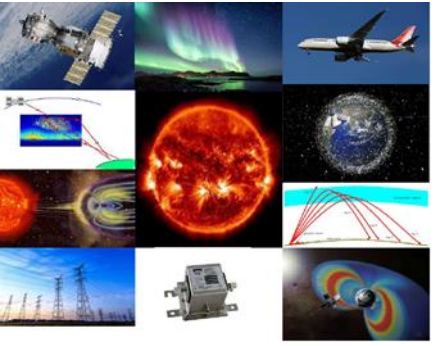


UK Research and Innovation

Radars, Radiation and Operational Space Weather

From EISCAT to Space Situational Awareness and SWIMMR

Ian McCrea

STFC Rutherford Appleton Laboratory

Who am I?

- PhD in Space Physics (Radio and Space Plasmas Group, Leicester, 1989)
- Joined RAL in 1991 (UK EISCAT Support Group)
- Head of Space Data and Operations Division (2016-2024)
- Resilient Society Theme Lead (2024 – present)

PhD Thesis (1989)

- How is energy from the solar wind deposited in Earth's environment?
- What effects does it have on the ionosphere and neutral atmosphere?
  - Density changes
  - Heating (neutrals, ions, electrons)
  - Changes in composition
  - Changes in dynamics

Radar Observations of Energy Deposition and Dissipation in the High-Latitude Ionosphere

Ian William McCrea

Abstract

The high-latitude ionosphere is a dynamic region, in which a variety of phenomena including particle precipitation, currents and waves contribute to the energy budget. In this thesis, statistical and case studies of ion frictional heating are presented, including investigations into the dependence of enhanced ion temperature on time and altitude. The relationship between parallel ion temperature and ion velocity is compared to simplified forms of the ion energy balance equation. In addition, the generation mechanisms of atmospheric gravity waves are studied by means of measurements made during the WAGS campaign of October 1985.

The results indicate that auroral precipitation can influence frictional heating events to a greater extent than has previously been realised and that during frictional heating the molecular content of the lower ionosphere is enhanced, affecting the electron density. Any analysis which takes no account of the modified composition underestimates the parallel ion temperature, particularly between 200 and 300 km altitude. The relationship between ion velocity and parallel ion temperature is most easily explained by an anisotropic ion velocity distribution, consistent with resonant charge exchange collisions. The relationship varies with altitude, however, possibly due to ion-ion collisions. An experimental method is described by which the temperature anisotropy can be obtained directly and early results are discussed.

For the investigation of atmospheric gravity waves and their sources, HF Doppler observations in the UK enabled wave speeds and azimuths to be deduced, whilst EISCAT simultaneously observed the possible source region. Although the study was characterised by moderate activity, more active days showed higher phase speeds and southerly azimuths. Some of these waves may have originated at high latitudes during positive bay activity, when both Joule heating and the Lorentz force contributed to wave generation.

What is EISCAT?

- European Incoherent SCATTer scientific association
  - Not exclusively European ☺
  - Scatter isn't incoherent ☺
  - No longer a scientific association ☺
- Operates radar systems for scientific research in northern Scandinavia and on Svalbard
- Now moving from dish-based radars to phased arrays

Development of EISCAT_3D

- EISCAT's original radars were built in the 1970s and started taking data in 1981
- Despite a substantial renovation in 2000, the systems are aging and hard to maintain
- Hence it was long clear that a replacement would be needed
- Radar technology has evolved considerably – move from dishes to arrays
- Since 2003, I was involved with the effort to develop a successor radar system
- …..and now in 2025 it's almost ready…..

a SpringerOpen Journal

REVIEW Open Access

The science case for the EISCAT_3D radar

Ian McCrea[1*], Anita Aikio[2], Lucilla Alfonsi[3], Evgenia Belova[4], Stephan Buchert[5], Mark Clilverd[6], Norbert Engler[7], Björn Gustavsson[8], Craig Heinselman[9], Johan Kero[4], Mike Kosch[10,11], Hervé Lamy[12], Thomas Leyser[5], Yasunobu Ogawa[13], Kjellmar Oksavik[14], Asta Pellinen-Wannberg[4,15], Frederic Pitout[16,17], Markus Rapp[18], Iwona Stanislawska[19] and Juha Vierinen[20]

Abstract

The EISCAT (European Incoherent SCATer) Scientific Association has provided versatile incoherent scatter (IS) radar facilities on the mainland of northern Scandinavia (the EISCAT UHF and VHF radar systems) and on Svalbard (the electronically scanning radar ESR (EISCAT Svalbard Radar) for studies of the high-latitude ionised upper atmosphere (the ionosphere). The mainland radars were constructed about 30 years ago, based on technological solutions of that time. The science drivers of today, however, require a more flexible instrument, which allows measurements to be made from the troposphere to the topside ionosphere and gives the measured parameters in three dimensions, not just along a single radar beam. The possibility for continuous operation is also an essential feature. To facilitatefuture science work with a world-leading IS radar facility, planning of a new radar system started first with an EU-funded Design Study (2005–2009) and has continued with a follow-up EU FP7 EISCAT_3D Preparatory Phase project (2010–2014). The radar facility will be realised by using phased arrays, and a key aspect is the use of advanced software and data processing techniques. This type of software radar will act as a pathfinder for other facilities worldwide. The new radar facility will enable the EISCAT_3D science community to address new, significant science questions as well as to serve society, which is increasingly dependent on space-based technology and issues related to space weather. The location of the radar within the auroral oval and at the edge of the stratospheric polar vortex is also ideal for studies of the long-term variability in the atmosphere and global change. This paper is a summary of the EISCAT_3D science case, which was prepared as part of the EU-funded Preparatory Phase project for the new facility. Three science working groups, drawn from the EISCAT user community, participated in preparing this document. In addition to these working group members, who are listed as authors, thanks are due to many others in the EISCAT scientific community for useful contributions, discussions, and support.

