Institution: University of Bath

Unit of Assessment: Electronic & Electrical Engineering

Title of case study: Space Weather Awareness – Policy and Operations

1. Summary of the Impact

Space weather can adversely affect the performance of many communication and navigation systems. Research into space weather events and their mapping through our Multi-Instrument Data Analysis System (MIDAS) algorithms have highlighted the vulnerability of Global Satellite Navigation Systems (including GPS). The impact of our research has occurred in three main ways. Firstly, it has impacted on the global satellite and communications industry by enabling space-weather effects to be included in a sophisticated commercial GPS simulator. Secondly, it has impacted on UK government TEXT REDACTED. Thirdly, it has engaged and informed the public about GPS and space weather.

2. Underpinning Research

Key researchers involved in developing MIDAS algorithms: Prof C Mitchell, Dr P Spencer, Dr J Rose and Dr D Allain.

MIDAS (Multi-Instrument Data Analysis System) is a set of advanced mathematical algorithms that map space weather events and analyses their impact on global satellite systems like GPS. The algorithms carry out many complex signal-processing tasks, tomography and data assimilation and connect into an analysis of space weather that has proven to be both accurate and reliable.

Space weather occurs when solar flares and the solar wind interact with and perturb the near-Earth space environment. Through changes in the Earth's ionosphere (the ionised upper atmosphere), space weather can affect the performance of many communication and navigation systems. One important effect is the performance degradation of Global Satellite Navigation Systems (including GPS), reducing their accuracy in positioning and limiting their system availability. The ionosphere remains the largest source of error in single-frequency GPS navigation.

In the space-weather application of MIDAS, differential line-integral observations of the Total Electron Content (TEC) obtained from a network of ground-based and space-based GPS receivers are assimilated with other space-weather data and analysed. The resulting reconstructions provide a highly-accurate three-dimensional image of the Earth's ionosphere and its changes over time [1-2]. MIDAS works in real time, so it can continuously monitor and determine the changing nature of the ionosphere as it responds to space weather. Importantly, it then uses this information to calculate, again in real time, the exact effect of space weather on the position errors in GPS measurements [3-4]. The MIDAS algorithms can be used to warn of, or to remove, the delay error - and thus improve the accuracy of GPS. They also reveal and quantify the signal distortions known as scintillations that limit the availability of GPS (i.e., the loss of the system at user level). MIDAS is used under licence from Bath by many other academic institutions across the world TEXT REDACTED.

A further aspect of our MIDAS research is that huge quantities of data, collected from the polar and equatorial regions, have been used to quantify the effects of extreme space weather [5-6]. In several Bath-led international collaborations there has been considerable effort made to build, deploy and run reliable equipment at remote sites such as northern Scandinavia and Antarctica [5-6]. These successful experiments have yielded unique datasets that characterise ionospheric effects and are now being used in a TEXT REDACTED GPS simulator. TEXT REDACTED
The MIDAS algorithms were initially designed through an EPSRC grant to C Mitchell in 2000 and have subsequently been extended with multi-million-£ investment from UK research councils, including an EPSRC Advanced Fellowship (2003-2008) and an EPSRC Challenging Engineering Award (2006-2011). The on-going research is currently supported through a Royal Society Wolfson Research Merit Award (2009-2014).

3. References to the Research

[1] Spencer, Paul S. J.; Mitchell, Cathryn N., 2007. Imaging of fast moving electron-density structures in the polar cap. *Annals of Geophysics,* 50 (3), pp. 427-434. DOI: 10.4401/ag-3074
[2]* Mitchell, C. N. and Spencer, P. S. J., 2003. A three-dimensional time-dependent algorithm for ionospheric imaging using GPS. *Annals of Geophysics*, 46 (4), pp. 687-696. DOI: 10.4401/ag-4373
[3]* Allain, D. and Mitchell, C. N., 2009. Ionospheric delay corrections for single-frequency GPS receivers over Europe using tomographic mapping, *GPS Solutions*, 13 (2), pp. 141-151. DOI: 10.1007/s10291-008-0107-y
[4] Allain, D. and Mitchell, C., 2010. Comparison of 4D tomographic mapping versus thin-shell approximation for ionospheric delay corrections for single-frequency GPS receivers over North America, *GPS Solutions*, 14 (3), pp. 279-291. DOI: 10.1007/s10291-009-0153-0
[5]* Mitchell, C. N., Alfonsi, L., De Franceschi, G., Lester, M., Romano, V. and Wernik, A. W., 2005. GPS TEC and scintillation measurements from the polar ionosphere during the October 2003 storm. *Geophysical Research Letters*, 32 (12), L12S03. DOI: 10.1029/2004gl021644
[6] Rose, J., Allain, D. and Mitchell, C., 2009. Reduction in the ionospheric error for a single-frequency GPS timing solution using tomography. *Annals of Geophysics*, 52 (5), pp. 469-486. DOI: 10.4401/ag-4604
*denotes references that best indicate the quality of the research

4. Details of the Impact

Impacts on Industry: Extreme space-weather scenarios, based on real observations, are being generated by Bath for application in a TEXT REDACTED simulator. TEXT REDACTED [a].

