Institution: University of Birmingham		
Unit of Assessment: UoA12, Engineering		
Title of case study: Space weather resilience: Risk reduction through policy and forecasting		
Period when the underpinning research was undertaken: October 2011 to 31 December 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Paul Cannon (PSC) Prof. Matthew Angling (MJA) Dr Sean Elvidge (SE)	Professor Professor Research Assistant then Lecturer	MJA and PSC seconded (40% each) from Oct. 2011; PSC employed (40%) Nov. 2013–present; MJA employed May 2014–Feb. 2019; SE employed as a RA, Oct. 2014–Dec. 2018; as lecturer, Jan. 2019–present.
Period when the claimed impact occurred: 1 August 2013 to 31 July 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Space weather research at the University of Birmingham (UoB) has **stimulated and informed policy debate**. We advised the UK and Australian governments on policy and investment options to mitigate the impact of space weather on national critical infrastructure and security (e.g., power grids, communications systems, avionics and defence). This initiated **policy implementation** and new **practices and processes**, together with **reduced security risks** through **our innovative new technology**. The latter includes a global, real-time ionospheric and thermospheric forecast model (AENeAS) which has been selected for enhancement and operationalisation at the Met Office Space Weather Operations Centre.

2. Underpinning research

Space weather describes variations in the Sun, solar wind, magnetosphere, ionosphere and thermosphere that affect the performance of some technologies and also pose a danger to human health. Space weather varies over different time scales, with severe space weather a low probability, but high impact event. During extreme (sometimes called severe) space weather there may be electrical blackouts, failure of space-based navigation systems, restricted aircraft movements and other problems.

The key findings of our research fall into two areas: a) Extreme space weather risk evaluation; and b) Ionosphere/thermosphere forecasting.

a) Extreme space weather risk evaluation (PSC, MJA, SE)

Royal Academy Report [R1]. This research, with PSC as the initiator, leader, first author and principal expert on radio system impacts, brought together engineers and physicists to realise a balanced assessment of extreme space weather. Until this research, engineers and physicists (globally) worked as two separate communities with very different understandings and prejudices. The authors found that **extreme space weather is a major risk for national infrastructure**. Such events only occur 1 in 100 to 200 years, but their magnitude means they cannot be ignored.

Extreme Value Theory [R2] How often different magnitude space weather events occur is important because appropriate levels of mitigation are required to minimise the financial impact, variously estimated between billions and trillions of US dollars. Our novel application of Extreme Value Theory avoids assumptions about the underlying distribution patterns of solar events, and imposes mathematical rigour to **estimate the occurrence probabilities for solar flares, thus enabling a reliable evaluation of risk**.

Taylor Diagrams [R3] Globally, many researchers are developing space weather models, but critically and surprisingly there is no agreement on how to inter-compare the models' outputs. **This paper describes a technique for the visual and objective inter-comparison of a number of model metrics**.

b) Ionosphere/thermosphere forecasting of day-to-day variability (SE, MJA)

Ionospheric Scintillation [R4] New techniques that improve our understanding of scintillation, which occurs during space weather events, are important because scintillation impairs Global Navigation Satellite System (GNSS) operation. **This paper reports a new technique to map the irregularities in electron density that cause ionospheric signal scintillation**. The technique has been verified by Mohanty *et al*. [C1].

Forecasting [R5] Global real-time ionospheric forecasts are required to mitigate ionospheric effects on radio systems such as GNSS, space radar and some space communications systems. **We responded to this challenge by developing the only full-physics data assimilation ionosphere-thermosphere model designed for operational use**. It is uniquely able to assimilate non-linear data types and contrasts with those using a background statistical model which are unable to forecast beyond an hour or two.

Forecasting [R6] Low Earth Orbit satellites orbit in the thermosphere, which can vary in density by 250% during a solar storm causing accumulated orbit errors of several kilometres per day. Reducing this level of error was an urgent problem for both space situational awareness and to avoid collisions. **Our team was the first to do so by using multi-model ensembles to improve thermospheric forecasting**.