Keywords: EISCAT; EISCAT_3D; Radar; Incoherent scatter; Atmospheric science; Space physics; Plasma physics; Solar system research; Space weather; Radar techniques

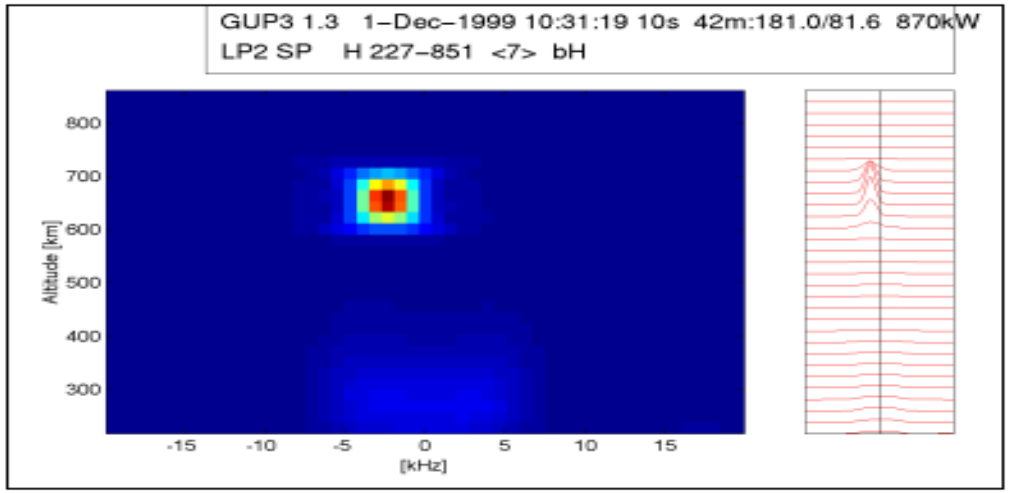
Review

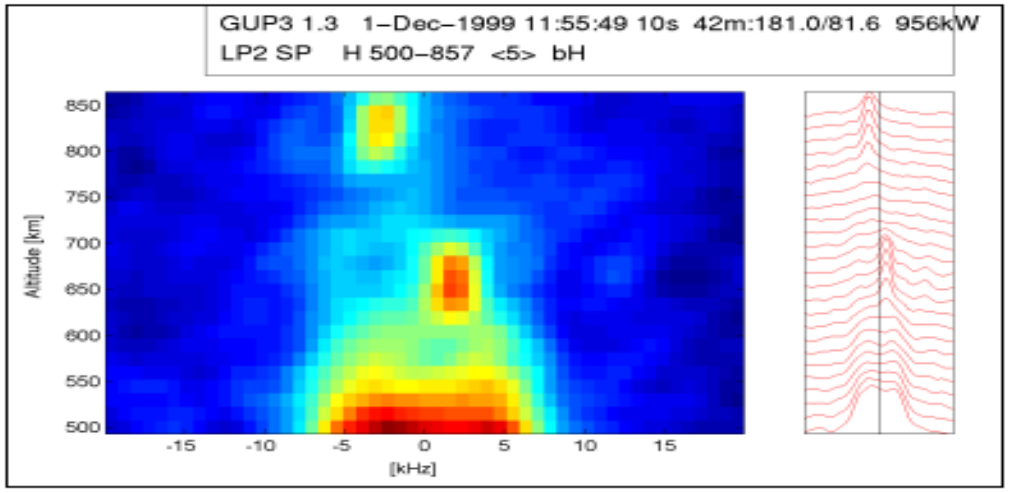
Introduction to EISCAT_3D

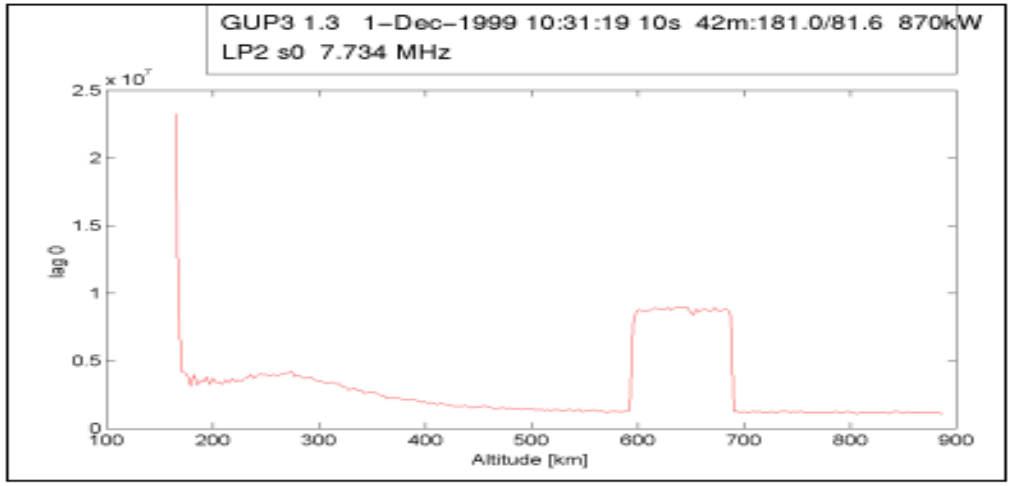
Why do we need EISCAT_3D?

