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RESEARCH ON GEODESY

2011 – 2014

Presented to the International Association of Geodesy at the XXVIth General Assembly of the International Union of Geodesy and Geophysics, Prague, Czech Republic, June 2015

Prepared on behalf of the Royal Society by the
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FOREWORD

This report outlines United Kingdom activities in geodesy for the period January 2011 to December 2014. It has been prepared for submission to the International Association of Geodesy (IAG) at its General Assembly in Prague, Czech Republic, during the XXVIth General Assembly of the International Union of Geodesy and Geophysics (IUGG) in June-July 2015.

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

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.

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June 2015

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1. SATELLITE LASER RANGING

NERC Space Geodesy Facility (SGF)

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

The Space Geodesy Facility is located at Herstmonceux, UK, with funding from the Natural Environment Research Council and the UK Ministry of Defence. In April 2013 management of the Facility transferred to the Hazards and Observatories Directorate of NERC's British Geological Survey (BGS). It is an observational and analytical facility with a highly productive and precise Satellite Laser Ranging (SLR) system, two continuously operating IGS GNSS receivers, one of the UK Ordnance Survey GeoNet GNSS receivers, FG5 absolute gravimeters and one of BGS' broadband seismometers that automatically contributes in realtime to BGS' British Isles seismic network. A very stable active hydrogen maser frequency source drives the timing systems of both the SLR and the long-running HERS GPS/GLONASS receiver. On-site automated meteorological, atmospheric and water table depth observations augment the geodetic observations. The Facility is an International Laser Ranging Service (ILRS) Analysis Centre.

The system is a 'new generation' ILRS station, making daytime and nighttime range measurements to geodetic, gravity-field, altimeter and GNSS satellites at heights of from 300 to 23,000km. The precision of the range normal points is about 1mm, and the station is ranked among the top five or six in the ILRS global network in terms of data productivity and close to the best in terms of accuracy. The two-laser system is unique in the ILRS worldwide network. One laser is a modern short-pulse, high repetition-rate (2 kHz) instrument, which, in combination with the high-precision event timer, delivers single-shot ranging precision at the 3mm level. The original 10Hz laser remains in operation when required for specific applications such as the LiDAR capability, and was also used regularly for one-way ranging support of the NASA Lunar Reconnaissance Orbiter, which programme came to an end in 2014. Modelling work done by SGF has improved to the mm level of accuracy the corrections required to relate the Herstmonceux 2kHz laser measurements to the centres of mass (CoM) of the geodetic spherical satellites, and this work has been extended to include observations made by the primary ILRS systems. Site- and time-specific tables of CoM values and accompanying software have been developed by SGF and are in use by all ILRS Analysis Centres.

A major investigation into the range accuracy achieved by the stations of the ILRS has been carried out and reported extensively. The work confirms that the SGF policy of working at single-photon return level from the LAGEOS geodetic satellites delivers a world-beating 1 or 2 mm range accuracy. The work also finds that systematic range error at a level of about 5mm in some major stations, caused probably by limitations in the instrumentation as well as error in the appropriate CoM values, impacts on the scale of the ITRF, which is determined by a combination of the SLR and VLBI techniques. The SGF results suggest that elimination of the range error will bring the ILRS and VLBI scales closer together.

Laser tracking of the GNSS satellites continues to increase in importance for the ILRS and IGS communities as new constellations are developed that include laser retro-reflectors on each vehicle for independent orbit determination and quality control. At the 18th International Workshop on Laser Ranging in Japan in November 2013, the ILRS agreed to expand the GNSS data coverage from the ILRS network, and a Study Group 'LAser Ranging to GNSS s/c Experiment' (LARGE) was set up both to define an operational GNSS tracking strategy for the ILRS that addresses all proposed requirements and then tests its realization with a tracking campaign to be run as a Pilot Project, and clarify outstanding ILRS and IGS issues with the GNSS satellites and ground stations. G. Appleby

from SGF is a member of the Study Group. Currently, all 24 Russian GLONASS, eight European Galileo, four Chinese COMPASS and four Indian IRNSS vehicles are tracked from Herstmonceux and by many of the more productive ILRS stations.

The Facility is an ILRS Analysis Centre and daily computes using SGF's SATAN analysis suite seven-day global station coordinates and daily Earth orientation parameters in support of the ILRS' contribution towards ITRF realisation work and rapid Earth orientation results for the IERS. A re-analysis of all global laser data taken since 1983 to the geodetic (two LAGEOS and two ETALON) satellites has been completed, taking account of historical range corrections and other modelling issues, for the SGF contribution to the laser ranging effort for ITRF2014, that will be published by the IGN in late-2015.

