Report of UK Geodesy Workshop, Herstmonceux Castle, 18-19 July 2016

Background For many years there has been an informal 'geodesy community' within the UK that met and discussed research issues within the wider geophysical discipline. Such formal and informal bodies as the UK Geophysical Assembly, the British Group of Altimetry Specialists, plus the various incarnations of the Steering Committee that continue to peer-review the Space Geodesy and British Isles Continuous GNSS Facilities (SGF, BIGF), have brought together scientists to exchange ideas and results. Whilst formulating a proposal by SGF to increase the capability of the Herstmonceux site, primarily by adding a VLBI antenna and thus to become an IAG Global Geodetic Observing System (GGOS) Core Site, the opportunity was taken to propose the concept of a UK Centre of Geodesy (CoG) that would formalise and strengthen the UK geodetic community. The SGF's CoG proposal, included in Steering Committee papers in 2014, is attached to this report as **Appendix B**. At the same time, from 2014, the NERC Services and Facilities started to be moved from direct management by Head Office to that from appropriate NERC Centres, with SGF being managed through the Hazards and Observatories directorate within BGS. Further, a NERC strategic need exercise began and is ongoing for the whole portfolio of S&F, based on a wide community consultation.
It was thus timely in 2016 to hold a geodesy workshop, and through the NERC Geodesy and Geophysics Facilities Steering Committee it was agreed that SGF would organise and host the meeting in Herstmonceux Castle, owned by the Bader International Study Centre, in whose grounds the SGF is sited.

Geodesy Workshop, 18-19 July 2016.
The outline concept of the workshop was to invite talks from the UK 'observations' community (BIGF, SGF, Ordnance Survey, COMET) followed by contributed talks on geodetic/geophysical research that depends upon geodetic observations. Attendees from the leading geodesy-based UK HEI Groups, Research Centres and Observational Facilities were invited to the 2-day meeting with the aim of developing a position paper on a vision for the future of UK geodesy. Ample time in the programme was set aside for discussion in order to begin to draft the position paper, based upon the science and ideas that should emerge from the meeting. Places at the meeting had to be limited both by the logistics of the venue and by the need to focus on the main aim of the meeting. A list of the names and affiliations of the 22 non-SGF attendees is given in **Appendix-A** of this report. All SGF team members attended and contributed to at least part of the workshop.

Day 1, Monday 18th July
Following welcome and logistical announcements, David Kerridge gave background information and status of the current NERC Services and Facilities Review process, affecting all 25 S&F, including the BGS Space Geodesy Facility (SGF) at Herstmonceux and the British Isles GNSS Facility (BIGF) at Nottingham. It is a strategic need, existential exercise with NERC soliciting input from a wide community of stakeholders and interested bodies, to be followed by a rebidding process. This process presents an opportunity for the community to raise the profile of UK geodesy and present a joined-up vision to sustain the infrastructure into the future.
This emerging opportunity to repackage the S&F elements of NERC's investment in geodesy was highlighted by BGS' Earth Sector Services and Facilities Advisory Group (ESSFAG) at its

3rd meeting that was held in February 2016. The Advisory Group was tasked with producing a short paper setting out the optimal position for national geodetic capability for the next 10 years, to include what it will look like, what science it will do and where it should be placed within organizational structures. At stake are questions that include whether or not the UK needs its own multi-technique geodetic observatory that contributes to global science through observations and analyses that support the realisation of a global reference frame and precise orbits of EO satellites within that frame.
Within that context, the purpose of this meeting is therefore twofold: to highlight and record through presentations the breadth and value of UK geodetic research; to consider a way forward that recognizes and builds on the underpinning strength and value to research of observational and analytical geodesy as practiced in the UK.

The invited talks were in two categories: those from the UK observational Centres and Facilities and those reviewing science from geodesy with speakers from HEIs and Centres.

The talks from the **Observational Centres and Facilities** were:

Richard Bingley on the British Isles continuous GNSS Facility (BIGF);
Tim Wright on the Centre for Observation and Modelling of Earthquakes and Tectonics (COMET);
Mark Greaves on the UK Ordnance Survey;
Graham Appleby on the Space Geodesy Facility. Herstmonceux (SGF).

