean tidal loading and atmospheric tidal loading] and an analysis of the resultant coordinate time series with the coordinate time series analysis software (CATS), to determine vertical station velocity estimates with realistic uncertainties. These estimates are available for ten tide gauges in the UK, namely Aberdeen (ABER), Dover (DVTG), Lerwick (LWTG), Liverpool (LIVE), Lowestoft (LOWE), Newlyn (NEWL), North Shields (NSTG/NSLG, established by Newcastle University), Portsmouth (PMTG), Sheerness (SHEE) and Stornoway (SWTG); with the first being established at Sheerness in 1997 and the last at Dover in 2005, and with all being operative until late-2011 after which time four of the ten have ceased operation, namely LIVE in 2011, DVTG in 2012, LOWE in 2012, and PTMG in 2016, while five of the ten have been upgraded to have 'full GNSS capability', namely ABER, LWTG, NEWL, NSLG, and SWTG. The BIGF derived products of daily station coordinates, and station velocities, for the stations at tide gauges are available from BIGF for further scientific research, e.g. Bradshaw et al. [2015].

School of Geographical Sciences, University of Bristol

http://www.bristol.ac.uk/geography

Resolving Antarctic ice mass trends (RATES): Martín-Español et al. (2015) presented spatiotemporal mass balance trends for the Antarctic Ice Sheet, and resulting contribution to sea level rise, from a statistical inversion of satellite altimetry, gravimetry, and elastic-corrected GPS data for the period 2003–2013 (Zammit-Mangion et al., 2015). This work has subsequently been updated and extended to 2015 and the results contributed to the first World Climate Research Programme (WCRP) global sea level budget (GSLB) assessment (WCRP Global Sea Level Group, 2018).

Global land ice, hydrology and ocean mass trends (GlobalMass): Bamber et al. (2018) developed a new estimate of the global land ice contribution to sea level rise during the satellite era (1992 onwards). The study was the first that has combined and updated estimates since the IPCC 5th Assessment Report in 2013 in a rigorous and holistic way using (i) published studies of ice sheet mass trends including from multiple space-geodetic observations, (ii) expert assessment of those studies and (iii) a new analysis of Arctic glacier and ice cap trends combined with statistical modelling.

National Oceanography Centre

http://noc.ac.uk/

Please see the bibliography for details.

13. GEOPHYSICAL, GLACIOLOGICAL, AND OCEANOGRAPHIC APPLICATIONS OF GEODESY

NERC British Isles continuous GNSS Facility (BIGF) and ***Nottingham Geospatial Institute (NGI), The University of Nottingham***

http://www.bigf.ac.uk and *http://www.nottingham.ac.uk/ngi*

Map of current vertical land movements in the UK. As reported in the IUGG reports on UK Research on Geodesy 2007-2010 and 2011-2014, the NGI (formerly the Institute of Engineering Surveying and Space Geodesy or IESSG) at the University of Nottingham had created a map of current vertical land movements in the UK. Since 2009, this research has been an integral part of the British Isles continuous GNSS Facility (BIGF), based at the University of Nottingham. The latest map of current vertical land movements was created by BIGF based on a CGPS re-processing of data from 1997 to 2015:273 with Bernese Software version 5.2 [connecting the BIGF network to the IGB08 via a global network of reference stations, and using C13 (CODE repro2/repro_2013) re-analysed satellite orbit and earth orientation parameter products; mitigation of 1st and higher order (2nd and 3rd order and ray bending) ionospheric effects; a-priori modelling of troposphere effects using VMF1G and mitigation using zenith path delay and gradient parameters; I08.ATX models for antenna phase centre variations; and models for Solid Earth tides, ocean tidal loading and atmospheric tidal loading] and an analysis of the resultant coordinate time series with the coordinate time series analysis software (CATS), to determine vertical station velocity estimates with realistic uncertainties. This latest map of current vertical land movements included 159 CGNSS stations that had time series >4.7 years, and incorporated all 12 OSGB GeoNet CGNSS stations that were all installed in late-2009 or early-2010 and are connected to solid rock. From a visual inspection, it can be seen that the latest map shows the expected general pattern of uplift in Scotland and Northern England (to a maximum of +1.3mm/yr) and subsidence in Wales and Southern England (to a minimum of -1.4mm/yr), and has a zero line running South roughly through Newcastle in England, West roughly along the coast of North Wales and then North-West roughly along the border between Ireland and Northern Ireland. Apart from that, it would appear that the addition of the OSGB GeoNet CGNSS stations does not significantly alter the contours on a national scale, suggesting that, although the majority of the CGNSS stations that are included on the map are located on buildings or other structures, their estimates of vertical land movements are not too dissimilar from those for a CGNSS station connected to solid rock. The BIGF derived products of daily station coordinates, station velocities, and maps of current vertical land movements, are available from BIGF for further scientific research.