G Appleby served two two-year terms as Chair of the ILRS Governing Board up until November 2013. M Wilkinson was elected as an at-large member of the Board in November 2013.

March 2013 was the 30-year anniversary of the first laser ranging measurements conducted at Herstmonceux. In 1983 the state-of-the-art range precision was 35 mm, and the Starlette and LAGEOS satellites were the only routine geodetic targets.

2. GLOBAL NAVIGATION SATELLITE SYSTEMS

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Real-time and kinematic positioning. Assiadi et al (2013) demonstrated that a local ionospheric zenith delay correction, generated from code pseudorange measurements at a receiver, could improve single-epoch relative position solutions obtained via an ambiguity search algorithm over long (60-120 km) baselines, from 30-50 cm in the uncorrected case to 10 20 cm median absolute deviation.

Systematic Errors. GPS signal modelling studies have focused on the propagation of unmodelled subdaily signals into spurious long period signal, including multipath and monument-antenna effects (King et al, 2011; Goebell & King, 2011). Gazeaux et al (2013) performed a community experiment to investigate the detectability of offsets in synthetic GPS coordinate time series with realistic noise properties, using both manual and automated time series analysis. Manual analysis continues to outperform automatic, although neither approach can be considered robust to within 0.5 mm/yr.

2a. GNSS – ATMOSPHERIC STUDIES

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Troposphere. Thomas et al (2011b) compared GPS, in situ and remotely sensed estimates of atmospheric water vapour over Antarctica. Penna et al (2012) examined tropospheric delay models for use in kinematic positioning over wide ranges in altitude, by comparing their effect on

positioning accuracy over a repeated trajectory on board a train traversing 1 km of relief on the Snowdon Mountain Railway.

Ionosphere. Petrie et al (2011) provided a review of higher-order ionospheric refraction effects on GPS. Keshin (2012) developed a new method for differential code bias estimation using a single GPS receiver and global TEC maps.

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*

CGPS near real-time processing for meteorology: As reported in the IUGG report on UK Research on Geodesy 2007-2010, 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 version 5.0. 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 is a move from processing data every hour to processing data every 15 minutes, thereby reducing the latency of the output so that the estimates are not just useful for assimilation in numerical weather prediction runs that take place every few hours, but can also be used in relation to severe weather events, such as thunderstorms. Since 2011, parallel systems to those that run at the UK Met Office have also been running as part of the NERC British Isles continuous GNSS Facility (BIGF), which is funded by the UK's Natural Environment Research Council (NERC) and 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 from the NERC BIGF for further scientific research. Furthermore, the original system has also been adopted by the University of Luxembourg, and used as the basis for comparison with real-time precise point positioning tropospheric ZTD estimates, as detailed in Ahmed et al. (2014).

2b. GNSS – ENGINEERING APPLICATIONS

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Newcastle University have produced a revised set of Best Practice Guidelines for using Network RTK in Great Britain, through a study commissioned by The Survey Association, Ordnance Survey, Leica Geosystems, Topcon and Trimble (Penna et al, 2012; The Survey Association, 2012). These

guidelines expand the previous edition to include further comparison of GPS-only and GPS+GLONASS positioning, and extensive testing in RTK detailing mode in a variety of real urban and semi-urban environments.

2c. GNSS – OCEANOGRAPHIC STUDIES

National Oceanography Centre

http://noc.ac.uk/

GNSS-Reflectometry for ocean remote sensing. Working in partnership with Surrey Satellite Technology Ltd (SSTL), NOC contributed to the development of new spaceborne GNSS receivers and algorithms for the exploitation of reflected GNSS signals for ocean remote sensing (Unwin et al., 2013). The interest in GNSS-R for ocean monitoring stems primarily from the low-cost, low-mass, low-power characteristics of GNSS-R receivers, which could lead to affordable multi-satellite constellations able to deliver dramatically improved space/time sampling to complement existing ocean surface observations from satellite scatterometers and altimeters. NOC and SSTL recently confirmed the capabilities of low-cost, low-mass, low-power GNSS-R receivers for wind monitoring with the low-earth-orbiting UK TechDemoSat-1, launched in July 2014. The results give new confidence in the technique ahead of the launch of the NASA Cyclone Global Navigation Satellite System (CYGNSS) mission in 2016, for which NOC is part of the Science team. Elsewhere, NOC also worked with GFZ and ESA to assess the performance of GNSS-R for ocean mesoscale altimetry and scatterometry in a project linked to the GEROS-ISS mission which aims to launch GNSS-R receivers on the International Space Station in 2019.