The science and review presentations were:

Stephen Millard (UK Hydrographic Office) An overview of Geodesy at the UKHO;
Stuart Marsh (Nottingham University) Ground motion monitoring in the UK;
Terry Moore (Nottingham University) Multi-constellation GNSS Precise Point Positioning;
Pablo J. Gonzalez (University of Liverpool) Contributions of high resolution geodetic measurements to geomechanics problems;
Simon Williams (NOC Liverpool) GNSS Multipath Reflectometry;
Peter Clarke (Newcastle University) GNSS and InSAR research;
Marek Ziebart (University College London) Contemporary Issues in the modelling of satellite vehicle orbit dynamics;
Philip Moore (Newcastle University) Gravity, orbits and SLR research;
Svetlana Jevrejeva (NOC Liverpool) GPS for global and regional sea level studies;
Toshi Otsubo (Hitotsubashi University, Tokyo) A GGOS site in Antarctica?

All the presentations have been made available by the authors, but are not included in this report.

Day 2, Tuesday 19th July

The attendees were tasked with thinking strategically, along the lines of:
- The future landscape of UK geodesy
- Ambitions
- Scientific drivers
- International context
- Where measurement and long-term observation fit

Three breakout groups were created, with attendees from the meeting choosing which one(s) to attend. The Group Themes were: **Ocean + Cryosphere**; **Solid Earth**; **Engineering + Space Science**.
The breakout groups met twice, with an intervening and a final Plenary session to report and share comments and ideas for scoping the discussions.

Each Group summarised its '**Prospectus for UK Geodesy**' discussions, based upon the questions raised by each Group in their brainstorming sessions. The summaries, slightly modified to a common style, are detailed below, preceded by a headline cross-group summary written by GA.

Summary of Workshop Recommendations.

As to be expected, all three Groups touched on many issues in common. This headline summary is an attempt to cover the major points raised.

- Full understanding and acceptance of the fact that geodesy underpins a very large number of geophysical research areas;
- Many examples, including sea-level, ice mass-balance monitoring from space;
- That a consistent, high-accuracy global terrestrial reference frame is crucial in this regard and needs to be maintained long-term through continuous observation;
- Geodetic observatories fundamental in this respect, the best ones having all four space geodetic techniques plus gravity measurements (GGOS Core Sites);
- In the UK there exists a very active geodesy community, from a next generation observatory (SGF/HGO), data archive and analysis facility (BIGF), distributed Research Centre (COMET), several world-class, active academic groups, a National Geodetic Survey (OS).
- Creation of a UK Centre for Geodesy:
    - able to attract funding, carry out doctoral training in both observational techniques and analyses;
    - UK National Capability in geodesy will be jeopardised if there is little investment now in subjects like the analysis of geodetic data
- Leadership of UK Geodesy:
    - This needs to be a group that represents the different elements of UK geodesy. It should be independent, meet regularly (the COMET model is great) and include academic, industrial, UKSA, NCEO, national facilities, government geodesy providers
- Publicity via an annual national geodesy meeting, presentations on UK Geodesy at EGU, AGU, etc.:
    - Dispel image of geodesy as routine, needs-to-be-done, but not exciting or sexy.

Report summaries from the three groups

Ocean and Cryosphere.

Background

One of the most dramatic impacts of climate change is sea level rise and resulting increased flooding hazard in the UK and around the world. Technology developments are opening up new opportunities to understand, predict and mitigate the effects of sea level change at a highly localised level. At the same time, the UK is encountering a gap in its long-term monitoring and underpinning science which feeds into this subject. The agencies which were historically responsible for such underpinning work, the Environment Agency, UK Hydrographic Office and Ordnance Survey, either because of changes in remit or funding constraints, are no longer providing such underpinning. The UK needs both coordinated long-term observations and infrastructure, and a vibrant science community exploiting those observations to provide both fundamental scientific understanding and the answers needed by government, planning agencies and the insurance industry.