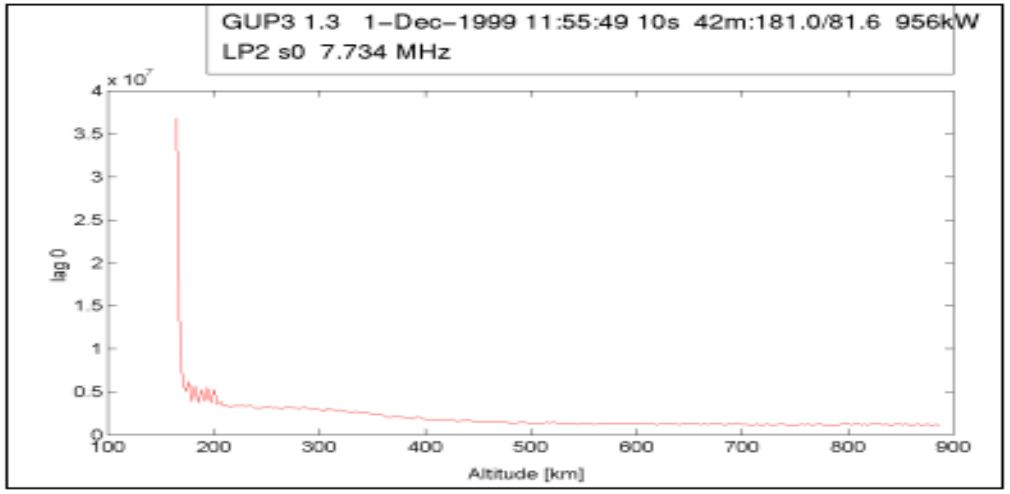
The interaction between the Sun and the Earth is v
to every aspect of human existence. As well as provid
us with heat and light, the Sun supplies the ene
which powers the motion of the Earth's atmosphere
oceans, governing our weather and climate. In additi
the Sun produces the solar wind—a stream of energ

Hard targets and soft targets in radar data





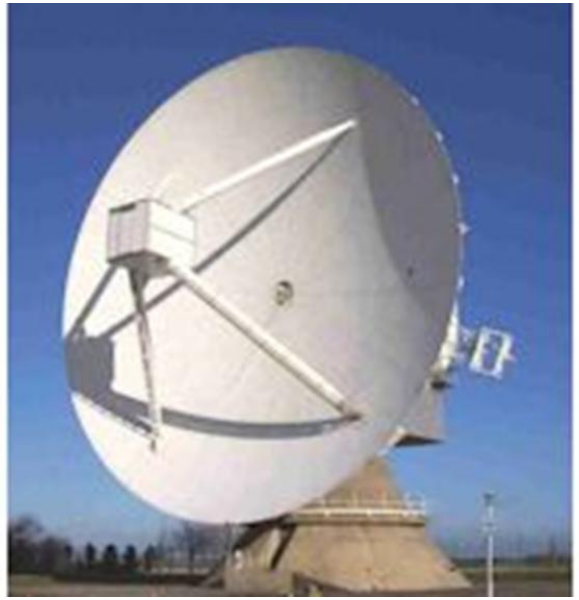


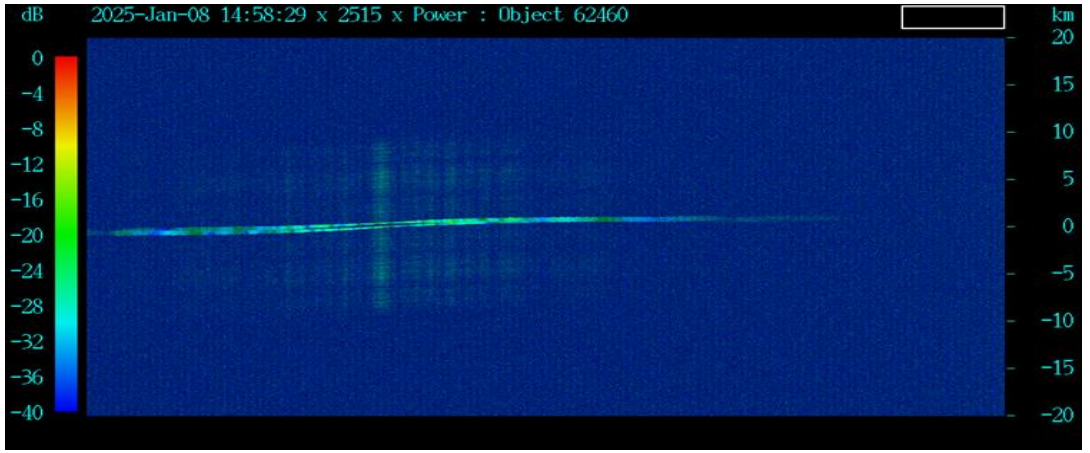


Porteous et el 20023 (https://doi.org/10.194/anngeo-21-1177-2003)

Space Surveillance and Tracking (SST)

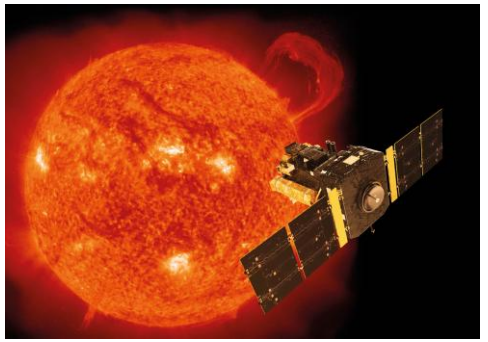
- We started using the 25m radar at our Chilbolton Observatory in 2011, to observe space debris for ESA – now developed into CASTR
- Since then, space tracking has become a much larger activity
- In 2024, UKSA launched the National Space Operations Centre to track UK assets in space
- NSpOC provides warnings for collision, fragmentation and re-entry for UK-registered satellites
- We are observing regularly with Chilbolton to track UK space assets as part of routine monitoring and safeguarding
- We are also upgrading Chilbolton to add imaging capabilities and adaptive tracking for objects with poorly known orbits
- There is a link between SST and space weather via thermospheric density and ion drag
- Hence UK Met Office is a partner in NSpOC