3. NATIONAL AND CONTINENTAL NETWORKS

National Oceanography Centre

http://noc.ac.uk/

National Tidal and Sea Level Facility (NTSLF), *http://www.ntslf.org/* . Based at NOC, NTSLF manages the Class A network of 42 tide gauge sites around the UK on behalf of the Environment Agency. The tide gauge data from this network are used for operational coastal flood warning as part of the UK Coastal Monitoring and Forecasting partnership. The data are also available through the British Oceanographic Data Centre (BODC) and the Permanent Service for Mean Sea Level (PSMSL).

UK South Atlantic Network. In 2015, NOC is marking 30 years of measuring sea level in the South Atlantic. The UK South Atlantic network is comprised of tide gauges at islands in the South Atlantic, as well as in Antarctica and Gibraltar. All of these tide gauges contribute to the Global Ocean Observing System (GLOSS), providing data in a sparsely-sampled region. The network also provides important measurements in monitoring the Southern Ocean (Meredith et al., 2011). NOC has been working with the University of Luxembourg to start and improve collection of GNSS data with levelling ties to the tide gauges at several of the sites in the South Atlantic.

Permanent Service for Mean Sea Level (PSMSL), *http://www.psmsl.org/* . Hosted at NOC, the PSMSL is responsible for the collection, publication, analysis and interpretation of sea level data

from the global network of tide gauges (Holgate et al., 2013). From 2011 through 2014, we added or revised 10,611 station-years of tide gauge data, introduced a new set of ocean bottom pressure products, and made numerous improvements to the website, such as links from each station to related data at other GLOSS centres. The PSMSL also provides a lead in management of GLOSS and has assisted with network development, particularly in Africa.

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*

The British Isles continuous GNSS Facility (BIGF). The NERC British Isles continuous GNSS Facility (BIGF) is funded by the UK's Natural Environment Research Council (NERC) and based at the University of Nottingham. 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, tropospheric integrated water vapour and ionospheric activity, to facilitate scientific users who are interested in these parameters but do not want to carry out their own high-level processing of GNSS data. 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. Users can request data and derived products using an online form and the service provided can be summarised in a 4-part Facility remit:

1. To provide an assured repository of data and derived products, so that the costs of users setting up an ad-hoc observation network and/or deriving their own products for research are reduced or eliminated.

2. To facilitate improvements in positioning quality for historic or current research, by providing reference station data, protecting researchers from the costs and delays of having to repeat data collection exercises.

3. To facilitate the least time delay in the examination of environmental and other variables, by providing extensive backward tracts of data and/or derived products for research.

4. To inform and stimulate the research community across the spectrum of science using various media.

Data are sourced from a network of over 150 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 3 months. These collaborators include the three national Ordnance Surveys (Great Britain (OSGB), Ireland (OSi) and Northern Ireland (OSNI)), Leica Geosystems Ltd., the Met Office, the University of Nottingham, the Environment Agency Thames region, the NERC Space Geodesy Facility, Newcastle University and the University of Hertfordshire, with the University of Nottingham's contribution being carried out in collaboration with the NERC National Oceanography Centre, Liverpool and the NERC British Geological Survey. The archive currently comprises 1,730 station-years of 30 second GPS, and GPS+GLO, data, and 617 station-years of 1Hz GPS+GLO data, with 158 CGNSS stations currently continuing to upload hourly [141/158] and/or daily [158/158] RINEX files of GPS only [16/158] or GPS+GLO [137/158] or GPS+GLO+GAL [5/158] data to the archive, at 30s [158/158] and 1Hz [114/158] data rates, as a nominal 58k station-days a year. The 5 with 'full GNSS capability' include 4 stations at tide gauges upgraded in 2013/14, with equipment funded by NERC in 2011/12, and 1

new station installed by the Met Office. Of the 158 CGNSS stations, this includes three stations (HERS, HERT, MORP) that are part of the International GNSS Service (IGS), and eleven stations (BELF, CSTB, DARE, ENIS, FOYL, HERS, HERT, INVR, MORP, NEWL, TLLG) 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) are included in the IGS TIGA Project, 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 1998/9 to 2014/15 was approximately 9,419k station-days (25,788 station-years), to about 1,000 discrete projects, comprising of approximately 5,697k stations-days (15,598 station-years) of 30 second data, 15k station-days [41 station-years] of 1Hz data and 3,707k product-days (10,149 station-years) of derived products, with the 1Hz data and the derived products having been available for 4 years. Details of the use of the derived products by BIGF in associated scientific research are given in sections 2a, 12 and 13.