- **Challenge**: Sea level and coastal flood risk “in my back yard”, on very local spatial scales. Equivalent to “downscaling” in climate projections, but feeding off new technologies to provide a “hard science” set of predictions and projections.
- **Scientific needs**. Local processes: filling the gap between open ocean measurements and the coast - near-coastal ocean dynamics, effects of rivers, vertical land movement at all length scales. Global contributors: Cryosphere, Hydrology, Ocean thermal expansion.
- **Basic infrastructure needed**: Continuity and development of geodetic satellite network – satellite altimetry, GRACE + GRACE-FO, Sentinel missions, etc. Tide gauges with GNSS monitoring and proper geodetic ties, fit for purpose for future needs. Coordinated GNSS and InSAR mapping to determine vertical land movement. Ocean models and geoid models. Precise, accurate and stable reference frame determination (VLBI, DORIS, SLR, GNSS).
- **New opportunities**: Fine resolution combination of GNSS/InSAR for precise, local vertical land movement; local ocean dynamics and near-coastal sea level variations (e.g. river influence); next generation 3D GIA modelling.
- **Required developments**: Coordinated geodesy infrastructure to allow us to make these products. Use of GNSS reflectometry, airborne gravity (CAGE?), with ties to accurate ground-based tie points, GNSS wave-gliders, geodetically-consistent ocean models. **Future development** – accurate clocks for direct determination of

geopotential at a point. Development of a geodetic network of ground stations and techniques towards GGOS goals to underpin reference frame requirements.

- **Education**: Geodesy Doctoral Training Centre.
- **Collaboration**: Create a COMET-Like network or **Geodesy Centre**. Annual meeting. Explore interface with the Geophysical Association.
- **Funding for basic infrastructure**: Long-term infrastructure needs coordinated support. Argue for some of Ordnance Survey and Hydrographic Office profits to government to be reinvested into underpinning infrastructure for future application. NERC to continue support for services and facilities.
- **Funding for new science**: NERC large grant proposal. SPAG proposal.

Solid Earth

What is the UK solid Earth science demand?

- The precision and accuracy of the reference frame must reach 1 mm and sub-mm for velocities (see GGOS document and Sustainable Development Goals).
- Improved models required of the Solid Earth behavior from time scales of from seconds to hundreds of years.
- Separate and identify the different phenomena (solid earth and non-solid Earth) deformation processes to improve understanding of phenomena of interest to society at large.
- Increase the types of observational data from altimetry, tide gauges (sea-level), GNSS, gravity, InSAR that are applied to UK problems.

Challenges:

- Increase spatial and temporal resolution, precision and timeliness of geodetic measurements and analysis techniques.
- Capability to monitor and understand land and seafloor motions due to different processes (e.g., able to separate tectonics and non-tectonics). Dynamic topography, UK crustal motion community model (from different institutions and expertise)
- Rapid response to geo-hazards (visualization and analysis in real-time). e.g., coastal management, flood monitoring, landslides, subsidence, etc.
- Transition from a description of kinematics of land motion to a comprehensive model of how the motion behaves in the way that it does (see also the UNAVCO model).
- Big data is a challenge in itself (Geodetic observatory)
- Improve water vapor estimation for atmospheric science, meteorology and the metrological aspects of geodetic analysis.

What facilities we need:

- Linkages to the ITRF and increase densification of the UK regional/local Reference Frame for scientific and other uses. -> Maintain the SGF and SLR capability.
- 21st century vertical datum requires absolute and relative gravity networks, with additional sites in continuous mode for absolute gravimetry and GNSS support for

national airborne gravity survey.

- Interoperability and tight integration of GNSS, tide gauges, leveling and InSAR techniques at core sites (GNSS network), realized for example via active transponders and corner reflectors.
- Data facilities: Central repository(ies) for EO data, GNSS data (validated before storage) and links with international datasets. UK data does not work in isolation but as part of large collaborative projects. The SGF is a fundamental player in these initiatives, Herstmonceux is a core site!
- SLR (Herstmonceux): Recent NASA study suggests that three sites in Europe are necessary to reach GGOS goals, but under an assumption that all sites are of equal quality. The two world-leading SLR sites in terms of data accuracy are Matera (Italy) and Herstmonceux (UK). SGF is also highly competitive in terms of tracking different satellites, number of tracks, continuity/temporal density.

Education / training / capabilities:

- Need to train at doctoral level to maintain the capacity to do all the required activities. Education of young scientists.
- Increase public awareness (the important role of geodesy in a wide variety of subjects).
- UK National Capability in geodesy will be jeopardised if there is little investment now in subjects like the analysis of geodetic data. e.g., just one/two PhD on SLR in Newcastle. Need for a DTP or CDT.

What community / collaboration / communication activities can we do to promote the subject

- Use the phrase "space geodesy" at every opportunity;
- Geodesy prestigious/distinguished lectureship
- Branding
- Getting together for discussing scientific, in association with BGA (section of geodesy).
- Hold a National Annual Geodetic meeting.
- A flagship project as community
- Use the wording of "Collaborative" and "Community"
- IAG presence (National reports ongoing).