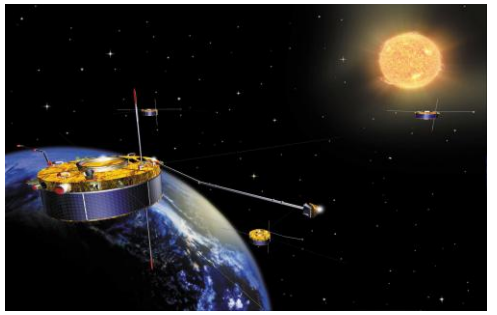




Space Weather at RAL

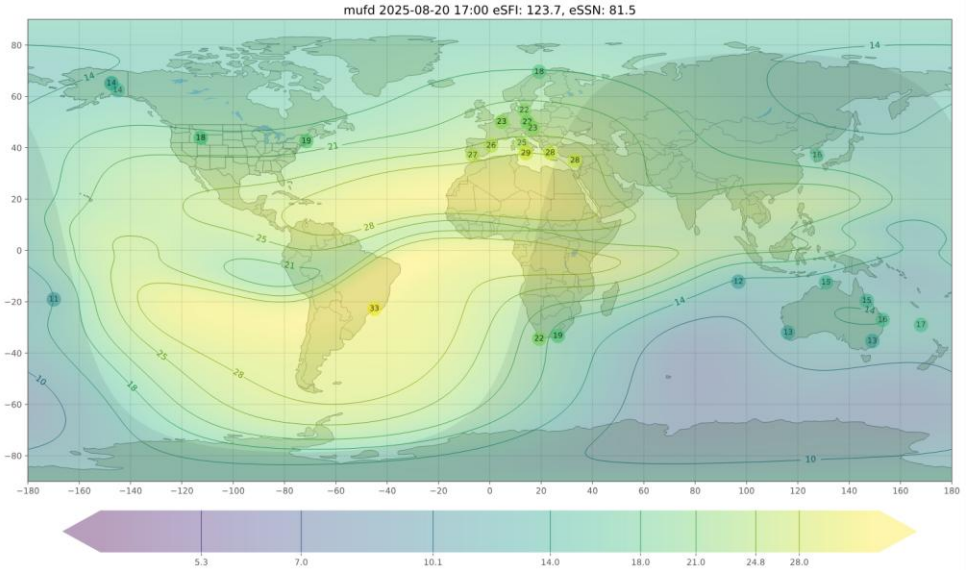
- We have a long history of space weather involvement at RAL
- Heritage dates from the original UK Radio Research Board, established 1924
- Direct links include the UK ionosondes at Chilton and Stanley
- Data archives in the UK Solar System Data Centre (UKSSDC) contain data from 1931 onward
- Since the establishment of the Rutherford Appleton Lab (1981) we have a long history of work on space missions
- Especially notable in the space weather area are involvements with SoHO, Cluster, STEREO and Solar Orbiter
- Our role is not to do space weather operations, but to support the underpinning science that makes monitoring and prediction possible
- We have had a very close relationship with the Met Office Space Weather Operations Centre (MOSWOC), since it was established in 2014

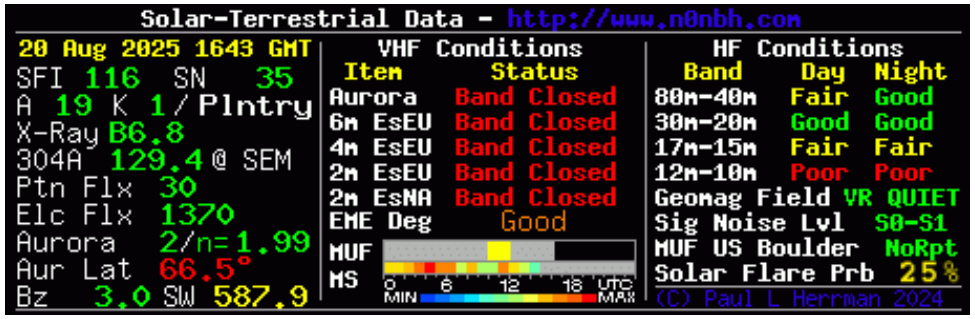




Radio Amateurs and Space Weather

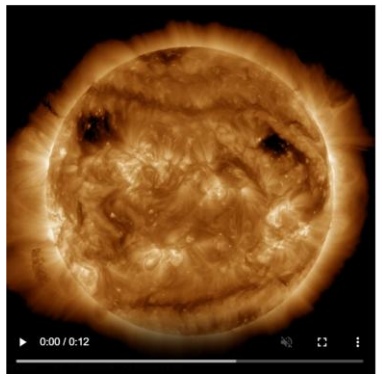
- Several radio amateurs have excellent space weather pages
- Special mention to W5MMW, EA4FSI, W5NOR, VK3FS
- Also to dx.qsl.net and "Ham Radio for Non-Techies"
- The reason is obvious, given the importance of space weather for the ionosphere (not just at high latitudes)
- However, space weather is also important to many other communities:
  - Satellite operators (radiation and comms)
  - Aviation operators (radiation and HF comms)
  - Other transport operators (global positioning and timing)
  - Grid, pipeline and rail operators (induced currents)
  - Electronics and materials manufacturers (space, avionics and ground sectors)
  - Other communications providers
  - Aurora tourism operators
  - Government risk and civil contingency managers
  - Space scientists