NERC Space Geodesy Facility (SGF)

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

The two IGS stations HERS and HERT remain in continuous operation, with HERT, a Leica GRX GG Pro system, also streaming GPS and GLONASS navigation data into the Internet in support of the EUREF-IP and IGS Real-time Projects. The HERS GPS/GLONASS Septentrio Timing receiver continues to be driven by the active hydrogen maser and is now processed by sufficient numbers of IGS ACs to be included in the combination product. As a result, the HERS data is amongst the highest-weighted clocks in the IGS final clock product. The Ordnance Survey GeoNet system HERO, installed by the OS in 2009 close to the SOLA trig pillar, continues to be fully operational and has become useful as a fourth site for local stability monitoring work. A detailed investigation into the site-wide inter-technique stability is reaching the conclusion that the site is stable vertically at the sub-mm level, but that the HERS tower is subject to thermal expansion of a few mm on diurnal and seasonal timescales, in agreement with a model of the structure.

Ordnance Survey of Great Britain

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

Ordnance Survey's national RTK GPS network OS Net™ has been developed since 2003 and now covers the whole of Great Britain with more than 120 stations. Current European permanent network (EPN) submissions from OS Net include hourly data from DARE and INVR (previously 24 hour files). It is still intended to ultimately submit all the OS Net stations that were part of EUREF GB/IE 2009 stations as EPN stations and submit hourly data from them as well. It was hoped to do this in the last year but the extra work involved in moving from virtual to physical servers has meant a delay. RTCM 3.0 data from EPN stations DARE, INVR and from OS Net station SHOE are streamed in real time via NTRIP.

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Newcastle University continues to contribute to the International GNSS Service as an Associate Analysis Centre, providing weekly (and since 2013, daily) global coordinate combinations in parallel with the official IGS product. The IGS08 reference frame is now being used to align the weekly solutions. Booker et al (2013) used combination solutions from the first IGS reprocessing experiment, in tandem with forward models of glacial isostatic adjustment, to derive secular trends in surface mass loading and Euler poles for the major tectonic plates. We continue to operate

IGS/EPN site ‘MORP’ (Morpeth) and TIGA site ‘NSLG’ (North Shields Tide Gauge), both of which contribute to the NERC ‘BIG F’ data repository.

4. INTEGRATED SYSTEMS AND INERTIAL NAVIGATION SYSTEMS

No activities reported.

5. SATELLITE ALTIMETRY

National Oceanography Centre

http://noc.ac.uk/

NOC has contributed for several decades to research and development in satellite altimetry and oceanographic applications of altimetry data. NOC staff continue to be valued members of the international altimetry community. In recent year NOC has been at the forefront of the new field of SAR Altimetry (Ray et al., 2014) and Coastal Altimetry (Vignudelli et al, 2011; Gommenginger et al., 2011), concerning methods for improving measurements of sea level, significant wave height and wind from altimetry close to the coast, and the many applications enabled by those improved measurements. In particular NOC has contributed to the design and implementation of a new technique for processing the altimetric returns in the coastal zone (Passaro et al., 2014, 2015a) and its application to sea level studies (Passaro et al., 2015).

As development of coastal altimetry continues to improve, improved estimates of the “inverse barometer correction” are needed in the analysis of the data. Woodworth and Horsburgh (2011) find that storm surge models, commonly employed by operational flood forecasting centres, can provide the best estimate of this correction and suggest the collection of regional dataset or development of global barotropic models for this purpose.

NOC is also contributing to the Sea Level Climate Change Initiative funded by the European Space Agency to ensure the accuracy of long-term measurements of Sea Level from the existing and planned constellation of altimeters (Ablain et al., 2015)

NOC staff are expert in the technical details and oceanographic applications of the new SAR altimeter, thanks to their significant involvement with the SIRAL instrument on ESA’s CryoSat-2 mission via the ESA SAMOSA and CP4O studies (Ray et al., 2014). The SAR altimetry technology, which has improved precision and along-track resolution with respect to conventional altimetry, has been adopted also for the forthcoming SRAL altimeter on Sentinel-3, and NOC have led the design and specification of the SRAL Detailed Processing Model. In parallel to these activities, NOC have been tasked by ESA to carry out the global validation of conventional ocean products from CryoSat-2 using NOC’s expertise in altimetry for oceanography and first hand access to a vast range of in situ data (including tide gauges, floats and HF radars) and models.

