2018 - SSAP project summaries (permission to publish confirmed):			
Project number	**PI / Lead Contact**	**PI institution**	**Project title (with link if available)**
1	Prof Nicholas Achilleos	UCL	UKPMC: UK Planetary Modelling Centre
2	Dr Neil Bowles	Oxford	CASTaway: A mission concept to map the evolution of our Solar System
3	Dr Claire Cousins, Dr Matthew Gunn	St. Andrews, Aberystwyth	Surface Exploration of Icy Bodies
4	Dr Jackie Davies	RAL Space	A coronagraph for a solar polar mission
5	Dr Ian Franchi, Dr Colin Snodgrass, Prof Geraint Jones	Open, Edinburgh, UCL-MSSL	MBC: Main Belt Comet Low-Speed Impact Lander Volatile Characterisation
6	Prof Richard Harrison	RAL Space	CERISE: Coordinated Exploitation of Research Into the Space Environment
7	Dr Sasha Hinkley, Dr Beth Biller	Exeter, Edinburgh	From JWST to METIS: Mid-Infrared Exoplanet Spectroscopy
8	Prof Stephen Milan	Leicester	PRIME: Prime Meridian Space Weather Network
9	Dr Jonathan Rae	UCL-MSSL	Sub-orbital science from rocket and balloon field-schools
10	Prof Giovanna Tinetti	UCL	Twinkle – a mission to unravel the story of planets in our galaxy
11	Dr Jonathan Eastwood	ICL	Virtual Centres of Excellence (ViCE) Programme
12	Dr Ian McCrea	RAL Space	SSA: A UK National Programme in Space Situational Awareness

Note:

The Solar System Advisory Panel (SSAP) received a total of 29 project summaries in response to the 2018 Priority Projects exercise. Permission to include the above summaries has been given. It is hoped to add to this in due course.

Priority projects –

summary outline for Advisory Panels

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Project Name: **Principal Investigator/Lead Contact: Professor Nicholas Achilleos, UCL**

Project outline

Project: UK Planetary Modelling Centre (UKPMC)
Objectives:

- Establish a UK-based centre of excellence, for software development and student training related to numerical modelling of planetary atmospheres and space environments.
- Conduct software development to augment existing UK modelling codes, and develop new ones, for simulation of planetary upper atmospheres, magnetospheres, and the coupling between these regions.
- Use the software development lifecycle as a platform for delivering training in numerical and programming methods to students; and for forming nascent collaborations with industrial partners (particularly in the Space sector).

Scope:

- Focus on projects related to science exploitation of recently-completed, ongoing and future space missions. The research topic of ‘gas giant’ planets is appropriate, since the Cassini mission (Saturn orbiter) ended in Sept 2017; the Juno mission (Jupiter orbiter), soon to end; and the JUICE mission (JUpiter ICy moon Explorer) is in pre-launch development phase.
- Have a dedicated knowledge transfer activity for delivering relevant results and products to stakeholders in academia and industry.

Stakeholders:

- UK / international academics in planetary / space science research.
- Space sector firms involved in mission planning / spacecraft construction of the above-mentioned missions.
- Graduate student cohorts seeking training in software development and numerical techniques.

Scientific: Simulation of gas giant planet atmospheres and space environments;

Modelling existing, abundant datasets for the space environments of Jupiter and Saturn.

Scientific case

- UKPMC is essential for a full scientific exploitation of in situ and remote datasets associated with the Cassini and Juno (eventually, JUICE) missions. Unique science can be done by applying models of planetary atmospheres and magnetospheres to the interpretation of such data.
- UKPMC is a means of unifying expertise in planetary modelling across the UK community, bringing relevant academics together to participate in development and training activities.
- UKPMC is a means to make model development more efficient by involving large teams of academics working towards common scientific goals within the framework of a well-defined software development lifecycle. We can only be competitive with international modelling centres for planetary science by establishing one of our own in the UK.
- Computing infrastructure for starting the centre would initially be required. The main need would be a multi-processor cluster and / or shared memory computing facility for development and training purposes.

Leadership & potential team members To be led by an appointed panel of UK academics / developers with recognized expertise in planetary modelling / software development. We envisage participation of students in UKPMC training programmes, and possible internships related to software development / usage for postgraduate work. We envisage participation of industrial partners, interested in using model outputs for mission planning purposes, development of testbeds.

Societal and Economic Impact Space missions such as Cassini have enjoyed very high public profiles during their lifetime, and attract younger generations to careers in space science. UKPMC will also benefit students working in the realm of planetary modelling. A dedicated Knowledge Exchange Officer will work on transferring knowledge and UKPMC results to other potential areas of application, such as Space Weather effects at the Earth's environment, other astrophysical / planetary environments, autonomous software systems, and meteorological applications. The key technologies to emerge will take the form of software for performing simulations of planetary atmospheres and space environments.

Scale of investment Small scale (<10M). Envisage an initial 'start-up' phase over approximately five years, involving paid internships for several students per year, two dedicated posts for Software Design Authorities, one dedicate Knowledge Exchange Officer and one dedicated Director of Operations.

Science & Technology Facilities Council

Priority projects –

summary outline for Advisory Panels

Project Name: CASTAway - A mission concept to map the evolution of our Solar System
Principal Investigator/Lead Contact: Neil Bowles, University of Oxford. (neil.bowles@physics.ox.ac.uk)

Project outline

CASTAway is a multiple asteroid flyby and spectroscopic survey mission to explore our Solar System's past and future, originally proposed to ESA's Cosmic Vision "M5" call in October 2016. We believe it has the capability to transform our understanding of the evolution of planetary systems by mapping the compositional diversity of the Main Asteroid Belt (MAB) and allowing detailed connections to be made between meteorites, returned samples and the structures we see in the Solar System and other planetary systems at the grandest scales. This project would allow the UK to continue leadership of CASTAway's science and prepare for participation in future small bodies missions that are being proposed to ESA or as bilateral opportunities with e.g. US (NASA), Japan (JAXA) etc. Depending on the flight opportunity, options for participation include full mission-leadership (UK-led), payload-leadership (e.g. space-based telescope and camera systems, similar to ESA's ARIEL Medium 4 mission) or individual instruments (e.g. Thermal Imaging System, camera) or subsystems (vis/near-IR detectors etc.) as part of a bilateral.