School of Engineering, Newcastle University

http://research.ncl.ac.uk/geodesy/

Glacio-isostatic adjustment. Martín-Español et al. (2016) reprocessed continuous and campaign GPS data from across Antarctica and assimilated this along with ice sheet altimetry and GRACE gravity products to obtain an empirical model of glacial isostatic adjustment and present-day ice mass change for the continent. Nield et al. (2016) showed how uncertainties in ice sheet history and ice stream stagnation could cause significant variations in present-day bedrock uplift rates along the Siple Coast of west Antarctica. Stockamp et al. (2016) reviewed the observational datasets and models relating to GIA in the British Isles. Sasgen et al. (2017, 2018) derived a new multi-technique geodetic dataset comprising GPS deformation monitoring, radar altimetric snow surface elevation change, and GRACE time-variable gravimetry and applied it to the problem of separating present-day ice mass change from bedrock mass change in Antarctica.

Cryospheric applications. Andrews et al. (2015) developed and validated a mascon approach for the recovery of basin-scale Antarctic ice mass trends from GRACE range-rate data. In Greenland, Murray, Selmes et al. (2015) and Murray, Nettles et al. (2015) used data from a semi-autonomous network of low-cost GPS receivers temporarily installed on the Helheim Glacier to infer the dynamics of iceberg calving episodes. Shepherd et al. (2018) presented another analysis of Antarctic ice mass change in the modern satellite era, based on the elevation change, gravity change, and input-output methods.

Ocean tide loading. Penna et al. (2015) used continuous GPS data from across western Europe to demonstrate the ability to recover harmonic displacements at semi-diurnal tidal periods with ~0.2 mm accuracy, and in doing so showed the need to estimate residual tropospheric zenith delays simultaneously with these sub-daily position variations, contrary to previous studies elsewhere. Bos et al. (2015) used the GPS tidal harmonic displacement estimation method developed by Penna et al. (2015) and applied it to a 259-site network of continuous GNSS receivers spanning western Europe (many of them being EUREF Permanent Network sites). They showed that modelling of ocean tide loading (OTL) using a standard elastic Earth model derived from seismology, such as PREM, leads to residual vertical errors at the dominant M2 period of up to several millimetres around the British Isles and near the Atlantic coasts of continental Europe. These errors, which cannot be explained by plausible ocean tide model uncertainties, can be reduced to below the noise floor if anelastic dispersion in the asthenosphere is incorporated into the Earth response model.

Tectonic applications. Feng et al. (2016), Li, Shen et al. (2016), Lin et al. (2015) and Li, Feng et al. (2015) used InSAR to observe co-seismic and inter-seismic strain associated with fault movements at locations in Nepal, Pakistan and USA. Liu et al. (2016) used InSAR to study the time-dependent post-seismic motion following the 2009 Dachaidan (China) earthquake, and thence to infer the viscosity of the lower crust in this region. Wang et al. (2016) also used InSAR to observe a 17-year earthquake sequence under the Tibetan plateau, and to investigate the extent to which Coulomb stress triggering governed this sequence. Amouzgar et al. (2016) used fault slip models of the 2011 Tohoku earthquake, derived from GPS, within a highly-efficient numerical model of tsunami propagation optimised for use on Graphical Processing Units (GPUs). Walters et al. (2018) used InSAR measurements of the 2016 central Italy earthquake sequence to develop a model of fault interaction. Yu et al. (2018) provided another study of co-seismic ground deformation, showing that small displacements could be observed effectively by InSAR with the aid of an assimilative tropospheric model.

Other geodetic deformation monitoring. Dai et al. (2015), Li, Zhang et al. (2016) and Liu et al. (2016) used InSAR imagery to observe vertical land motion associated with hydrocarbon extraction in China. Featherstone et al. (2015) used GPS to investigate local subsidence associated with groundwater extraction near to the tide gauge at Fremantle, Australia. Tomás et al. (2015) used InSAR observations to identify the triggering factors of landslides with the assistance of wavelet tools. Deng et al. (2018) measured city subsidence in Beijing using PS-InSAR; Liu et al. (2018) performed similar investigations in Shenzen with InSAR time series analysis. Al-Husseinawi et al. (2018) carried out the first InSAR-based study of post-seismic dam deformation.