On the coordination side, NOC staff continue to co-organize the international Coastal Altimetry Workshops as they have done since 2008 (Paolo Cipollini is the chair of the organizing committee for the 9th edition of the Workshop which will take place near Washington, US, in October 2015).

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Berry et al (2012) demonstrated inland water altimetry by retracking of burst echoes from Envisat. Birkinshaw et al (2013) used retracked radar altimetry data to observe inland water level changes at a number of ungauged river sites. Pereira-Cardenal et al (2011) investigated the possibility of using such data in real time. Moore & Williams (2014) used retracked radar altimetry data to observe inland water level changes at a number of sites in Africa, and compared these with surface water mass changes inferred from GRACE gravity data.

6. SYNTHETIC APERTURE RADAR

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

Li et al (2013) and Jolivet et al (2014) demonstrated improvements in InSAR deformation monitoring using tropospheric delay and geoid models respectively. Qu et al (2014), Wang et al (2014), Fielding et al (2013), Walters et al (2013), Zhang et al (2013), Wen et al (2014) and Feng et al (2013, 2014) used InSAR to observe co-seismic and inter-seismic strain associated with fault movements at a variety of locations in the Alpine-Himalayan belt and south-east Asia. Singleton et al (2014) used SAR image co-registration to observe episodic landslide displacements in vegetated terrain, whereas Liu et al (2013) and Tomas et al (2014) used a combination of InSAR techniques for this. Liu et al (2015) used InSAR imagery to observe vertical land motion associated with hydrocarbon extraction in SE Asia.

Smith & Berry (2011) evaluated the differences between SRTM and radar altimetric height measurements used in global digital elevation models.

7. SATELLITE ORBIT AND GRAVITY FIELD DETERMINATION

National Oceanography Centre

http://noc.ac.uk/

Gravity Recovery and Climate Experiment (GRACE) non-sea-level studies. Working with Newcastle University, NOC has examined autocorrelations in the mass trends and accelerations derived from the Gravity Recovery and Climate Experiment (GRACE) satellite data. In the case of solutions over Antarctica (Williams et al., 2014), the results indicate that uncertainties estimated assuming white noise are too small by a factor of up to four for accelerations and six for linear rates. The analysis was also utilised in an analysis of terrestrial water storage in Africa (Moore and Williams, 2014).

Future space missions. Panet et al. (2012) set out challenges and scientific return for a proposed future gravity mission, e.motion.

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Andrews et al (2015) reviewed methods of determining such surface mass changes from GRACE data, and showed distinct advantages of the mascon approach.

8. GRAVITY SURVEYS

National Oceanography Centre

http://noc.ac.uk/

Absolute gravity measurement. While regular absolute gravity measurement near the tide gauge sites in Newlyn, Lerwick, and Aberdeen ceased in 2010, collaborations continue with NERC Space Geodesy Facility on their measurement at Herstmonceux and Eskdalemuir, and we have used the data to examine vertical deformation in western Europe (Van Camp et al., 2011).

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

National Oceanography Centre

http://noc.ac.uk/

Tidal research. At Loch Ness, Pugh and Woodworth (2011) observed the loch tide, which primarily originates from ocean tide loading and whose M2 constituent is approximately 1.5 mm. The loch provides a very effective tilt meter, being able to obtain an accuracy of better than 10-8 over 35 km. The observed results, despite their accuracy, did not require changes to Earth tidal models in order to be in agreement with predictions. Woodworth (2012) explored the ability of nodal tide to be removed from tide gauge records. Torres and Tsimplis (2011) examined tides in the Caribbean Sea and Pickering et al (2012) examined the impact of future sea level rise on tides.

NERC Space Geodesy Facility (SGF)

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

In March 2015 the gravity measurement campaign using SGF absolute gravimeter FG5-X#229 was reconfigured to provide one set of monthly data instead of the weekly measurements that have been carried out since installation in 2006; the decision was taken to preserve the operational lifetime of the instrument between services. The instrument was also used in a successful few days' campaign at BGS Eskdalemuir in November 2014, where it was operated for 53 consecutive hours in order to make a comparison with the results previously taken at the site using the two NOC gravimeters. These instruments have been since 2014 on long-term loan at SGF, where their condition and serviceability was assessed. Given that the necessary funds are made available for essential electronic upgrade and services, it is planned to use the two NOC gravimeters in collaborative campaigns, with the AG lab at SGF the valuable pre- and post-campaign calibration node.