Scientific case

The study of Solar System minor bodies is essential to answer basic questions of planetary system formation, evolution and the conditions for the emergence of life, because they uniquely retain compositional, structural and dynamical evidence from the earliest processes of planetary formation. Asteroids and comets provide a window into Solar System formation and evolution, as variations in composition across these populations provide a tracer for their formation locations and the subsequent dynamical evolution of the entire Solar System. Despite discovery of >800,000 asteroids, limited information on their composition and global physical properties can be inferred from ground-based remote sensing, their connection to meteorites is poorly constrained and only a handful have been spatially resolved. The Earth's atmosphere obscures diagnostic near-IR spectral features of organics and water, and hence evidence for the transport of key components for the development of life. Therefore, a space-based spectroscopic survey of the asteroids as both point sources and spatially resolved objects via flyby is essential to characterise the population and place the detailed analytical studies of meteorite samples and the expected returned samples from OSIRIS-Rex and Hayabusa2 into global context.

Working with our international partners and colleagues we propose a mission concept, CASTAway, that will conduct this survey on a carefully targeted trajectory that loops through the main asteroid belt and allows asteroids of all sizes to be observed spectroscopically, with a large number (>10) of flybys and the first characterisation of the 1-100 m population in the main asteroid belt. During flybys the spacecraft's cameras, survey spectrometer and thermal imaging system will provide consistent information on shape and surface properties to allow study of geological processes, impact history and ground truth for modelling of radiation-induced physical and orbital evolution. Cruise operation will allow CASTAway's spectroscopic survey mode to provide detailed compositional information on more than 10% of all currently known main belt asteroids with a radius >10 km, mapping composition variations throughout the main asteroid belt.

Leadership & potential team members

N. Bowles (Univ. Oxford), C. Snodgrass (The Open University), J.P. Sanchez (Univ. Cranfield), P. Eccleston (STFC/RAL Space), E. Pascale (Univ. Cardiff), K. Donaldson Hanna (Univ. Oxford), M. Patel (The Open University), J. Davies (UK ATC/ROE), M. Cosby (Goonhilly Earth Station), S.F. Green (The Open University). G. Jones (MSSL/UCL), B. Rozitis (The Open University), S. Russell (NHM),R. Jones (Univ. Manchester), M. Tecza (Univ. Oxford), A. Fitzsimmons (Queen's Univ.),S. Lowry (Univ. Kent), E. Brown (Univ. Oxford). The CASTAway consortium is open to new contributions from the UK and overseas.

Societal and Economic Impact

The technology developments and data analysis techniques that are driven by the CASTAway concept will allow the UK to extend its leadership in remote sensing instrumentation for e.g. small satellite and UAVs from the visible to the near and thermal infrared. Detector developments catalysed by CASTAway would enable new downstream applications from e.g. near-real time thermal infrared imaging from small satellites and real-time pollution or volcanic ash monitoring. In the visible, procurement of sensors from e.g. e2V will help maintain the UK's expertise in cutting edge vis/near-IR detectors. CASTAway's survey and flyby observations will drive developments in machine learning for the analysis of large, multispectral datasets. Leadership of missions such as CASTAway are vital to encourage the next generation of scientists and engineers into STEM subjects and into the space sector.

Scale of investment

If selected as a national, UK-led mission the project will be at the large (>£50M) scale, including a UK-led spacecraft flight system, leadership of the scientific payload consortium with options to host payloads from other countries as part of a UK-led bilateral. If selected as e.g. a major contribution to an ESA Medium class or similar mission the CASTAway concept would require a medium scale contribution. For the 2016 proposal the UK led the payload consortium and the thermal imager with a ROM cost of ~£18M (2016). If selected as part of a bilateral, with e.g. NASA, then the total cost of the selected instrument or sub-system will be in the small-scale (<£10 M).

Priority projects –

summary outline for Advisory Panels

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Project Name: Surface Exploration of Icy Bodies	
Principal Investigator/Lead Contact:	Claire Cousins (Co-PI/Lead Contact; Univ. St Andrews) Matthew Gunn (Co-PI; Aberystwyth Univ.)

Project outline

We will develop leading technology and the underpinning science to enable surface exploration of icy bodies in our solar system, with the capability to detect and characterise cryominerals, organics, and biosignatures. Our aim is to put the UK at the forefront of icy moon surface exploration. Key stakeholders include the outer solar system and astrobiology communities, and industrial partners who require compact, imaging instrumentation. The scientific driver is to unravel the habitability of icy moons. This addresses STFC's Science Challenge of establishing whether life is unique to our planet.

Scientific case

Icy moons have huge astrobiological potential, arguably more so than anywhere else in the Solar System. This is reflected in efforts by NASA towards developing a Europa landed mission. The next wave of spectroscopic and imaging instrumentation must be capable of investigating the habitability and astrobiology of icy moons. We will deliver:

(1) A novel UV-enhanced Hyperspectral Imager for Icy Moon Exploration

Using hyperspectral imaging for landed missions has been challenged by the cost, volume, mass and power requirements of conventional diffractive and tunable filter technology. Likewise, UV-stimulated photoluminescence has yet to be utilised for planetary surface exploration, despite its applicability. We will develop and test a novel, UV-enhanced Hyperspectral Imager that will conduct UV – Near Infrared hyperspectral imaging combined with UV-induced photoluminescence analysis. This will be achieved through the use of linear variable filter technology combined with a high-resolution UV-NIR sensitive detector and UV light sources to enable reflected and photoluminescence light to be spatial resolved on the scale of millimetres to decimetres. This will build on work by Gunn, on the initial development of novel hyperspectral imaging technology at Aberystwyth, to raise the TRL of the instrument to 7 so it is ready for a future mission. Additionally, distances between the Earth and icy moons necessitate the development of greater levels of autonomy and self-calibration, and onboard data processing in a landed imaging instrument. We will develop techniques to allow the instrument to return the maximum amount of useful data whilst minimising the required resources.

(2) Underpinning Science: Development of our hyperspectral imager requires low temperature spectroscopic and photoluminescence investigations of natural and synthetic, organic and inorganic, icy moon analogue materials. Building on studies led by Cousins (Fox-Powell et al., 2018, *EPSL*; Submitted, *Icarus;* Laurent et al., Submitted, *Icarus*), we will investigate: (i) cryoprecipitated minerals; (ii) photoluminescent organics; (iii) natural and synthetic analogue materials exposed to radiation and particle implantation; and (iv) UV excitation wavelengths, intensities, and temperature effects on analogue measurements. A dedicated environmental chamber with integrated spectroscopic capabilities will be built at the University of St Andrews, using existing heritage from the Hyperspectral Luminescence Imaging and Optical Spectroscopy instrument at Aberystwyth University, with a sister chamber with additional imaging capability built at Aberystwyth. Results will feed into the development of the hyperspectral imager, culminating in rigorous scientific testing of instrument prototypes to enable a tight coupling between science requirements and technological capability. The project requires no special computing infrastructure.