Who is going to lead?

- Board of "UK Geodesy Centre" (shared leadership rather than one individual)
- OS could lead it, BGA subcommittee.
- National geodesy meeting
- Virtual Geodetic Community

Funding across councils?

- Dynamic topography project (as funding scheme): Work packages to maintain SGF, increase gravimetry, improve geodetic techniques, improve/promote airborne

gravimetry), fracking, train planning and tolerance for ground motion (infrastructure)
- Improvement of knowledge of the geoid (next generation of height datum)

- European funding: like EPOS (large component of geodesy), Eurosurveys, SubCOAST and Terrafirma, TopoEurope, finding the right call in H2020, etc. ESA would consider extending Terrafirma (via Geohazards Exploitation Platform).
- NC (national capability)

Engineering/Space Science

Challenges

Reference Frame:
GGOS has set a target of an accuracy of 1mm position and 0.1mm/yr velocity for the terrestrial reference frame (ITRF). To achieve this will involve several technical advances: improvements in modelling, and mitigation of systematic effects in, geodetic observables (VLBI, SLR, GNSS and DORIS) and associated advances in determining the ties between the various contributing sensors. The terrestrial reference frame is a fundamental component of several branches of global science and technology.

Support for Key ESA Science Studies:
As an example, the anomalous eccentric orbits of the two Galileo satellites that were launched in 2016 gives the opportunity to study general relativistic clock effects in a way that was previously impossible and laser ranging plays a key role in that work.

SSA/SDA: Space Situational Awareness and Space Domain Awareness.
These relate to civil, scientific, commercial and military utilisation of space as a resource. That resource is increasingly congested and polluted. New actors are entering the space arena, many of whom have no heritage in space and hence will most likely behave in an irresponsible manner. Licenses for the launch of literally thousands of cube-sats have been sought in the last year from emerging commercial companies. In a similar vein, the existing constellation of space debris is, even now, unmanageable. Infrastructure and technologies to help mitigate against these potentially very threatening developments will be required. One could consider the idea of NERC broadening its remit to include the space environment.

Fracking/Deformation Monitoring:
The challenge relates to meeting a national need of how to measure local/regional deformation caused by fracking. By extension this involves having an audit trail to be able to show what has changed and by how much. The problem may involve innovation to develop

new technologies to address the problem at a variety of spatial scales. The underpinning use of the ITRF will be paramount.

Space Weather:
The UK has invested heavily (via the Meteorological Office) in a Space Weather capability. The existing OS Continuously Operating Reference Stations, CORS, (OS Net) network currently provides real-time data streams for numerical weather analysis. The possibility that these data streams could inform space weather now-casting and fore-casting could be investigated. However, is the current network fit for purpose in that regard? What other products or data could be supplied? What products are required?

Precision time and frequency:
There should be a strong link between the atomic frequency standard groups at NPL and the wider geodesy community and the space geodesy facilities (SLR and GNSS). There is a strong and growing demand for precision timing nationally and internationally (e.g. from within the banking sector). Providing real-time access to a high precision time scale cannot be accomplished solely by NPL, nor are they the only stakeholders in such infrastructure. This also begs the question of what involvement should be pursued in ACES (Atomic Clock Ensemble in Space). Globally, SLR will provide a component of the link to ACES via laser transmission. Tests and calibrations from visiting European experts have already been carried out at SGF in anticipation of laser tracking the ACES package on the Space Station from 2018/19 onwards. What is crucially needed to make this experiment a meaningful comparison with UTC (UK) is a fibre link from NPL to SGF. Discussions have been held between NPL and SGF and technically this is feasible, but costs to maintain a dedicated link are high (~£200k annually)

Support for high accuracy engineering tasks:
Do we have sufficient geodetic infrastructure to support the new generation of high speed rail links; dams and bridges; driverless cars?

Infrastructure/Facilities

CORS
Multi-GNSS.
Generating realtime and archive data and products; (e.g.; space weather).
Archive: faster access to data and products for ‘users’.
Realtime/NRT? For free?
More products TBD.
Integration with other sensors (e.g.; retro for InSAR with good site-tie to local GNSS).
Enhancements to OS Net:

- Expansion of tracking capability to multi-GNSS - when should this take place? What use should be made of the observations?