Internationally, to improve the traceability of AG measurements to fundamental standards, the geodetic and metrological communities have combined to produce a strategy document for comparisons of AGs, known as CCM-IAG Strategy for Metrology in Absolute Gravity. This document outlines the accepted protocols for comparisons of AGs and is important for the future of AG measurements and for collaboration between the two communities. The strategy was accepted by the IAG in March 2015.

10. GEOID DETERMINATION

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

The EGM2008 geoid has been assessed in relation to historical data in Great Britain (Featherstone & Olliver, 2013). Work is in progress on a unified East African (Kenya, Tanzania, Uganda) high-resolution (1-minute) gravimetric geoid, using the latest geopotential and terrain models, and supported by GPS observations.

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Dayoub et al (2012) estimated the Gauss-Listing parameter W0 and its rate of change, using tide gauge, GPS and GRACE data around the UK, the Baltic Sea and globally. Results were used to show how vertical datums could be unified across a range of spatial scales. Penna et al (2013) reconsidered the apparent British sea slope, using levelling-based Ordnance Datum Newlyn heights of benchmarks, EGM2008 quasi-geoid data and GNSS observations at selected tide gauges and benchmarks, and concluded that the apparent slope is caused by the vertical geodetic datum.

11. DEFORMATION MONITORING

University of Nottingham Ningbo, China

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

The University of Nottingham Ningbo, China (UNNC) is a campus of the University of Nottingham. UNNC has been in operation for 10 years, and currently has approximately 6,500 students. The campus plans to expand to 8,000 by 2020, including approximately 20% international students and 20% postgraduate students. A surveying and geodesy group has been established within the department of civil engineering.

Activities focus on engineering surveying; GPS/GNSS; deformation and deflection monitoring of large structures using GNSS; the integration of multi-GNSS, in particular BeiDou; photogrammetry; and laser scanning. The location enables access, in addition to the global systems, to the full BeiDou constellation, including the MEO and IGSO, as well as QZSS, MSAS, GAGAN and future IRNSS.

UNNC participated in the European Space Agency Competition “Listen to the Song of Galileo Signals” and were awarded a certificate as one of the first 50 institutions to position using the system.

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Martin et al (2014) developed a low-cost semi-autonomous GPS receiver/antenna/telemetry/power system suitable for rapid deployment in extreme environments, and demonstrated its use for the study of glacial calving events on the Helheim Glacier, SE Greenland.

School of Earth and Environment, Leeds University

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

Work at Leeds has concentrated on using synthetic aperture radar interferometry to measure deformation associated with volcanic and tectonic activity. A particular focus has been the Afar region of Northern Ethiopia, where a series of dyke intrusions have been intruded along the plate boundary. Other work has focused on the North Anatolian Fault in Turkey; China, Japan and Iceland.

12. MEAN SEA LEVEL STUDIES

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

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Monitoring of vertical land movements at tide gauge sites in the UK: As reported in the IUGG report on UK Research on Geodesy 2007-2010, 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, Liverpool (formerly Proudman Oceanographic Laboratory), since 1997, with Teferle et al. (2009) and Woodworth et al. (2009) presenting 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, and Woodworth et al. (2010) presenting estimates of long term and recent changes in sea level in the Falkland Islands. Since 2009, this research has been an integral part of the NERC British Isles continuous GNSS Facility (BIGF), which is funded by the UK's Natural Environment Research Council (NERC) and based at the University of Nottingham (Hansen et al., 2012). 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 the NERC BIGF based on a CGPS re-processing of data from 1997 to 2014:180 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 latest 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 SHEE in 2013, while five of the ten have been upgraded to have 'full GNSS capability', namely ABER, LWTG, NEWL, NSLG, and SWTG. Woodworth et al. (2009) determined estimates of changes in mean sea level (decoupled from vertical land movements, based on CGPS) around the coast of Great Britain over the past few decades/past century of +1.06±0.16mm/yr and estimates of changes in mean sea level (decoupled from changes in land level, based on Holocene geological studies) around the coast of Great Britain over the past few decades/past century of +1.37±0.24mm/yr, and concluded that there had been a 1.4mm/yr regional sea level rise of climate change origin, which was several one-tenths of mm per year lower than global estimates for the 20th century. When the latest NERC BIGF results are considered, these lead to revised estimates of changes in mean sea level (decoupled from vertical land movements, based on CGPS) around the coast of Great Britain over the past few decades/past century of +1.35±0.46mm/yr, equating to estimates of changes in mean sea level (decoupled from changes in land level, based on CGPS and a consideration of the change in the geoid) around the coast of Great Britain over the past few decades/past century of about +1.75mm/yr, which is more in line with global estimates for the 20th century. The NERC BIGF derived products of daily station coordinates, and station velocities, for the stations at tide gauges are available from the NERC BIGF for further scientific research, and research in this field is continuing in collaboration with the NERC National Oceanography Centre, Liverpool, as in Tamisiea et al. (2014).