Leadership & potential team members

The project will be jointly led by Claire Cousins and Matthew Gunn, who have an established history of working together to merge science and technology (Gunn & Cousins, 2016; Cousins et al., 2012; 2015) for UK Space Agency and Leverhulme Trust funded projects. Additional team members include Prof. Adrian Finch (University of St Andrews) who is an expert on material luminescence; Dr Karen Olsson-Francis who leads astrobiology research at the Open University, Dr Jonathan Cloutier (St Andrews) who works closely with the mining industry; and the Rutherford Appleton Laboratory (RAL) who will enable technology developed in this project to achieve a high TRL.

Societal and Economic Impact

(1) Knowledge exchange: this project involves knowledge exchange between instrumentation, planetary exploration, and astrobiology. The project will provide individuals who can operate at the interface of science and technology, expanding the UK's STEM skill base.

(2) Capability and skills: this project will greatly enhance the UK's role in Icy Moon exploration. First-order investigations into cryo-materials and their luminescence properties will also serve the material science communities.

(3) Industry and Key technology: Hyperspectral imaging and photoluminescence have been acknowledged by the mining sector, with which we have established links. We will work with the mining industry to transfer hyperspectral imaging technology into mineral exploration.

(4) Public Engagement: Astrobiology and space exploration capture the imagination of the public, and serve to inspire many new generations of future scientists. We will build on our strong track record of public engagement to incorporate Icy Moon science and exploration into established outreach events and educational resources.

Scale of investment

We require small-scale (<10M) investment to enable research and technical personnel to carry out aspects of the project, hardware costs for instrument prototypes and environmental chambers, and materials costs for scientific development. Our project will be supplemented by contributing projects through PhD studentships and industry support in kind.

Priority projects –

summary outline for Advisory Panels

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Project Name: Coordinated Exploitation of Research Into the Space Environment (CERISE) **Principal Investigator/Lead Contact:** Professor Richard Harrison, RAL Space

Project outline The UK has world-class scientific strengths and a long heritage in solar, coronal, heliospheric, magnetospheric and ionospheric physics, encompassing instrumentation, observation, theory and modelling. All of these disciplines are directly relevant to the developing space weather effort. We recognise that STFC and NERC, between them, effectively 'own' the scientific areas that underpin severe space weather, a major item on the UK National Risk Register of Civil Emergencies. Ownership of that risk resides with BEIS, delegated to the UK Met Office. Critical to the continued development of Met Office forecasting activities is the efficient application of research from the academic community. To date, the approach to this has been ad-hoc; here, we propose a strategic UK coordination activity overseeing the development of relevant scientific work to address this national risk. Stakeholders include the UK Government, through BEIS, the UK Met Office and the academic community, including RAL Space.

Scientific case The UK's strong research and underpinning instrumentation heritage in space weather relevant disciplines is funded by a combination of STFC, NERC and UKSA. This is a programme of pure science that resides in academia, including groups such as RAL Space. At the other end of the spectrum are the operational space weather forecasting activities performed by the Met Office in response to the identified national risk, an applied programme funded by BEIS. To advance UK forecasting capabilities, we need to identify and develop the relevant research strands from the scientific community. To date this has not been done in a coordinated fashion. It also needs careful management to avoid a bandwagon effect; this is not an opportunity to develop all research aspects of the disciplines mentioned above, but must focus on practical, realistic research lines that are likely to benefit forecasting endeavours. Hence, we currently space weather research is lacking the following, and we propose to resolve this through the proposed effort:

1. The need for a coordinated approach to identifying specific lines of work (relating, e.g., to skills, instrumentation, models) that could provide realistic, practical space weather applications, if developed effectively.
2. From the lines of work identified, there needs to be a focused proof of concept development programme for space weather applications and a corresponding programme to ingest the deliverables into the space weather applications effort.

These activities need national coordination – involving all stakeholders, including the Met Office - and appropriate funding. Thus, as the first element to the project, we propose a coordination group or panel that has the expertise to manage the coordination required, working with the wider community.

Regular peer-reviewed research programmes are not conducive to these kinds of activities, e.g. STFC's Astronomy Grants Panel assesses proposals on scientific merit, topics are not ring-fenced, and the overall driver is top-drawer science; we should not expect such a programme to fund a science to exploitation activity as described. Thus, the second element is the provision of funds (administered by the coordination group) to support a range of lines of work. Such work could include activities ranging from the development of models to instrumentation. Examples of potential projects, each of which could provide practical benefit but might not be likely to receive pure research funding (with funding for each in the range £100k to £300k), would include: (1) Modification of an existing full-Sun magnetic model to enable real-time event assessments in a space weather forecasting environment, (2) Testing of novel heliospheric imaging instrument optical designs for potential flight on future space weather platforms, (3) A study of Mercury's magnetosphere to give insights into how the Earth's magnetosphere will behave in extreme space weather conditions such that the magnetopause is pushed inside the ring-current region (as happened at Earth in 1972), (4) A study of EUV coronal dimming analysis methods to assess their use in real-time CME onset detection. We would run a number of projects simultaneously.

We take the view that whilst UKRI (STFC and NERC) 'owns' the science, there should be some obligation on STFC (and, indeed, NERC) to interface formally with the Met Office in the delivery of that science for the benefit of the UK, i.e. addressing the established national space weather risk. We stress that the scientific areas are continually developing and the management of the space weather aspects emanating from that is a continuous requirement.

Leadership & potential team members The project must include stakeholders from STFC, NERC, UKSA, the Met Office and academia, including the Universities of Aberystwyth, Reading, St Andrews, Imperial College, UCL/MSSL, and RAL Space, all of whom should be represented on the oversight/coordination body. Given RAL Space heritage in the relevant scientific disciplines and leadership in key space weather activities, in addition to its National Laboratory role, it is proposed that RAL Space manages the project. The aim is to ensure that all academic groups with relevant research programmes be involved at some level.