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Impacts on Policy: Our MIDAS research has contributed to a situation in which "*the management of an environmental risk or hazard" has changed*, in this case through policy decisions made at government level. TEXT REDACTED [b]. Rose (PhD student supervised by C Mitchell) played a key role in raising awareness at UK Government level, when he presented his Space Weather MIDAS research and was awarded the *2010 SET for Britain Engineering and Westminster Medals*.

Quoting from the REF guidelines, "*policy debate has been stimulated and informed"* - here by real-time monitoring of the ionosphere by MIDAS. The research resulted in an invitation to C Mitchell to take lead authorship of a European Space Agency white paper on the effects of ionospheric scintillation on GNSS systems [c], as well as authorship of both a white paper by the US Federal Aviation Authority's Satellite-Based Augmentation System Working Group in 2010 [d] and a Royal Academy of Engineering report in 2013 [e]. Further, following the UK-US Space Weather Policy Round Table in 2010, The National Oceanographic & Atmospheric Administration (NOAA) in the US organised workshops to define how this policy would be delivered. One of the five areas addressed (co-led by C Mitchell) was the ionosphere and the development of MIDAS to provide real-time ionospheric imaging. This has contributed to a Roadmap Document (in 2011) to both UK and US governments detailing how UK/US research can be delivered as an operational system for space weather monitoring.

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Finally, "*the development of policies and services of benefit to the developing world"* have resulted. Bath led a special workshop on MIDAS in South Africa, in 2009, funded by the Royal Society and subsequently led a successful bid to ESA to lead an initiative to involve more researchers from African nations in space weather research. The Bath group consequently organised a workshop, including training sessions on MIDAS, in Africa in 2013, funding the attendance of researchers from six African nations [g].

Impacts on Public Awareness: *"Public interest and engagement in science and engineering has been stimulated"* and "*the awareness, attitudes or understanding of the public have been*

increased." In April 2013, the Bath team mounted an exhibition, "Antenna Live: Space Weather", at The Science Museum in London. The exhibition presented the concepts of space weather, explained why it is important to some technological systems, described how MIDAS works to image the ionosphere and described the dramatic fieldwork undertaken in the Antarctic to deploy GPS receivers at the South Pole for MIDAS analysis. The exhibition was attended by about 3,200 visitors over 3 days [h]. The Science Museum curator comments, "*Thanks again for the time and effort you put in to the Antenna Live last week – we had ~3200 people visit the display over the three days, which is great, and I think there was a really nice mixture of objects and media for the visitors to see and talk about*." In the same month, C Mitchell was interviewed for "Solar Storms", a Radio 4 documentary programme on space weather [i]. She also completed a 'Science Explained' webcast for the BBC website in 2010, explaining the fundamental concepts of how GPS works [j].

In summary, the space-weather MIDAS research at Bath has had significant impact on industry, policy and public awareness.

5. Sources to Corroborate the Impact

a) TEXT REDACTED
b) www.gov.uk/government/uploads/system/uploads/attachment_data/file/61929/CO_NationalRiskRegister_2012_acc.pdf
c) Status Report on Ionospheric Scintillation by the Galileo Science Advisory Committee, report commissioned by ESA, 2012
d) Effect of Ionospheric Scintillations on GNSS – A White Paper, report by the Satellite-Based Augumentation System Iono Working Group commissioned by the FAA, 2010
e) Extreme space weather: impacts on engineered systems and infrastructure, Royal Academy of Engineering, February 2013, ISBN 1-903496-95-0, see http://www.raeng.org.uk/spaceweather
f) TEXT REDACTED
g) Ionospheric Monitoring: Africa, Workshop held at Hermanus, South Africa, January 2013
h) Email from Science Museum curator, 8 April 2013
i) "Solar Storms", BBC Radio 4, 25 April 2013
j) http://news.bbc.co.uk/1/hi/sci/tech/8643772.stm