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Sea-level research. Taking a lead from hosting of the PSMSL, NOC has conducted a large number of mean sea level (MSL) studies. These studies cover a large range of time scale, from centennial to annual. Several areas of specialism exist within this set. A number of papers focus on the centennial evolution of sea level, examining salt marsh and long-term tide gauge records and creating global reconstructions. Several papers explore dynamic ocean influences in sea level, and in particular how these processes influence sea level observed at the coasts. In addition, we investigate the variability in the records and the impact this variability has on our ability to determine long-term trends. We also examine external drivers to sea-level change, such as ice mass water loss from the continents and glacial isostatic adjustment. The studies cover a range of observational techniques (tide gauges, ocean bottom pressure, altimetry, satellite gravity mission, GNSS, and absolute gravity), and we wrote an introductory review paper highlighting how these different geodetic techniques contribute to our understanding of MSL change (Tamisiea et al., 2014). Not included in the reference list, but important companion studies to mean sea level changes, are a number of papers on projections and observations and modelling of extreme events.

Community participation and leadership. NOC contributed a Lead Author and a Review Editor to Chapter 13 "Sea Level Change" of the IPCC AR5. The Permanent Service for Mean Sea Level (PSMSL) continues to provide a leadership role in Global Sea Level Observing System (GLOSS), and hosted a workshop to celebrate its 80th anniversary before hosting the 13th Session of the GLOSS Group of Experts in Liverpool in 2012. NOC also participated in the leadership of the GGOS Theme 3 "Sea-Level Rise and Variability". NOC also contributed by participating in various selection panels, including the AXA-Fellowships environmental panel (2014 and 2015), the selection panel for ANR (2014 for post-doctoral positions; 2015 for post-doctoral positions and research proposals) and the advisory board for the sustainable development of Mediterranean coastal areas.

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Bingham & Hughes (2012) have investigated effects of seafloor and coastline topography on local sea level rise. King et al (2012a) have investigated effects of local and regional vertical land movements on tide gauge estimates of regional sea level rise. King et al (2012b) have used a GPS-validated model of Antarctic glacial isostatic adjustment to provide improved estimates of the Antarctic ice sheet's contribution to present-day sea level change, derived from GRACE time-variable satellite gravity measurements.

13. GEOPHYSICAL, GLACIOLOGICAL, AND OCEANOGRAPHIC APPLICATIONS OF GEODESY

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

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Map of current vertical land movements in the UK. As reported in the IUGG report on UK Research on Geodesy 2007-2010, 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, as published in Teferle et al. (2009) and used in Bradley et al. (2009). Since 2009, this research has been an integral part of the NERC British Isles continuous GNSS Facility (BIGF), which is funded by the UK's Natural Environment Research Council (NERC) and based at the University of Nottingham (Hansen et al., 2012). The latest map of current vertical land movements was created by the NERC BIGF based on a CGPS re-processing of data from 1997 to 2014:180 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 NERC BIGF map of current vertical land movements includes 158 CGNSS stations that had time series >4.7 years, in order to incorporate 10 of the 12 OSGB GeoNet CGNSS stations that were all installed in late-2009 and connected to solid rock. From a visual inspection, it can be seen that the latest NERC BIGF map shows the expected general pattern of uplift in Scotland and Northern England (to maximum of +1.7 mm/yr) and subsidence in Wales and Southern England (to a minimum of -1.4 mm/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 NERC BIGF derived products of daily station coordinates, station velocities, and maps of current vertical land movements, are available from the

NERC BIGF for further scientific research. Two examples of how the vertical station velocities for specific CGNSS stations have been used are firstly, to validate land motion in the urban area of Nottingham observed by ENVISAT-1 (Leighton et al., 2013), and secondly, to enable the geological interpretation of current subsidence and uplift in the London area, UK, as shown by high precision satellite-based surveying (Aldiss et al., 2014).