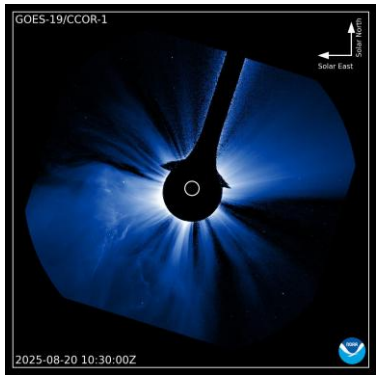


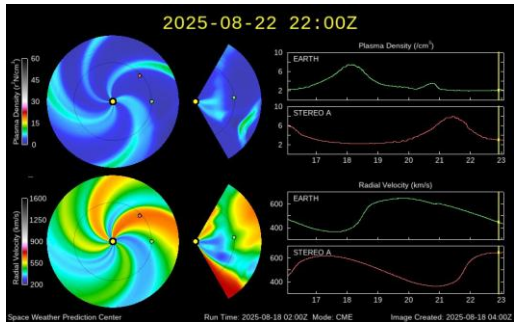


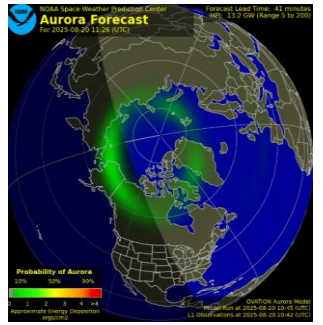
What do Space Weather Forecasters care about?

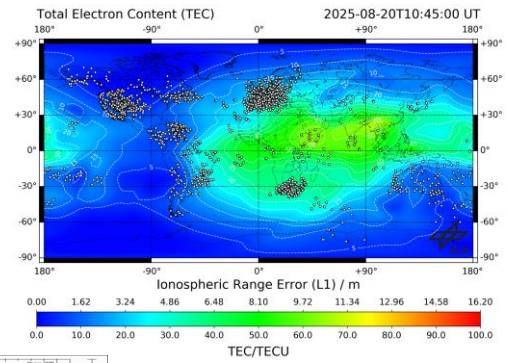
- Solar Conditions
  - Sunspot groups, active regions, coronal holes, flares
  - Solar magnetic structure
  - Solar radio emissions
- Solar Wind Propagation
  - Coronal morphology
  - Solar wind structure
  - Arrival time of transients
- Geomagnetic Activity
  - Storms and substorms
  - Auroral oval location
  - Effects on grounded infrastructure
- Radiation Environment
  - Radiation belts and effects on spacecraft
  - Energetic particles in the atmosphere (aerospace)
  - Ground-level neutron events
- Ionosphere and Communications
  - Global morphology – profiles and TEC
  - Propagation, absorption and scintillation
- Neutral Atmosphere
  - Thermospheric density and satellite drag