Societal and Economic Impact As stated, severe space weather is on the UK Risk Register. This project addresses that risk head on, identifying and developing the necessary tools for enhancing UK forecasting capability - exploiting our scientific skills to develop these tools. The potential for novel hardware and software developments within this project could well be beneficial to UK industry (e.g. the long-running partnership with UK industry in the provision of detector systems for solar missions). We note that particular methods or technology could be exported for application by other countries. Space weather is often in the news, and is of major interest to the media and the public, especially in relation to the health of the environment around us and the enormous public interest in space. This project would play its part in inspiring young people to follow the STEM subjects.

Scale of investment The project needs to be costed thoroughly, but under the assumption that it includes the coordination activity plus a number of development activities, we regard this as a medium (£10-50M) scale project.

Priority projects – summary outline for Advisory Panels

Project Name: From JWST to METIS: Mid-Infrared Exoplanet Spectroscopy

Principal Investigator/Lead Contact: Sasha Hinkley (Exeter) & Beth Biller (Edinburgh)

Co-Investigators: Alistair Glasse (ATC), Rene Oudmaijer (Leeds), Mark Wyatt (Cambridge), Grant Kennedy (Warwick), Isabelle Baraffe (Exeter), Nathan Mayne (Exeter), Eric Hebrard (Exeter), Niranjan Thatte (Oxford), Matthias Tecza (Oxford), Ray Pierrehumbert (Oxford), Ingo Waldmann (UCL), Ian Parry (Cambridge), Ken Rice (Edinburgh), Jean-Loup Baudino (Oxford).

Project outline

As extremely large ground- and space-based telescopes come into operation in the next decade, the direct imaging of exoplanets will become the leading method to characterize a wide range of exoplanetary systems. Deep characterization of the atmospheres of giant exoplanets is essential now to develop the expertise and techniques for similar studies of Earth-like exoplanets in future decades. In particular, JWST and the first-generation ELT instrument METIS will explore the mid-infrared spectra of these planets from 3 to 28μm, a particularly rich wavelength range for testing atmospheric models of these objects. *To bridge between current state-of-the-art characterization efforts for young, giant exoplanets and next generation instruments which will image the first habitable zone planets, we propose here to enhance the UK's existing ELT instrument program by adding an increased effort share within the METIS consortium.* This will elevate our collection of UK Universities to become official partners in the METIS consortium, resulting in guaranteed observing time. This goal cannot be completed in the current funding envelope. In addition to achieving breakthrough science, this opportunity will broaden UK participation in ways that bolster the UK exoplanet community and build instrumentation capability for the future through our increased effort share.

Scientific case

Since 1995, more than 3000 exoplanets have been discovered, ushering in a completely new field of astronomy. The diversity among these planets is staggering, from hot Jupiters, to super-Earths, to young directly imaged giant planets beyond 10 AU from their stars, and even a small population of planets with masses similar to the Earth in the "habitable zone" of their parent star. The transit method is currently the most productive detection method, but this technique is only sensitive to exoplanets with a narrow range of star-planet inclinations, meaning that less than 10% of exoplanets are detectable this way. In contrast, the direct imaging method can detect and characterize a vastly wider population of exoplanets and collects photons directly from planets themselves, eventually allowing us to determine whether "habitable zone" planets are truly habitable or inhabited. Characterizing the physical properties of these planets, especially their atmospheres, is a key goal of modern science with upcoming ground- and space-based telescopes. The United States Astronomy community clearly recognizes that direct imaging is the future of exoplanetary science, and will be making multi-billion dollar investments in this area (e.g. WFIRST, HabEx, and Exo-C). Without significant involvement in exoplanet direct imaging efforts, *the UK risks being excluded from what will eventually become the most important exoplanet detection and characterization technique*.

Here we propose an intensive program of directly imaged exoplanet atmospheric characterization, leveraging the transformative capabilities of JWST (launch in 2021) as demonstrated by our successful Early Release Science Program (see below), and continuing with detection and characterization of lower mass, cooler, planets with ELT-METIS (first light expected in 2025). Our 52-hour JWST ERS programme is already allocated. We *propose here* *for resources to increase the UK's effort share in the ELT METIS consortium, which will translate directly into guaranteed GTO time for UK observers*, allowing us to continue and extend the science started with our JWST ERS programme. Specifically, an increased effort share in the METIS consortium will allow several of the coronagraphic optical elements for the METIS 3-5 μm R~100,000 spectrograph to be tested in the upcoming Exeter Exoplanets Laboratory, an 50m^2 cleanroom laboratory dedicated to developing astronomical instrumentation for exoplanet characterization. This testing currently does not exist in the METIS baseline instrument design, and without this work there will be no opportunities for the high-resolution spectroscopic study of exoplanets.

These instruments represent a paradigm shift for this field, allowing us to image and acquire high-quality spectroscopy of young planets (T_{eff}=500-2000 K, previously imaged only via their own self-luminosity in the near-IR) for the first time at wavelengths of 3-28 μm. This wavelength region provides novel probes for characterizing clouds, chemistry, and atmospheric structure of young imaged planets. Furthermore, deep characterization of giant exoplanet atmospheres is necessary before similar studies of Earth-like exoplanets can be attempted, especially spectroscopic studies to determine the degree of their habitability and look for possible atmospheric bio-signatures. Indeed, simulations suggest METIS will be capable of detecting an exo-Earth around a nearby M star (Crossfield 2014, Quanz 2014), potentially including the first images of the nearby habitable zone planet around Proxima Centauri b. METIS may also map the surface of an exoplanet in detail using Doppler imaging. Support from STFC will allow full, official partnership in the METIS consortium, and ensure involvement of our Universities (Exeter, Edinburgh, Leeds, Cambridge, Oxford, Warwick, UCL), for this future instrument for many years.

Leadership & potential team members

We are leading the JWST Early Release Science (ERS) programme "High Contrast Imaging of Exoplanets and Exoplanetary Systems with JWST" (programme ID 1386, PI Sasha Hinkley, co-PIs Beth Biller and Andy Skemer). One of the key science goals of this project is to gather *the first-ever observations of an exoplanet over its full luminous wavelength range from 2 to 28* μm. The observations obtained during our JWST ERS program, as well as the first few cycles of JWST, will be the much needed "bridge" between our current understanding of the mid-infrared luminosities of exoplanets and the upcoming opportunities with METIS. The leadership team for this project is two-thirds UK-based. This is a "big-tent" effort to unify the exoplanet direct imaging community, in order to best understand and utilize JWST during its short 5-10 year lifetime. We have established a broad, inclusive consortium of ~120 international scientists from the exoplanet imaging community, with deep experience using space- and ground-based coronagraphs, and across national borders and career stages.