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GNSS time series analysis. Integral to many of the analyses is understanding the GNSS time series. Working with Newcastle University Gazeaux et al. (2013) examined the ability to detect realistic offsets in GNSS time series, which impacts the ability to recover long-term trends. Montillet et al. (2014) looked at using offsets in studies of earthquake deformation. Davis et al. (2012) explored the influence on the variable seasonal cycle in time series analysis.

Geophysical, Glaciological, and Oceanographic Applications. Two studies explored the deformation caused by non-tidal ocean loading and the improvement in time series analysis by accounting for this effect (Williams and Penna, 2011; Geng et al., 2012). GNSS was also used in studying the Nubia-Eurasia plate boundary (Serpelloni et al., 2013), and ice mass changes and glacial isostatic adjustment in Antarctica (Thomas et al., 2011).

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Glacio-isostatic adjustment. Vermeersen et al (2011) reviewed the state of the art in modelling and observations of GIA. New results for Antarctic GIA based on a state-of-the-art GPS global reprocessing were provided by Thomas et al (2011). Nield et al (2012) examined the effect of century-timescale ice sheet mass balance on present-day vertical land movement in the Antarctic Peninsula and showed that this could perturb site velocities significantly from the “long-term” GIA rate. Whitehouse et al (2012) used previously-published Newcastle GPS estimates of land movement in Antarctica to calibrate and test a new model of Antarctic GIA which appears to be considerably more accurate than previous models. As the British Geophysical Association’s 2012 Bullerwell Lecturer, King (2013) provided a review of recent progress in the modelling of glacial isostatic adjustment in Antarctica and its implications for the measurement of present-day sea level change. Nield et al (2014) investigated the sensitivity of present-day surface uplift in the Antarctic Peninsula to changes in surface mass balance over the last 1½ centuries, and found that significant viscoelastic deformation over this timescale could partially explain discrepancies between modelled and observed glacial isostatic adjustment rates in this region. Gunter et al (2014) produced a refined empirical model of glacial isostatic adjustment in Antarctica, using a combination of altimetric ice elevation data and GRACE gravity change data.

Cryospheric applications. Makinson et al (2012) investigated the effects of tides on the Ronne Ice Shelf, Antarctica. Sole et al (2011), Bartholomew et al (2011) and Mueller et al (2012) examined more generally the response of glaciers and ice shelves to tidal forcing in their grounding line. A review of the uses of GPS positioning in glaciology was provided by King (2011). Kunz et al (20120 and James et al (2012) have used a combination of geodetic and remote sensing techniques to study glacier mass balance in Antarctica and Svalbard respectively. Shepherd et al (2012), and also King et al (2012), combined GRACE data with GIA models that had been calibrated using Newcastle-reprocessed GPS data, to achieve improved estimates of continental-scale ice sheet mass balance over Antarctica. At large spatial scales, Williams et al (2014) reconsidered the detectability of recent ice mass changes in Antarctica using GRACE gravity field data, once realistic temporal

correlations within the time series had been considered. Joughin et al (2013) and Sole et al (2013) used GNSS data at local scales to investigate seasonal changes in ice flow in Greenland, and Beem et al (2014) used GNSS data at local scales to investigate seasonal changes in ice flow in Antarctica.

Non-tidal ocean loading. Williams & Penna (2011) observed the effects of North Sea storm surge on vertical positions of nearby continuously-operating GNSS sites in northwest Europe.

Volcanological applications. Parks et al (2012) used data from a GPS network established on Santorini volcano (Greece) to examine the evolution of the volcano in terms of the timing and location of magma fluxes.

14. VERTICAL DATUMS

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NOC has taken part in a series of ESA-funded activities as part of World Height System Unification studies (Woodworth et al., 2012). This effort relates to GGOS Theme 1.

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Vertical Offshore Reference Frames (VORF). Sponsored by the UK Hydrographic Office, the VORF project commenced in 2005 with the aim to integrate vertical datums (Chart Datum, MSL, LAT, HAT, ETRF89, ODN etc.) in the offshore and coastal zones. Recent research has focused on the following areas:

1. Studies on the efficacy of VORF in the UK continental shelf which has shown that the transformation models meet the target accuracy (1 ☐ value offshore) for the vast majority of the applicable area [Iliffe et al. 2013].

2. VORF-Global: Extension of the concept to provide a global model defining the relationship between the DTU10 MSS, the EGM08 geoid, tidal levels (LAT, HAT, MLLW, MLWS) and ITRF08 for the zone 12nm and further from land. [Turner et al. 2013].

3. The VORF-Global Coastal Approach Tool (V-CAT) which permits the re-computation of the global transformation models given new/revised observations of tidal levels and/or MSL.

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