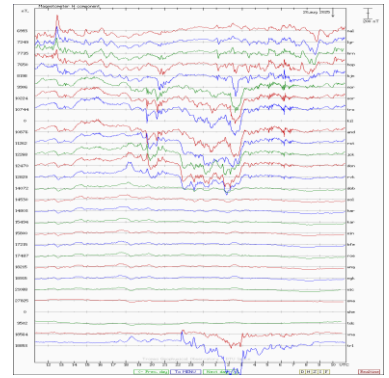


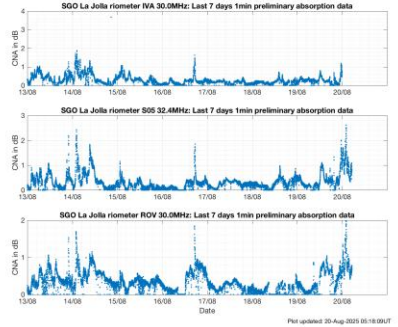






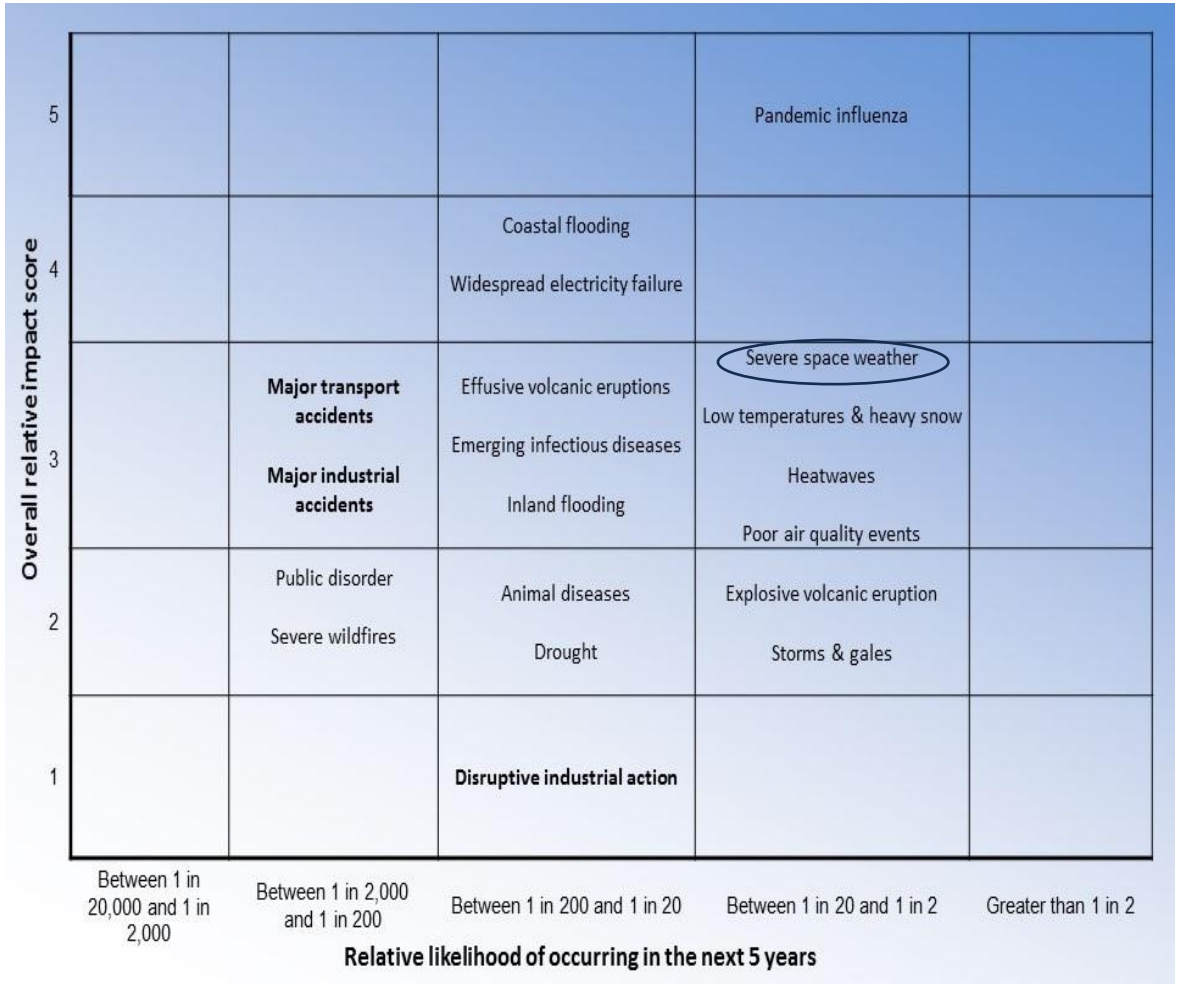


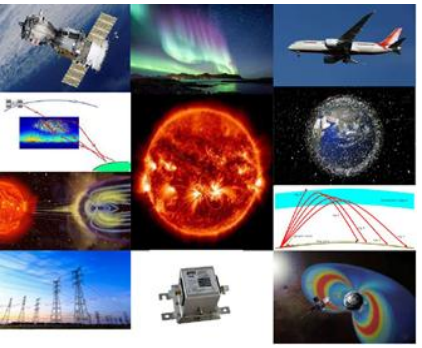




Severe Space Weather and the National Risk Register

- Space weather was added to the UK National Risk Register in 2011
- Relatively high impact and reasonably high likelihood
- Paradigm is the “Carrington Event” of 01-02/09/1859
- Aurora seen as far south as the Caribbean, with global impacts on the telegraph system
- A Carrington event has odds of about 2%-12% in a given solar cycle
- Financial impacts of such an event could be huge without adequate warning and mitigation
- Being on the National Risk Register implies:
  - A risk-owning ministry (was BEIS, then DESNZ, now DSIT)
  - An expert committee (SEIEG) feeding into the SAGE civil contingencies mechanism
  - A centre for monitoring and forecasting the risk (Met Office Space Weather Operations Centre)





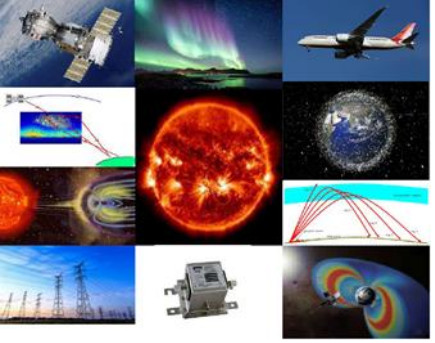
Government-Level Context

UK Research and Innovation

- Space Domain Awareness is one of five capability areas identified in the Space Industrial Plan, which followed on from the National Space Strategy

- This includes a new national capability goal for Space Weather:
  - *"In support of our national space goals, by 2035, the UK will be capable of high confidence [24 hour] forecasting lead times for operational space weather predictions, enabling actionable space weather mitigation within a focussed R2O2R approach."*

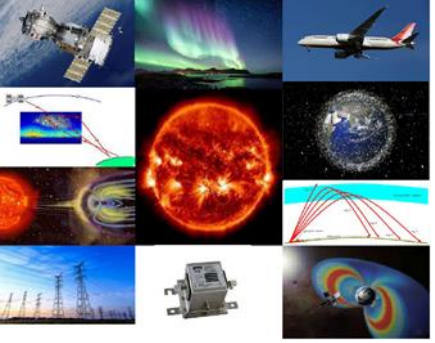
- Our aim has been for UKRI (STFC and NERC) to help deliver this objective…..



What is/was SWIMMR?

UK Research and Innovation

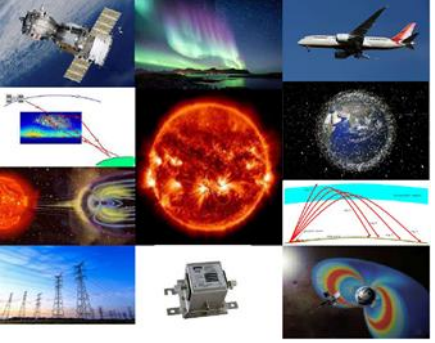
- A £20M five-year programme in UKRI SPF Wave 2, funded jointly by STFC and NERC
- To develop and deploy new models, instruments and test facilities to support the UK space weather community and national capabilities in MOSWOC (UK Met Office)
- Addressing priorities identified by UK government (BEIS, MoD and DfT) – based on input from MOSWOC and senior members of the academic community
- Aimed at improving predictions and establishing a legacy of enhanced operational capabilities, aligned with National Severe Space Weather Preparedness Strategy and UK National Space Strategy (both issued September 2021)
- We are functionally at the end of the programme, with some unspent resource but unable to carry funding into another financial year
- There are still some loose ends uncompleted, but the programme has achieved the overwhelming majority of its original aims
- Met Office will receive 6 new models, some new instruments and model components
- New airborne monitoring instruments are now operational, and two space launches have deployed monitoring instruments into space