Societal and Economic Impact

The success of exoplanet direct imaging relies crucially on our ability to model, and then remove, the contaminating starlight that prevents the detection and characterization of faint planets. This task is made vastly easier when a large number of stable reference images of the star (usually contained in the same dataset) can be used to model the starlight. The highly stable nature of infrared images redward of ~3 μm, as well as the very large datasets generated in a typical observation sequence, are ideal for the application of machine learning and "big data" analysis techniques (cf. the application of similar techniques for transit spectrum retrieval in Zingales & Waldmann 2018). Our research is thus an area extremely well suited to partnerships with industrial sectors focusing on the analysis of "big data" and machine learning. The STFC-funded Centre for Doctoral Training (CDT) "ScotDIST" based in Edinburgh, Glasgow, and St. Andrews will be a natural platform for training students and forming relationships with industries in this area.

Scale of investment

The work proposed here will easily fit into a small-scale range. The majority of the cost will be the resources (~£3M) associated with increasing the overall effort share within the METIS consortium. There are no other expected contributions from sources other than STFC, and establishing ourselves as official partners will ensure that the exoplanet imaging capabilities in the METIS consortium will be one of the leading "science-drivers" for this instrument for many years.

Project Name: PRIME – Prime Meridian Space Weather Network
Principal Investigator/Lead Contact: Steve Milan, University of Leicester, ets@le.ac.uk

Project outline

We propose to deploy, operate and exploit a real-time space weather remote-sensing network, PRIME, from the pole to the equator, centred around the Greenwich meridian, complementing existing infrastructures on the US and East Asian meridians. Space weather effects impact infrastructure and society at all latitudes. PRIME will place the UK at the forefront of space weather monitoring and understanding, the need for which is described in the UK National Risk Register and UK Space Weather Preparedness Strategy. The network will involve instrumentation, coordination, and computing infrastructure for data assimilation and modelling. PRIME is designed to add value to the leading three UK capital investments by UKRI and UKSA in space weather research over the next decade – the EISCAT_3D radar and the Solar Orbiter and Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) space missions. PRIME will do this by providing the key missing link in completing the Sun-to-mud chain of space weather events by focussing on their impact on the atmosphere and ground where the societal impacts of space weather are mostly concentrated. Key stakeholders are UK scientists, the UK Met Office, satellite operators and end-users, and UK, European, and African society in general.

Scientific case

The UK has significantly invested in the Solar Orbiter mission which will study the origin of disturbances in the solar wind, in the SMILE mission which will remotely sense the interaction of the solar wind with the magnetosphere and associated disturbances of the aurora, and in the EISCAT_3D radar, which will image the 3-D ionospheric response to this above northern Scandinavia in unprecedented detail. All three projects are due to begin operations around 2023. To fully exploit this investment and gain maximum scientific return, it is necessary to develop a network of instruments that will allow us to understand how the large-scale solar wind structures measured by Solar Orbiter and the consequent auroral disturbances imaged by SMILE connect to the small-scale ionospheric perturbations imaged by EISCAT_3D that ultimately determine many of the space weather impacts experienced by a user, including disturbances to global positioning and satellite communications systems, ground-induced currents experienced by National Grid, and satellite drag.

PRIME will provide continuous real-time observations of space weather phenomena from the pole to the equator within 25 degrees of the Greenwich Meridian. This covers important geophysical regions including: the cusp region near the pole, where variability in geospace most directly affects the upper atmosphere; the auroral electrojets above northern Scandinavia which produce intense geomagnetic disturbances on the ground that induce dangerous electrical currents in power grids and pipelines; the subauroral regions at UK latitudes where fast ionospheric jets disturb communications and GPS; and the equatorial electrojet, which hampers technological systems in developing countries. All these regions are linked by poorly understood physical processes, controlled in turn by the dynamics of the overlying magnetosphere. The pole-to-equator PRIME network is required to study these phenomena and their teleconnections, to understand their physical causes, their impact on technology, and to develop predictive and mitigation schemes.

A key scientific target of SMILE is the northern hemisphere cusp region. The Norwegian island of Svalbard is the only location from which ground observations of the cusp can be made. PRIME would operate specialised auroral cameras from Svalbard. The European Incoherent SCATter (EISCAT) Svalbard radar, of which the UK is a stakeholder, makes detailed observations of ionospheric disturbances associated with the cusp, but its geographical coverage is highly limited. In addition, the new EISCAT_3D radar being developed with UK investment will make novel volumetric measurements of the auroral ionosphere, but only in the region over northern Scandinavia. PRIME will place these observations in context by installing new coherent scatter radars on Iceland and in Finland, to measure ionospheric electric fields over the whole Scandinavian sector. Similar radars will be installed in mid latitudes and in Africa to monitor ionospheric flows and atmospheric waves generated by energy deposition at higher latitudes. These would be supported by a chain of magnetometers to measure associated geomagnetic disturbances on the ground, and ionosondes, riometers, and GPS receivers to monitor changes in ionospheric morphology and scintillation in satellite communications, produced by space weather effects at high-, mid-, and low latitudes. The whole network will be coordinated by centralised computing systems that will archive, assimilate, and disseminate in real time the observations, and run simulations and modelling, providing the most complete description of the space weather state ever obtained in this longitude sector, matching that available at other longitudes.

Leadership & potential team members

PRIME will be developed, operated, and exploited by a consortium of UK universities and laboratories, including Leicester, Lancaster, and the British Antarctic Survey (radars, magnetometers, riometers), Southampton (cameras), and Bath (GPS), UCL Mullard Space Science Laboratory (simulations), STFC Rutherford Appleton Laboratory (ionosondes, computing infrastructure and mission coordination), and the UK Met Office (public and user engagement, simulations). These institutions have provided world leadership in observations and theoretical understanding of space weather for over 30 years.

Societal and Economic Impact

PRIME will provide improvements in space weather characterisation and forecasting, aligning with the UK Space Weather Preparedness Strategy, with benefits for UK space operators, satellite service providers, National Grid, and corresponding communities in European and African countries, the latter linking to the Government's ODA and GCRF agenda. PRIME will provide training, capacity-building, and public engagement opportunities in the UK and abroad, including developing nations. The real-time observations of PRIME will provide crucial input to the UK Met Office Space Weather Operations Centre (MOSWOC). There are also on-going efforts to raise the upper boundary of the Met Office Unified model of the atmosphere to include the region influenced by space weather. The observations by PRIME will provide key input to and verification of these simulations, leading to improved space weather forecasting capability. Key instrument technologies already exist, but computing infrastructure for assimilation, simulation, and dissemination must be developed.