- Relocation of stations to optimise the utility of the network. For example, stations should be established systematically adjacent to key tide gauges.

Satellite Laser Ranging

- SLR uniquely determines origin and, with VLBI, the scale of reference frame at mm level.
- Thereby provides link **for all co-located GNSS** into ITRF origin.
- Tracking of altimeter/SAR satellites for POD with other techniques (GNSS, DORIS). UK SGF is a leading player in growing international efforts in this work.
- Increased demand for SLR:
- All GNSS next generation satellites will carry retro-reflectors - that will mean in excess of 120 satellites requiring SLR data in support of on-board clock monitoring and dissemination of the reference frame to users. This increases the demand for SLR bandwidth. This reflects a general trend: as long as the SLR facility has been in existence then the requests for tracking of various classes of mission have increased.
- Another SLR system in UK?
- Move to a bedrock site?
- Be able to support better the growing numbers of missions, incl. SST, SSA.

Gravity

Need for a permanent station to develop the operational and analysis expertise:

Serves crucially as a calibration lab for episodic survey work, e.g., at UK coastal tide gauges, establishing benchmark sites overseas, etc.

Long-term monitoring.

Relative gravity for new UK height datum.

Other permanent site(s) in UK, e.g., Eskdalemuir, Hartland, Lerwick?

VLBI

UK VLBI facility:

The SGF would become a GGOS core site, via colocation with SLR, GNSS, AG, that would contribute to the International Terrestrial Reference Frame and to the International Celestial Reference Frame. Costs for modern 'VGOS' have dropped now and this could be accomplished for £1.5M using small-scale 12m 'VGOS' VLBI dishes currently being deployed at several sites around the world (e.g., by NASA at McDonald, Texas; Hawaii; Yarragadee, W. Australia; by ROSCOSMOS at Baikonur).

- Requirement in UK would need to be established, emphasizing the value of colocation with world-leading SLR, culture of tracking down systematics, etc.:
- An SGF-written proposal for VLBI, that was submitted to NERC by BGS under a capital AO, is attached as Appendix-C

Spin-off from having a geodetic observatory:

- Infrastructure ready to address non-geodetic work, e.g., space situational awareness; e.g. time transfer via satellite between timing labs.
- New and growing income streams

Additional contribution to global geodetic infrastructure

Expansion of UK Space Geodesy facilities to islands owned by the UK:
The UK still owns numerous small islands that could be used to 'fill in the gaps' of the global observing system. Countries like the UK are in a privileged position in that regard. Such islands could provide powerful sites for additional SLR tracking facilities. The expertise that has developed at SGF would be very valuable in this regard.

Organisational Structure

Education / training

Develop a national geodesy and space geodetic techniques doctoral training centre (in the COMET model). It is not easy to recruit, attract and fund new geodesy students – having a centre will enable them to get a diversification & broad understanding and background across disciplines and across institutes. Ensure that data providers are linked into this programme to provide insight into operational facilities, to steer the programme, etc.
CPD – work with RICS, ICES, etc., to link professional development programmes and CPD into the UK geodesy community. This will help get more people aware and interested in geodesy in regard to International opportunities, for example a visiting scientist programme. This to aid collaboration and to ensure UK is linked through to the right communities across the world.

Geodesy Promotion

To help promote the importance of geodesy and to aid the development of funding opportunities.
Better engagement with professional bodies.
Use the publicity that has been developed by the UNGGIM, to promote the power of geodesy and what UK should do to answer the calls.
Lobby agencies to help them understand where geodesy fits in.
Look to create a flagship collaborative project across the geodetic community in the UK.

Leadership

This needs to be a group that represents the different elements of UK geodesy. It should be independent, meet regularly (the COMET model is great) and include academic, industrial, UKSA, national facilities, government geodesy providers. The aim would be to own the UK geodetic vision and to look for opportunities to deliver the roadmap of activities.

Funding

- Look at joint EPSRC / NERC route to fund the DTC.
- There are UKSA, ESA, etc., funding competitions that should be investigated.
- Global challenges research fund / Newton Fund to look at funding across international borders.
- Specific contract grants, e.g., DSTL (Defence Science Technology Ltd)
- NERC
- Can we build a case to UK government outside of current funding frameworks / competitions to deliver a part / all of the UK geodesy vision?