Centre for Polar Observation and Modelling, University of Leeds

A.Shepherd@leeds.ac.uk

CPOM uses pioneering Earth observation techniques alongside state-of-the-art models to improve understanding of Antarctic and Greenland ice sheet dynamics, as well as controls on individual glaciers. This includes identifying key signals of climate change such as the ice sheet contribution to global sea levels. Results show that ice losses from Antarctica have accelerated over the past 25 years with the continent contributing 7.6 mm to global sea levels since 1992, 40% of which has occurred in the past 5 years (The IMBIE Team, 2018). Nearly a quarter of West Antarctica's ice is meanwhile now unstable (Shepherd et al., 2019), including the majority of the sector's largest ice streams – the Pine Island and Thwaites Glaciers – which are losing mass five times faster than they were in 1992. The onset and spreading of drawdown at key Antarctic glaciers is, however, non-uniform (Konrad et al., 2016), with fast-flowing ice streams retreating, on average, by 110 metres per metre of ice thinning (Konrad et al., 2018), linked in places to the presence of warm circumpolar deep water (Hogg et al., 2018). The mass balance of the Greenland ice sheet is found to be highly variable in space and time, with an exceptionally warm summer in 2011 leading to a record deficit in 2012, followed by more moderate losses (McMillan et al., 2016). Within the overall picture, seasonal variations in the flow of key ice streams (Lemos et al., 2018) have been identified, alongside with the relative stability of North-West Greenland's Petermann Glacier (Hogg et al., 2017). These satellite observations are improving our understanding of ice sheet change, as well as being integrated into the models that inform climate change policy development.

Declining Arctic sea ice cover leads to polar amplification of planetary warming with consequences that are global in reach, including increased ice sheet melting, reduced snow cover, permafrost degradation, changes in marine ecology, altered patterns of weather and ocean circulation and, as a feedback, further reductions in sea ice. Although the first signatures of this amplification have appeared in correlated trends of Arctic warming and sea ice loss, climate models have struggled to replicate the reduction in sea ice cover - in part due to simplifications in their representation of key physical interactions. The prospects of rapid sea ice loss and of a seasonally ice-free Arctic Ocean are matters of pressing environmental, economic and political concern, and so there is a strong motive for improved cryosphere models with which to build reliable climate projections. CPOM has pioneered methods for tracking key cryosphere parameters in satellite data - including measuring the extent, thickness and drift of sea ice – and the use of these observations to improve our understanding of present and future environmental change. Recent developments include the production of near real time observations of Arctic sea ice thickness (Tilling et al., 2016; Tilling etal., 2018), improving estimates of snow depth on Arctic sea ice (Armitage et al., 2016; Lawrence et al., 2018), and improved estimates of sea ice freeboard (Skourup et al., 2017). Combining data and models has allowed us, for example, to explain key signals of climate change such as variability in Arctic sea ice thickness (Tilling et al., 2015; Stroeve et al., 2018; Robson etal., 2018) and variability in the Arctic and Southern Oceans (Armitage et al., 2017; Dotto et al., 2018), and to improve forecasts of sea ice extent (Schröder et al., 2014, Allard et al., 2018).

School of Geographical Sciences, University of Bristol

http://www.bristol.ac.uk/geography

Resolving Antarctic ice mass trends (RATES) Martín-Español et al. (2016) assessed recent estimates of glacial isostatic adjustment (GIA) for Antarctica, including those from both forward and inverse methods. The assessment was based on a comparison of the estimated uplift rates with a set of elastic-corrected GPS vertical velocities observed from an extensive GPS network and computed using data over the period 2009–2014.

Regional glacial isostatic adjustment and CryoSat elevation rate corrections in Antarctica (REGINA) Researchers from the University of Bristol worked with partners from three other institutions (GFZ, TU Munich and U Newcastle) to provide a regionally refined estimate of glacial-isostatic adjustment (GIA) in Antarctica from space-geodetic measurement (GOCE, GRACE, GPS and satellite altimetry), as well as advanced modeling of the solid Earth. Making use of the different sensitivities of the respective satellite observations to current and past surface-mass (ice mass) change and solid Earth processes, the ESA-funded REGINA project estimated GIA based on viscoelastic response functions to disc load forcing, compared this GIA estimate with published GIA corrections and evaluated its impact in determining the ice-mass balance in Antarctica from GRACE and satellite altimetry (Sasgen et al., 2018).

Global land ice, hydrology and ocean mass trends (GlobalMass) Schumacher et al. (2018) developed a fully-automated strategy to post-process GPS measurements and to correct for non-GIA artefacts. The output is a dataset of ~4000 GPS time series which provides an observational estimate of global GIA uplift rates and which is hence suitable for validating global GIA forward models. The dataset will subsequently be used in the ERC-funded GlobalMass project to combine global geodetic data on GIA, ice mass and hydrological mass changes, changes in sea level (e.g. from GRACE and altimetry) and prior information from geophysical models within a Bayesian statistical framework (Sha et al., 2018) to offer new insights about the different contributors to sea level rise on regional and global scales.

School of Geographical & Earth Sciences, University of Glasgow

Elizabeth.Petrie@glasgow.ac.uk

Stockamp et al. (2016) and Stockamp (PhD, 2018) investigated the possibility of detecting glacial isostatic adjustment using InSAR in Scotland.

National Oceanography Centre

http://noc.ac.uk/

Please see the bibliography for details.

14. VERTICAL DATUMS

[No activities reported]

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The Royal Society
6-9 Carlton House Terrace
London SW1Y 5AG, UK
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http://www.iag-aig.org/

The International Union of Geodesy and Geophysics
http://www.iugg.org/

School of Engineering,
Newcastle University,
Newcastle NE1 7RU, UK
http://www.ncl.ac.uk/