Scale of investment

Development, deployment, and operating costs for 5 years are expected to be 5-10 M.

Project Name: Sub-orbital science from rocket and balloon field-schools
Principal Investigator/Lead Contact: Jonathan Rae, UCL/MSSL

Project outline

The objectives of this proposal are to:

1. Deliver cutting edge science across the SSAP remit from sub-orbital platforms through exploitation of the new UK SpacePorts, immediately Sutherland;
2. Provide a Technology Readiness Level pathway for UK-built space instrumentation;
3. Train the next generation of scientist and engineers through hands-on training in space-related hardware development and build phases.

The UK are world leading instrument developers and were once world-leading sub-orbital scientists. Globally, successful and high-impact sub-orbital programmes continue, e.g., NASA Space Technology Mission Directorate (STMD) and Grand Challenge Initiative (GCI), however, with little UK involvement. We propose to reinvigorate the UK sub-orbital programme providing science opportunities, instrument development pathways and training opportunities across the entire space sector and SSAP remit by providing rocket and balloon opportunities from the new UK Space Port(s). This programme will be exploiting the new investment in the UKs National Space Strategy, and spans both STFC and NERC science goals within UKRI.

Understanding the physical processes behind space weather is a key science goal that spans a large fraction of the SSAP remit. Sub-orbital locations are essential for making progress in understanding the spatio-temporal coupling of the magnetosphere-ionosphere-thermospheric system. Moreover, high fidelity measurements of the solar environment can be made from sub-orbital platforms, as well as testing technologies for planetary, and indeed astronomy, missions.

This programme would provide significant training opportunities, enabling us to maintain our status as world-leading student educators within the space and technology sectors by providing flight opportunities compatible with the timescale of student courses. International programmes flown out of Andoya Rocket Range have already proven to be hugely successful in recruiting students to space-related careers. A comprehensive and streamlined training programme for the next generation of highly-qualified personnel in space-related disciplines with a complementary student rocket/balloon programme is thus a key goal.

Scientific case

In terms of SSAP remit, it is possible to cover all of the Solar System and potentially some Astronomy projects from rockets and balloon borne instrumentation. For example, solar system science would include the direct in-situ measurement of auroral processes (e.g. ACES, ICI-3 and ICI-4, Grand Challenge Initiative; https://www.andoyaspace.no/the-grand-challenge-initiative/), high resolution images of the Sun (e.g. HI-C and FOXSI; http://foxsi.umn.edu/), and high-altitude atmospheric measurements. On balloons, X-ray scintillators can measure the effects of precipitation from the radiation belt environment on the Earth's upper atmosphere (https://science.nasa.gov/missions/barrel) and measure solar EUV emissions (SUNRISE; https://www.mps.mpg.de/solar-physics/sunrise). Rocket-based observations can also be envisaged to be of interest for the development and launch of planetary (ASPIRE; https://www.space.com/40137-mars-2020-rover-supersonic-parachute-test.html) and astronomical imaging instrumentation (WRX-R; https://sites.wff.nasa.gov/code810/).

Specific science goals that are key to understanding the coupled solar wind-magnetosphere-ionosphere system can be achieved using long-duration balloon flights from both Sutherland or other future UK SpacePorts and the UKs Antarctic base to measure neutral winds and electric fields that are important for atmospheric drag, energetic particle precipitation from the Van Allen Radiation Belts into the upper atmosphere that plays a role in atmospheric chemistry, and long-duration imaging of the aurora. On the other hand, rocket flights also allow in-situ measurements at spatial and temporal resolutions that are highly challenging to reach with space missions.

Globally, student rocket and satellite programmes (e.g. REXUS/BEXUS, CaNoRock, CSLI) give the next generation of rocket scientists and engineers the chance to experience real mission scenarios as students, however opportunities for UK students are limited. Of the 25 REXUS rocket launches, co-sponsored by ESA, only seven UK payloads have been flown, compared with 42 payloads from Germany (one of the REXUS leads). This proposal would deliver hands-on training during undergraduate, Masters and PhD projects, and hence would build upon this experience to significantly enhance our leadership and international standing in the field. Access to the relevant Space Port equipment is all that is needed for the programme, alongside infrastructure that is already in place at relevant Universities.

Leadership & potential team members

A consortium of UK universities, laboratories and industries are interested in science, instrument development and training opportunities afforded by this programme. Led by UCL/MSSL, institutes such as Imperial, Leicester, Reading, Lancaster, UCL, British Antarctic Survey, Bath, Rutherford Appleton Laboratory would be keen to participate.

Societal and Economic Impact

This project would provide platforms to raise the TRL of key new technologies that the UK expects to develop for wider use, thus decrease the risks involved in future space instrumentation development. This programme would also leverage the significant UK investment in SpacePorts that will be constructed in the near future. Further, low-cost access to space also allows SMEs to develop innovatove spacecraft systems which would lower risks in developing improvements over existing systems. In addition, this programme will provide hands-on post-doctoral, graduate and indeed undergraduate level opportunities to train the next generation of highly qualified space personnel. Finally, understanding the response of near-Earth geospace to solar forcing is a key goal in mitigating risks due to "Space Weather", which is part of the UK National Risk Register.

Scale of investment

The investment would be at the upper end of the small project range, but be scalable based upon the number of planned flight opportunities. It is not clear what the costs for using a SpacePort is, but for flights over a 5-year period, science rocket and balloon flights would be expected to be of order £10-15M programme; student rocket and balloon flights with more rudimentary instrumentation and smaller rockets only for would be expected to be at the £5M level, depending on how often launches occur.

Priority projects – summary outline for Advisory Panels

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Project Name: Twinkle – a mission to unravel the story of planets in our galaxy
Principal Investigator/Lead Contact: Marcell Tessenyi, Giovanna Tinetti and Jonathan Tennyson (UCL/BSSL)

Project outline

The Twinkle Space Mission is a small (45 cm telescope), low-cost mission that will use spectroscopy in the optical and infrared to analyse exoplanets and solar system objects. The mission is designed to address two cutting edge areas of science with currently limited access to data: spectroscopy of exoplanets and solar system objects. Twinkle will be able to reveal the chemical composition, weather and history of worlds orbiting distant stars. In addition, the satellite design is compatible with other science areas including solar system spectroscopy (asteroids, NEOs, moons, planets, comets). The Twinkle satellite will be built in the UK and launched into a low-Earth orbit within 3 to 4 years.