3. References to the research

R1. Cannon, P. S., *et al*. (2013), *Extreme space weather: Impacts on engineered systems and infrastructure*, Royal Academy of Engineering, ISBN 1-903496-95-0.
R2. Elvidge, S., and M. J. Angling (2018), 'Using Extreme Value Theory for Determining the Probability of Carrington-Like Solar Flares', *Space Weather*, 16(4), 417–421, DOI: 10.1002/2017SW001727.
R3. Elvidge, S., M. J. Angling, and B. Nava (2014), 'On the use of modified Taylor diagrams to compare ionospheric assimilation models', *Radio Science*, 49(9), 737–745, DOI: 10.1002/2014RS005435.
R4. Belcher, D. P., C. R. Mannix, and P. S. Cannon (2017), 'Measurement of the Ionospheric Scintillation Parameter C_kL From SAR Images of Clutter', *IEEE Transactions on Geoscience and Remote Sensing*, 55(10), 5937–5943, DOI: 10.1109/TGRS.2017.2717081.
R5. Elvidge, S., and M. J. Angling (2019), 'Using the Local Ensemble Transform Kalman Filter for Upper Atmospheric Modelling', *Journal of Space Weather and Space Climate*, 9(A30), DOI: 10.1051/swsc/2019018.
R6. Elvidge, S., H. C. Godinez, and M. J. Angling (2016), 'Improved forecasting of thermospheric densities using multi-model ensembles', *Geoscientific Model Development*, 9, 2279–2292, DOI: 10.5194/gmd-9-2279-2016.

4. Details of the impact

Our work has had direct impact on **public policy**. It **changed policy direction**, increased our **technological capability** to recognise and respond to space weather in the UK and **reduced security risks** in the UK and Australia. These impacts were achieved by **stimulating policy debate**. This enabled **UK and Australian policymakers** to both recognise the importance of space weather and to moderate the threat it poses **through the implementation of new policy** and **new practice**.

I1. Initiating policy change

Prior to the development and publication of the Royal Academy of Engineering (Academy) Report [R1], the UK Government had an immature requirement for mitigating extreme (sometimes called severe) space weather. The publication of the report radically **changed the policy landscape**. It is recognised by both government [C2, C3] and industry [C4, C5a] as pivotal ("the gold standard" [C3]), leading directly to these four developments.

1. A **national Severe Space Weather Steering Group (SSWSG) has been established**. In response to the Report's recommendations, national policy has been developed and coordinated, first by the UK Cabinet Office (Civil Contingency Secretariat) Severe Space Weather Project Board and then by the establishment of the Department for Business, Energy and Industrial Strategy (BEIS) Severe Space Weather Steering Group (SSWSG). The SSWSG is chaired by the Deputy Director Energy Resilience and Emergency Response, with oversight by the BEIS Chief Scientific Advisor. The SSWSG is designed to be the basis for a space weather Scientific Advisory Group for Emergencies (SAGE) if and when the need arises.
2. PSC is one of two academics **co-opted to membership of the government committees**, the Cabinet Office Board and the SSWSG. His role is to contribute research-based critical evidence synthesis in the development of policy within these policy committees [C2].
3. A **'Space Weather Preparedness Strategy' has been developed to guide UK government departments** [C6]. The importance of the UoB team's work is evidenced by the five references to the Academy Report [R1] in the 2015 edition.
4. The **Australian Government's policy has been informed** by this research. The Australian Government Bureau of Meteorology (BOM) used the Report [R1] as the starting point for a review (PSC first author; [C7a]) of its space weather forecasting capacity. The review confirmed the position of space weather in the Australian Meteorology Act and ensured that space weather was incorporated in the Australian Critical Infrastructure Resilience Strategy. Prior to the publication of R1 and C7a the Australian space weather services were at risk of closure. The management response from the BOM states that "the review answers the challenge posed by Option 20 of the Munro Review ("cease or reduce the Ionospheric Prediction Service or offer it as a commercial service") with a convincing case for continuation of the service as a core function of the Bureau" [C7b]. A letter of recognition from the BOM provides further context of how this led to "improved economic, security and safety outcomes for [its] customers in the energy, aviation and national security sectors" [C8].

I2. Practice and process change

Following the change of policy direction in the UK, **changed practices and processes** have been introduced.

1. As part of the hierarchy of government responses to the Report [R1] a **Space Environment Impacts Expert Group has been established** by the SSWSG. This group

ensures that government space weather policy developed by the SSWSG is informed by scientific evidence [R2, R3, R4, R5, R6].

2. The National Grid **changed its operational practices** as a result of the government policy change. It was encouraged by government to develop and sustain its severe space weather management and upgrade programme. National Grid now maintains additional spare capacity to enable it to react to severe space weather, while the Academy Report [R1] "significantly accelerated the implementation of [its] mitigation strategies" [C4].
3. **Better access to finance opportunities** were afforded to the sector. In December 2013, the Met Office was awarded funding for a UK 24/7 operational space weather forecasting service which started operation in April 2014. The Academy Report [R1] was crucial to the case which elicited the original funds (currently £2.3M per annum) for this service [C3].
4. The research **changed the practice** of the UK Civil Aviation Authority (CAA). The CAA confirmed that the Report [R1] "provided sound evidence of the potential impacts of severe space weather on aviation" [C5a]. As a result, it established a space weather working group and, in 2016, published advice for the aviation industry [C5b; part authored by PSC]. A space weather scenario was used to exercise the CAA Executive Committee's crisis management response [C5a].