Appendix-A List of Attendees

Dr Paul Cruddace, Ordnance Survey
Mark Greaves, Ordnance Survey
Prof Tim Wright, COMET Leeds University
Prof Peter Clarke, Newcastle University
Dr Nigel Penna, Newcastle University
Prof Philip Moore, Newcastle University
Dr Zhenhong Li, Newcastle University
Dr Andrew Hooper, Leeds University
Dr Simon Williams, National Oceanographic Centre, Liverpool
Dr Svetlana Jevrejeva, National Oceanographic Centre, Liverpool
Dr Richard Bingley, BIGF Nottingham University
Prof Marek Ziebart, University College London
Dr David Kerridge, BGS Edinburgh
Prof Terry Moore, Nottingham University
Prof Stuart Marsh, Nottingham University
Steve Millard, UK Hydrographic Office
Kim Eastaugh, UK Hydrographic Office
Dr Pablo Gonzalez-Mendez, Liverpool University
Dr Liz Petrie, Glasgow University
Dr Ciprian Spatar, Newcastle University
Prof Chris Hughes, Liverpool University

From SGF Herstmonceux:

Dr Graham Appleby
Dr Jose Rodriguez
Rob Sherwood
Matthew Wilkinson
Vicki Smith
Toby Shoobridge
Christopher Potter
Prof Toshi Otsubo

Appendix-B

Thoughts on a ‘vision’ statement from SGF Herstmonceux submitted to NSGFSC September 2015; pre-cursor to the Geodesy Workshop at Herstmonceux, July 2016

Introduction The key question for us is ‘why does the UK need a geodetic observatory?’ Then, the follow-up question, ‘and what should that observatory look like?’
In this short note, we do not enter into all the detailed reasoning that will be required in order to address fully the upcoming S&F Reviews, but rather set out the arguments that we consider we will have to make. We also suggest that the UK geodetic community should seek to be more joined-up through collaboration between existing centres.

Outline Argument The point to be made at the outset is that it is beyond question that the study of global environmental change absolutely depends upon global geospatial information at the highest possible level of precision and accuracy (GGOS, Plag and Pearlman). This view is now well established not only within the worldwide scientific community, but also at inter-governmental levels (UN Resolution on Geospatial Information, May 2015). At all levels it is realized that, for example, disaster management depends on such information, as does an accurate measurement of trends in sea-level rise. Satellite technology (a growing and important UK industry) has made important observational contributions to many areas in the study of the dynamic Earth at a global scale over recent decades. As Earth observation satellite missions develop and improve they will require an increasingly more accurate and stable reference frame and precisely determined orbit solutions. It is also clear that the acquisition of high-quality global geospatial information depends upon a network of geodetic observatories to make observations in order to determine their 4-D coordinates and to drive high-accuracy orbital determination of space-based sensors.
Why a UK geodetic observatory For many years satellite geodesy, or geomatics, has been taught and research carried out at a large number of UK HEIs, including Newcastle, Nottingham, Bristol Universities and at University College London. The UK clearly needs a Centre where geodetic observations are made and where expertise in the techniques and their analysis can be honed, lest the HEIs become distanced from state-of-the-art practitioners. The UK SGF is a shinning example of what can be achieved by a small team: high-quality laser ranging observations are made at the necessary 7-day-per-week coverage, automated continuous GNSS observations are maintained, the technique of absolute gravimetry is practiced and developed and many other complementary observations are made to the highest standards. Crucially for a remote site, engagement with the UK and international observational and research communities is practiced to the benefit both of those communities and of SGF; for example, analysis at SGF of global laser ranging data yields products that feed into international efforts to realize a global geodetic reference frame at mm levels of accuracy; research into gravity measurements is revealing previously unknown tidal signals as well as systematic features in the technique.

Three and a half years ago, the SGF responded to a GGOS call for ‘next generation’ observatories that would meet the GGOS observational and analytical challenges. The response from Herstmonceux included SGF’s existing ‘next generation’ kHz laser ranging capability as well as aspirations to become a GGOS ‘core site’ by adding a geodetic VLBI capability. The response also and crucially included a UK community-build exercise initiated

by SGF that listed the UK leading HEIs and Centres including NOC and BIGF. The proposal was delivered to the GGOS Executive by NERC's then Science Director (P Newton) and accepted, giving SGF 'next generation SLR' status and flagging its aspirations regarding Core Site status. At that time, the idea of a UK centre for geodesy was suggested, but not pursued in light of the transfer of SGF from SO to BGS that began in 2013.
During the last 18 months, there has been much new interest in SGF capabilities, stemming primarily from the UK's emerging awareness of its responsibilities in monitoring the security of its orbiting assets. This has lead to engagement by the UKSA, MoD, STFC, Dstl and, through SGF, NERC, in the emerging EU Satellite Surveillance and Tracking Project, the first development and community-building phase of which is now EC-funded. The prior existence of SGF's sensors and expertise in tracking satellites was a fundamental element in UK's involvement in the EU Consortium.