Twinkle offers spectroscopic capabilities from the visible to the infrared (0.4 to 4.5 μm). The provision of this visible-IR coverage from space is a highly sought after capacity (e.g. oversubscription of HST, Spitzer). Some observational targets can be viewed from ground-based telescopes at certain wavelengths (e.g. visible) but significant issues are encountered in other bands due to atmospheric absorption, particularly if observing at IR or UV wavelengths. Additionally, ground observations can be affected by weather and atmospheric distortion. Space telescopes avoid these issues and thus are fundamental to increasing our knowledge of the Universe.

Twinkle is a new mission concept that aims to exploit the off-the-shelf capabilities developed by the earth observation community to launch a low-cost, quick (3 years to launch) mission. Twinkle is entering its mission definition phase (Phase B) funded through PPPs (public-private-partnerships); and is on course for launch in 2021/22.

Scientific case

Exoplanet science: Nearly 4000 exoplanets have been discovered and many more will be found in the next 5 years with upcoming surveys from space (e.g. TESS and CHEOPS) and the ground (WASP, NGTS, RV surveys). Twinkle will be able to probe a large number of planets at low spectral resolution, useful to refine planetary, stellar and orbital parameters, search for transit time variations (TTVs), refine the ephemerides and monitor stellar activity through time. For planets orbiting bright stars, Twinkle observations at higher spectral resolution will probe atmospheric chemical and thermal properties, with the potential to revisit them many times over the mission lifetime to detect variations such as non-uniform cloud cover. Existing and upcoming surveys mentioned above will reveal thousands of new exoplanets, many of which will be located within

Twinkle's field of regard. The James Webb Space Telescope (JWST) is expected to launch in 2021. Although a good fraction of JWST observation time is likely to be allocated for exoplanet science (e.g. Cowan et al. (2015)), for a space observatory of this scale, oversubscription is likely to be an issue and not all interesting science cases will necessarily require the sensitivity and accuracy of JWST. By 2028, the UK-led ESA ARIEL mission will be launched with a focus on characterising 1000 exoplanets to reveal the bigger picture of planetary formation through a statistical sampling of planets of many types. Twinkle's observations will be able to flag optimal targets for further analysis by the larger facilities, and will allow Twinkle to be available as a precursor facility.

Solar system science: Spacecraft studies of Solar System bodies have increasingly contributed to our knowledge of these objects over recent years. Whilst in-situ measurements provide the best means of understanding a target, dedicated lander, orbiting or fly-by missions are rare and thus remote sensing missions offer a great chance to observe objects of interest. Solar System targets, for which Twinkle's capabilities allow for the acquisition of high quality, high-resolution spectroscopic data within a single observation is found to incorporate planets and some larger moons. The potential also exists for observations of smaller moons and large asteroids at a lower resolution whilst photometric observations should be possible for a vast number of objects. The targets vary with spectral band; for instance, absorption features of water and OH of primitive asteroids (0.7, 3μm), as well as organic material on asteroid surfaces (3.2 to 3.6 μm) can be studied with Twinkle. In addition, spectral features at 2.7-3 μm make Twinkle especially well suited to surveying the larger objects in the asteroid belt.

Leadership & potential team members

MT, GT and JT are founding co-directors of the UCL start-up Blue Skies Space Ltd (BSSL) that is managing Twinkle. The Phase A technical feasibility studies were carried out by a number of UK research institutes, government organisations and space companies including Airbus-Surrey Satellite Technology Ltd, Selex/Leonardo, RAL Space, UKATC, UCL MSSL, Open University, Cardiff University. The satellite benefits from a high-heritage design: we will use a flight-proven low-Earth orbit satellite platform and will reuse existing components for the science instruments (e.g. UVIS spectrometer from the ExoMars NOMAD instrument).

Societal and Economic Impact

This model has the scope to dramatically changing the provision of space science satellites to the scientific community, by introducing a parallel stream of small, quickly launched satellites to address near-term science requirements.

Scale of investment

The total cost of the Twinkle Space Mission is estimated at £30M (excluding launch & operations) – "medium". BSSL is currently contacting the international scientific community, obtaining a very positive response. Twinkle is accessible to all scientists worldwide, interesting in buying telescope time to perform their science. The data will be provided encrypted to users. The UK community could have access to Twinkle via STFC or university funds/grants.

Priority projects –

summary outline for Advisory Panels

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Project Name: Virtual Centres of Excellence (ViCE) Programme **Principal Investigator/Lead Contact:**Dr. Jonathan Eastwood, Imperial College London (jonathan.eastwood@imperial.ac.uk)

Project outline

Please briefly describe the Project, including objectives, scope, key stakeholders and the scientific drivers and areas of excellence.

In the remit of STFC science, the UK is world leading in many areas. However, this excellence is often fragmentary, largely as a consequence of the AGP process which does not foster long term alignments in research areas except at the highest level. To increase the impact and visibility of STFC science, I propose the formation of a Virtual Centres of Excellence (ViCE) programme – a vehicle to consolidate expertise in different STFC science areas to strategically address challenges relevant to STFC's science roadmap that require a large-scale, coordinated approach. Further notes:

- **The ViCE programme is deliberately envisaged as being flexible and applicable across the STFC remit.**
- **The focus of the Centres would be challenge-led.**
- **These could be directed by STFC (e.g. selected via a panel process) or proposed from the community (a combination may be advisable).**
- **Consequently, whereas the grants line is 'blue sky', the ViCE programme would be more applied in nature.**
- **Cross-cutting initiatives should also be encouraged.**

Scientific case

Describe the scientific relevance of the Project, and of the unique science to be carried out, in an international context as well as any international activities in this area and how competitive the Project will be in comparison with others in the field. Summarise access to, and level of, computing infrastructure or any other relevant enabling infrastructure, required to exploit the project.

As explained above, the goal of each ViCE would be to consolidate and translate STFC science to maximise impact. Each ViCE would be a multi-institution network, (5 year initial lifetime), consisting of academic, STFC and industrial/government/end-user stakeholders. To reach critical mass, a typical budget per Centre might be £1m p.a., funding a network of 5-10 institutes at the order of 1 FTE p.a. and associated equipment/facilities.

Leadership & potential team members

Describe the expected UK leadership of the project, as well as possible participation by other individuals or groups.

There are a number of application areas that would be well served by the ViCE programme: e.g. detector technology, data science, healthcare, natural hazards, etc. If it is preferred to have a more science-challenge-oriented approach, Centres could be based around e.g. the ESA science programme and specific areas with major UK investment via UKSA.