I3. Risk mitigation

As a consequence of these policy changes, **risks to security have been reduced**.

1. The UK's ability to **respond to the threats of adverse space weather have been improved**. The National Risk Register [C9] is a core element of the UK's resilience plan. In its development, the Government Chief Scientific Advisor, Civil Contingencies Secretariat and BEIS policymakers made best use of the research-based critical evidence synthesis found in the Academy Report [R1], stating that the "Royal Academy of Engineering report on *Extreme Space Weather* analysed potential impacts of space weather on the UK's infrastructure, and this is being used to inform measures to reduce the risk" [C9].
2. The UK's **resilience to space weather threats has been enhanced** through the development of international networks, between the UK Met Office and the US National Oceanic and Atmospheric Administration, and a joint programme between the UK Defence Science and Technology Laboratory (Dstl) and the US Department of Defence (DOD). The Dstl Space Weather Lead states that "I would also like to highlight here that AENeAS makes a further international impact through its recognition by our US DOD colleagues, in support of a MOD-DOD project arrangement, where it enables the UK to provide a quid pro quo exchange technology" [C10].
3. **The MOD has developed new strategies**. A classified review of UK preparedness for extreme space weather events was held by the Ministry of Defence (MOD) and led by PSC "at the express request of the Government Chief Scientific Advisor" [C10]. The Dstl Space Weather Lead recognised PSC's "leading role" and stated that "[a]s a consequence of this exercise, MOD is focused on developing appropriate mitigation strategies for specific identified scenarios" [C10].
4. The **impact of SpWx on the global navigation satellite system** (GNSS) service in the UK is better understood. PSC contributed to the Blackett review, undertaken to inform government of the risks, including space weather, to GNSS [C11].

I4. Enhanced technological capability

Throughout this REF period, UoB has been developing **new and improved space weather forecasting technology and capability**.

1. AENeAS [R5, R6] **has been licensed to the US Air Force** (October 2018) and the University of Texas at Arlington (April 2019). MOD's Space Weather Lead asserted that "MOD is also pleased to acknowledge and confirm the impact made by Sean and Prof. Matthew Angling in the development of their AENeAS real-time ionospheric model" [C10]. In addition, Taylor Diagrams [R3] have made possible model inter-comparisons between the MOD and the US DOD Air Force Research Laboratory.
2. **Further investment**, in the form of a £20M UKRI-funded project (SWIMMR), has been **provided to develop new technologies** for operational space weather forecasting at the Met Office and within the MOD.

5. Sources to corroborate the impact

C1. Mohanty, S., G. Singh, C. S. Carrano, and S. Sripathi (2018), 'Ionospheric Scintillation Observation Using Space-Borne Synthetic Aperture Radar Data', *Radio Science*, 53, 1187–1202 DOI: 10.1029/2017RS006424.
C2. Letter of recognition from the Deputy Director, Energy Resilience & Emergency Response, Department for Business, Energy and Industrial Strategy (7 Aug. 2020).
C3. Letter of recognition from the Head of Space Weather, Met Office (5 Aug. 2020).
C4. Email of recognition from the Modelling and Insight Manager, National Grid (2 Oct. 2020).
C5. (a) Letter of recognition from the Policy Specialist — Meteorological and Aeronautical Information, Civil Aviation Authority (16 Jul. 2020); (b) Impacts of space weather on aviation (2016), CAA, CAP1428 [accessed 5 Oct. 2020].
C6. Space Weather Preparedness Strategy, version 2.1 (2015), Department for Business Innovation and Skills [accessed 5 Oct. 2020].
C7. (a) Review of the Bureau of Meteorology's Space Weather Service (2014), [accessed 5 Oct. 2020]; (b) Management response to Review of the Bureau of Meteorology's Space Weather Service (2014) [accessed 5 Oct. 2020].
C8. Letter of recognition from the National Manager of Space Weather Services, Australian Bureau of Meteorology (17 Aug. 2020).
C9. Open version of the National Risk Register of Civil Emergencies [accessed 5 Oct. 2020].
C10. Letter of recognition from the Space Weather Lead, MOD/Dstl (23 May 2019).
C11. 'Satellite-derived time and position: A study of critical dependencies', Blackett Review (2018) [accessed 5 Oct. 2020].