What should it look like: It would be on the existing, but expanded, site and include the current kHz SLR, multi-GNSS, H-maser, AG, LiDAR and Sun photometer and, additionally, a superconducting gravimeter, a 2010 'VGOS' VLBI facility, an automated inter-technique survey device, and would develop a programme of visiting post-grad students, post-docs and sufficient operating funds to enable at least the replacement of critical components.
It may be called the Herstmonceux Geodetic Observatory (HGO), and it is suggested that it be the observational element of a new UK Centre for Observational Geodesy (COG), or perhaps the UK Centre for Observational and Applied Geodesy (COAG), that could include BIGF and perhaps COMET.

Appendix-C

Proposal to enhance the capability of the Space Geodesy Facility, Herstmonceux, by including a modern geodetic VLBI system. 2014

In the era of the Global Geodetic Observing System (GGOS), the techniques of space geodesy have matured to the level of being able to define, in principle at mm-levels of accuracy, the terrestrial reference frame, the Earth's time-variable gravity field and the orientation of the Earth in inertial space. The Satellite Laser Ranging (SLR) technique alone is sensitive to variations in the centre of mass of the Earth system with respect to the Earth's crust, the scale of the frame is provided by a combination of the SLR and Very Long Baseline Interferometry (VLBI) techniques, the SLR and GPS techniques each monitor variations in the length of the day, and VLBI provides the vital links between the terrestrial and celestial reference frames and uniquely provides Universal Time.

This underpinning definition of the reference frames is of critical importance in high-accuracy studies that rely upon space-geodetic techniques where knowledge of geophysical processes at the millimetre level is required. Examples of such studies include estimating sea level rise from satellite observations, measuring earthquake deformation using GPS or VLBI observations or estimating the reduction in heights of polar ice caps as a result of present-day melting. The millimetre accuracy required for extracting knowledge of these geophysical phenomena requires equally accurate determinations of such quantities as satellite orbit positions, atmospheric delays of transmitted signals, Earth orientation parameters (rotation rate of the Earth and the location of the spin axis) and the locations of radio sources used in VLBI. These parameters form a part of, and are used to define, the terrestrial (i.e. Earth-fixed) and celestial (i.e. inertial, space-fixed) reference systems. It is the terrestrial reference frame that most people are familiar with, being a set of site coordinates (in terms of latitude, longitude, height or, equally, Cartesian X, Y, Z coordinates) on the surface of the Earth. These coordinates effectively define the origin and orientation of the coordinate axes. Naturally, improvements in the ability to estimate more accurate coordinates will lead to improvements in the definition of the reference frame. Internationally, the International Earth Rotation and Reference Systems Service (IERS), is responsible for generating a definition of the International Terrestrial Reference Frame (ITRF). There have been several releases of an ITRF, beginning in the 1980s, from a combination of available space-geodetic observations. The most recent realization is the ITRF2008 (Altamimi, *et al*, 2011, Journal of Geodesy).

Through the work of the Space Geodesy Facility (SGF), Herstmonceux, the UK is directly involved in this international observational and data-analysis enterprise. The SGF Herstmonceux is a modern geodetic observatory carrying out very precise and accurate observations of Earth-orbiting artificial satellites. The Natural Environment Research Council (NERC) funds the SGF as a Service and Facility, with additional funding from the UK Ministry of Defence. The SGF satellite laser ranging (SLR) facility is currently ranked the most precise in the world in terms of range measurement quality among some 35 other stations that belong to the International Laser Ranging Service (ILRS; current governing board chair: G Appleby, SGF). The large quantity of laser ranging observations generated by the SLR to a wide range of geodetic, Earth-observation (EO) and navigational satellites places the SGF system currently 7th in the ILRS network in terms of productivity. SGF hosts the UK's longest-running Global Navigation Satellite System (GNSS) continuously operating receiver, one of two (named HERS and HERT) on-site receivers that contribute regular data to the International GNSS Service (IGS). Within the last two years, an active hydrogen maser has been installed in order to provide time signals and a very stable reference frequency for both the SLR and HERS systems. As a direct result, the HERS system is currently among the top five IGS GNSS systems in terms of providing the civil GPS timescale, upon which an enormous number of users worldwide depend. The permanent absolute gravimeter (AG) is used on a regular basis and is supplying a unique data set, being one of very few such instruments that is routinely operated and permanently sited at a multi-technique geodetic station. Results from several years of observations using the instrument are complementing the space geodetic solutions for site stability and providing insights into local loading and hydrological effects, which will themselves also have wider-ranging implications for the use of the technique.