Societal and Economic Impact

Describe the potential Societal and Economic impact of the Project in terms of knowledge exchange, capability/skills development, industrial partnerships and public engagement. Outline any key technologies and technology development associated with your Project. Please explain the technical importance of the Project and the scope for wider application of any technologies to be developed.

The ViCE programme is envisaged as including stakeholders from the start as a mandatory element. The success of the programme would be defined in terms of the creation of a critical mass of knowledge in a particular area, and demonstrated translation of knowledge towards solution of the headline challenge. A vigorous programme of public outreach would also be a mandatory element of the ViCE programme.

Scale of investment

State whether your project will be large (>50M), medium (10-50M) or small-scale (<10M). Identify any expected contributions from sources other than STFC. For international Projects, please describe the relative scale and significance of the UK contribution.

The ViCE programme is of the order of a medium scale project.

Project Name: A UK National Programme in Space Situational Awareness
Principal Investigator/Lead Contact: Ian McCrea, RAL, ian.mccrea@stfc.ac.uk

Project outline

We propose to create a UK national programme in Space Situational Awareness, covering the domains of space weather and SST (Space Surveillance and Tracking). These areas are significant UK priorities as evidenced by the UK National Risk Register and the National Space Security Policy. The programme addresses gaps in current capability, (defined in the bullet points below), complements UK efforts within the ESA Space Situational Awareness programme, and provides the opportunity for UK scientists to collaborate with colleagues working in the EU-SST (Horizon 2020) and the forthcoming EU-SSA (Framework 9) programmes, from which the UK currently seems likely to be excluded. It will also facilitate wider international collaborations to secure UK input toward the global aim of realising the requirements of the COSPAR space weather roadmap.

Scientific case

As currently defined, e.g. by the European Space Agency, Space Situational Awareness covers research and monitoring activities in three areas, namely space weather, Near-Earth Objects (NEOs) and Space Surveillance and Tracking (SST), the latter comprising monitoring and modelling the behaviour of satellites and space debris. Because the UK does not have significant activity in NEO work, we concentrate here on the other two disciplines of space weather and SST.

The UK has a strong scientific heritage and an active programme of research in space weather, i.e. solar, heliospheric, magnetospheric and ionospheric physics. Responsibility for this area is divided between STFC, whose remit includes the Sun and interplanetary space and NERC, whose focus is more on the terrestrial impacts. The UK programme includes instrumentation and observations, theory and modelling, funded by a combination of STFC and NERC, with UKSA also playing a role in respect of UK contributions to ESA's space weather programmes. The activities reside primarily in academia, including national labs such as RAL Space, BGS and BAS. In the past decade, significant effort has also gone into creating an operational forecasting capability for space weather, performed by the Met Office as an applied programme funded through BEIS.

The UK also has growing capabilities in Space Surveillance and Tracking, provided mainly by optical and radar sensors observing objects in all orbits ranging from Low-Earth Orbit to Geostationary. SST observations and their underpinning capabilities for coordination, data exchange, modelling, user interfaces etc. are currently supported through the EU-SST programme, led in the UK by the UK Space Agency. It seems likely, however, that the UK might be excluded from this after Brexit on March 29th 2019. In addition, the EU looks likely to adopt its own Space Situational Awareness programme as part of Framework Programme 9, in which UK participation is similarly uncertain. Particular aims of our proposed programme would include:

- Establishment of a coordinating body bringing together representatives from STFC (RAL Space), NERC (BAS/BGS) UK Space Agency, UK Met Office, industry and academia;
- A focus on improving the scientific understanding of space weather impacts on technological infrastructures, the risks that arise from such impacts and how engineers can best mitigate those risks. This will define the requirements for both science-based space weather services and the need for new science and is a dynamic process, leading to new requirements as science and technologies evolve.

- Support for the deployment and operation of a distributed network of ground-based instruments for synoptic space weather observation to support the requirements above and for the archiving and management of their data;
- Support for a programme of model development and validation to establish where current space weather models and predictive services are deficient and drive targeted improvements to support the requirements above;
- Provision of funding for bilateral collaborations with agencies other than ESA, with a focus on development and provision of UK instruments for future international space weather missions;
- Upgrading of existing UK sensors for Space Surveillance and Tracking, including the CASTR radar at STFC's Chilbolton Observatory and deployment of distributed optical sensors;
- Facilitating the analysis and reciprocal exchange of data from these and similar sensors and scientific collaborations with international SST partners;
- Collaboration between the space weather and SST communities on the use of space weather modelling for SST applications in predicting atmospheric effects on spacecraft orbits and verification of such predictions using observational data;
- Development and use of improved computing techniques for data assimilation into models, ensemble modelling, and calculation of diverse and rigorous model performance metrics, acknowledging the need to understand the uncertainties inherent in such modelling.

In particular there is a compelling need to facilitate the development of models and services from the research to the operational domain, with few sources of current funding to support this.

Leadership & potential team members

A programme of this kind would bring together scientists in HEIs and UK National Labs (e.g. RAL Space and the UK Met Office) across the domains of STFC, NERC and potentially also EPSRC. The UK Space Agency would also be an important stakeholder. It would secure a prominent role for the UK in areas where we might otherwise find it hard to participate, given current political constraints. STFC has strong connections to the domains listed above and would be well-placed to take a leading role. In addition it would put the UK in a strong position to collaborate with international partners in international efforts such as the realisation of the COSPAR space weather roadmap. Adding new space weather infrastructure and modelling capabilities will support existing UK investments in facilities such as EISCAT_3D (NERC) and in ESA missions including SMILE and Solar Orbiter. Improving the UK's monitoring and modelling capabilities for SST will position us for collaboration with future European SST efforts and with the UK's traditional international partners.

Societal and Economic Impact

Given their high level of relevance to UK public policy (position of space weather on the national risk register; relevance of SST to UK launch, large satellite constellation management, spacecraft licensing etc.), it would send a strong signal for STFC to take a strong scientific lead in both areas. Doing this would also strengthen our position as a scientific and implementation partner to the UK Space Agency, which has significant responsibility for UK policy in this field.

Scale of investment

Development, deployment, upgrade and operating costs for a programme of sensors, model development and data analysis lasting for five years are expected to be of order £50M. The true value would be greater, however, because the programme would also leverage existing UK assets and investments in other areas e.g. in ESA's science and SSA programmes, the current EU-SST programme and NERC investment in the construction of EISCAT_3D.