A frequent programme of inter-technique leveling and GPS baseline determination is carried out in order to monitor the stability of the site, and results are very encouraging. The long-standing SGF station is well regarded in the International community, to the extent that surveyors from the French Institut Geographique National kindly spent a week during 2008 at Herstmonceux re-surveying the vectors between the GNSS and SLR markers and checking the distances to the SLR calibration targets. It is worth noting in that context that no government-funded agency currently exists within the UK that is able to take on such a programme of work.

The SGF ILRS Analysis Centre daily provides tracking station coordinates and Earth orientation parameters (polar coordinates and length-of-day) as part of the ILRS contribution to rapid availability of the reference frame. Two years ago, the SGF AC provided weekly unconstrained solutions from 1983 onwards towards the ILRS combined submission for the ITRF2008 multi-technique solution (Altamimi, *et al*, 2011). SGF expertise in attempts to mitigate sources of potential systematic error in the SLR technique is valued within the community, and is cited in the ITRF2008 publication.

However, despite this strong contribution from SGF, which has earned it the title of a GGOS New Technology SLR station, in its current configuration the Facility continues to suffer a lack of capability to take its share in providing a complete determination of the reference frame including a link to the celestial reference frame. The addition of a state-of-the-art Very Long Baseline Interferometry system would address this lack, and open up a new and exciting area of research for the UK geodetic community as a whole.

The technique of VLBI uses radio telescopes working in geographically separated sub-networks tracking simultaneously the same quasars. The International VLBI Service (IVS, http://ivscc.gsfc.nasa.gov) coordinates and schedules the observational effort amongst its global network of operational stations. The data from a typically 24-hour session from the contributing stations are correlated in order to derive the following geodetic parameters:

- Intensive Earth Orientation Parameters (EOP) Series
- Terrestrial Reference Frame
- Celestial Reference Frame
- Daily Universal Time solutions
- Daily EOP + station-coordinates solutions

- Tropospheric Parameters
- Time Series of inter-station Baseline Lengths

The IVS is currently undergoing a programme of upgrade from older legacy systems, which makes a UK entry very timely. One of the aims of the IVS 2010 network evolution is to wherever possible, co-locate new VLBI2010 stations near existing or planned space geodesy observatories, with a priority to SLR sites. The modern VLBI2010 system is based on the so-called broadband delay, which uses four or more frequency bands in the range from 2.5 GHz to 14 GHz. The observations are to be taken by fast-slewing, 12-m class antennas at a high data rate of 8 Gbps and above. The implied higher sampling of the sky, as compared to the legacy system, will allow beating down the impact of random error components. Together with a reduction of systematic errors, this will result in an anticipated overall accuracy of 1 mm.

The proposal here is that SGF should enter the VLBI field by purchasing a complete 12-m system for installation close to the other techniques at Herstmonceux. Several options exist, including the 'Patriot" systems that NASA is commissioning for its geodetic sites, and potentially a system from a UK astrophysical VLBI consortium based at Oxford University. Accurate site-ties will be established and measured as frequently as possible between the fiducial points of the VLBI, SLR, two GNSS and AG systems and, along with the current levelling programme, will place SGF Herstmonceux as a GGOS observatory at the forefront of international efforts in space geodesy. This proposal will not be easy to accomplish; the expected cost of order £1.5m for a VLBI2010 system will be difficult to acquire in the current climate, and local planning issues may prove hard to overcome. But taking this step will assure the ongoing relevance and scientific value of the site for decades to come.

Schematic of one of two 2010 VLBI instruments being installed at the Wettzell Geodetic Observatory in Bavaria, Germany