How SWIMMR Started

UK Research and Innovation

- SWIMMR began as a one-page idea submitted by me to the "STFC Priority Projects" exercise in summer 2018
- Idea came from previous discussions between RAL Space and MOSWOC on how to pull UK academic work on space weather through into operations
- Janet Seed (then Acting STFC Strategy Director) advised us to steer this toward a business case for Strategic Priorities Fund "Wave 2"
- Initial advice was to keep it small (~£5M)
- Enthusiasm from the Met Office (Mark Gibbs) and NERC (Jacky Wood) meant that we ended up with a £20M bid, across two Research Councils
- Very useful advice from CLF (especially Rajiv Pattathil) who already had EPAC running as an SPF "Wave 1" project
- Support from three ministries (especially from BEIS) and from US colleagues was very important in helping us get funded

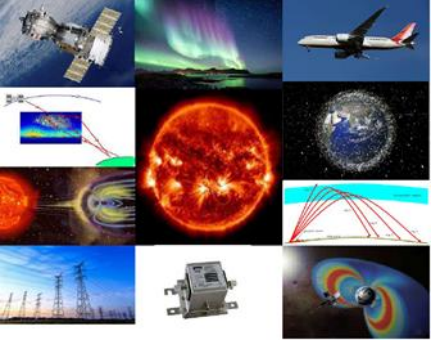


The SWIMMR Programme

UK Research and Innovation

- Eleven projects, funding divided almost equally between STFC and NERC

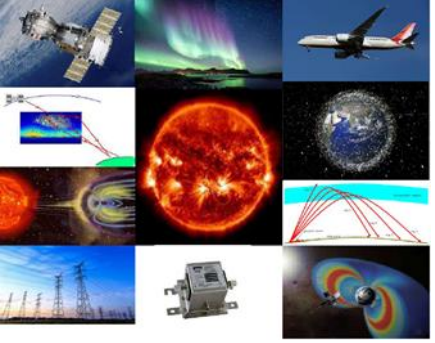
- Delivered through NERC (total budget £9.8M)
  - N1: Improvement of satellite risk forecasts (budget £1.9M)
  - N2: Improvement of aviation risk forecasts (budget £1.6M)
  - N3: Improved forecasting for GNSS and HF communications (budget £2M)
  - N4: Improved forecasting of ground level current effects (budget £2M)
  - N5: Improved forecasts of satellite drag (budget £1.1M)



The SWIMMR Programme

UK Research and Innovation

- Delivered through STFC (total budget £10.2M):
  - S1: In-situ radiation measurements for space and aviation (budget £5.7M)
  - S2: Support for technology testing and modelling (budget £655k)
  - S3: Support for the transition from research to operations (budget £920k)
  - S4: Forecasting from the Sun to L1 (budget £450k)
  - S5: Support for a ground radiation monitoring network (budget £1.4M)
  - S6: Production of an updated space weather impact study (budget £300K)



Satellite Radiation Forecast

UK Research and Innovation

SWIMMR N1 – Satellite Radiation Risk Forecast (BAS, Sheffield, UCL and Northumbria)

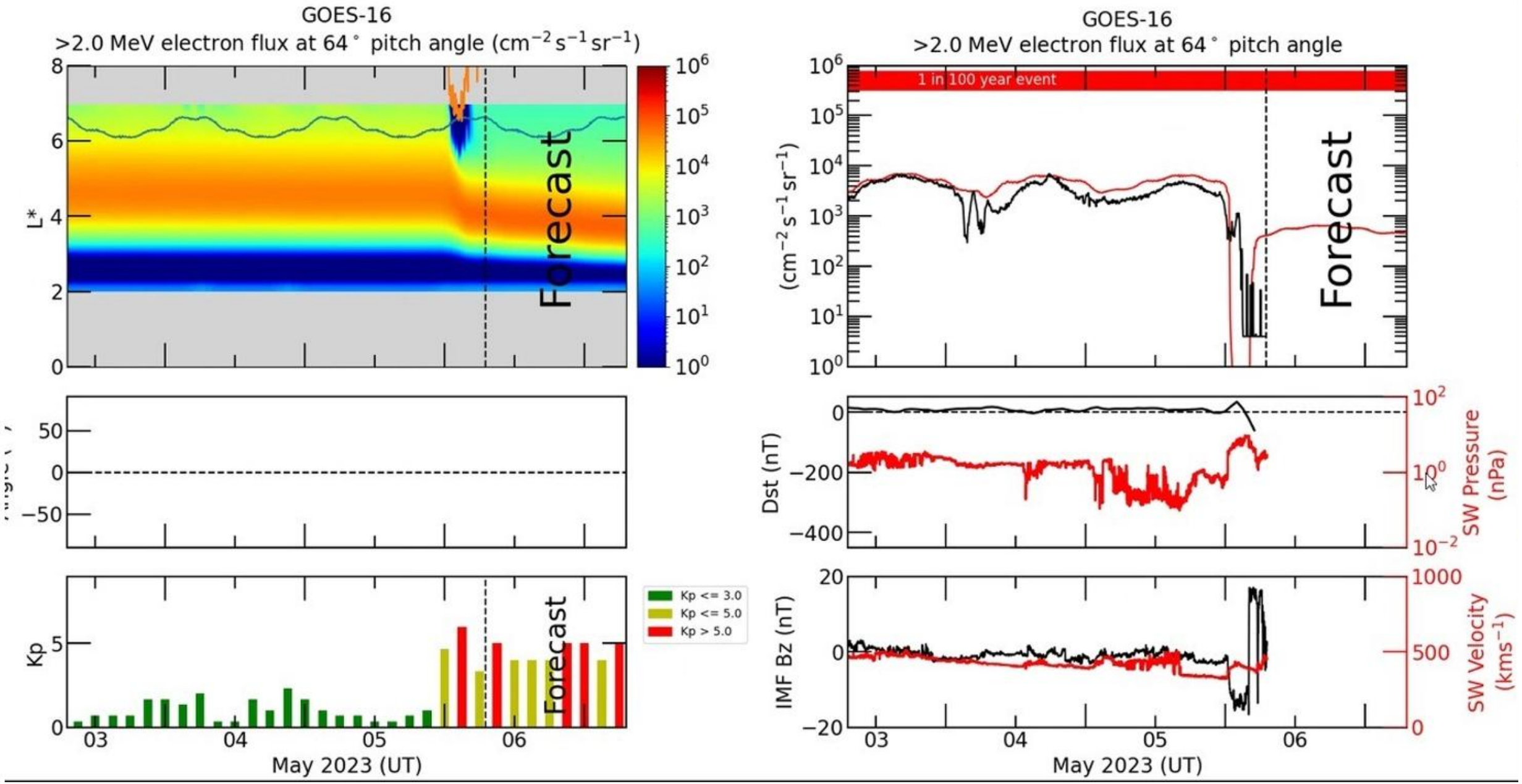
Objectives:

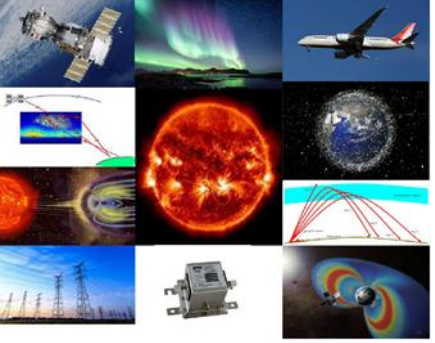
- "MOSWOC capability for satellite radiation forecasting"
- Develop a real-time system to forecast radiation exposure to satellites for different orbits
- Quantify the risks of damage or degradation

Status

- Electron belt (BAS-RBM) and proton belt (BAS-PRO) models now delivered to MOSWOC
- BAS-RBM running on MOSWOC AWS system, BAS-PRO implementation more problematic
- Research extensions (new diffusion models) to be implemented
- Inner belt extension model still in development (will need more funding to complete)
- Risk indicator tools developed, some still to be integrated, model discrepancies corrected
- Project ended September 2024

BAS-RBM - Relativistic Electron Forecast, issued at 0701 UT, 06 May 2023





Satellite Radiation Forecast

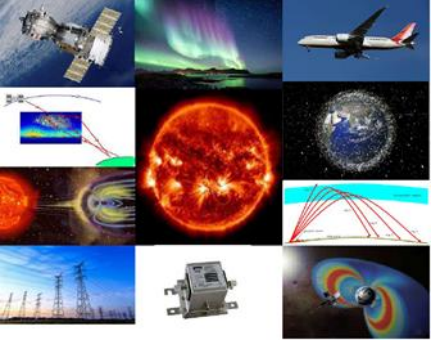
UK Research and Innovation

SWIMMR N1 – Satellite Radiation Risk Forecast

(BAS, Sheffield, UCL and Northumbria)

How did it go?

- Some key expertise (senior scientist/programmer) moved on during the project
- Heavily reliant on a few skilled but very busy people, but...
- ….mostly mission accomplished
- Two main models delivered, but one (BAS-PRO) not running at MOSWOC
- Integration of tools not fully completed, tools not fully integrated
- Inner belt extension delivery was not completed
- This project somewhat too ambitious?
- Probably would have fully completed, if not for changes in key personnel



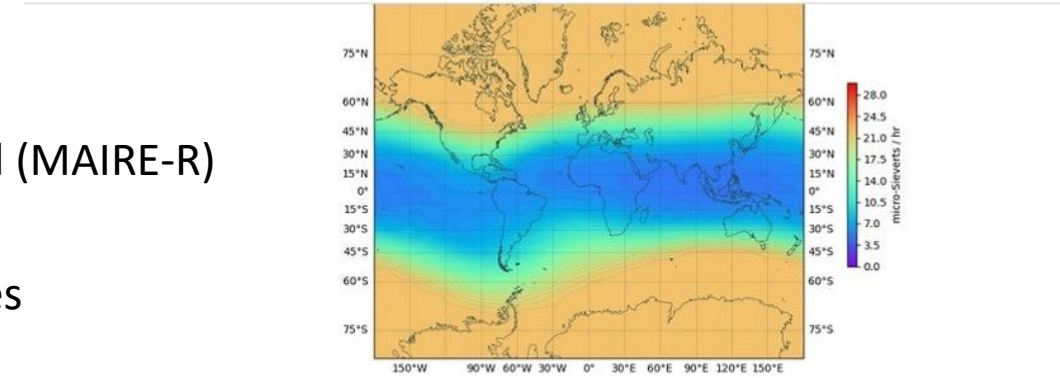
Aviation Radiation Modelling

UK Research and Innovation

<u>SWIMMR N2 - Radiation Modelling for Aviation</u> (University of Surrey, BGS, MSSL and UCLan)

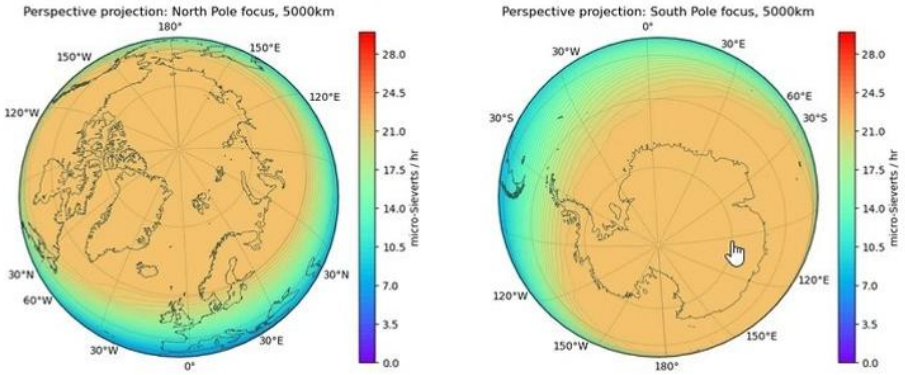
<u>Objectives:</u>

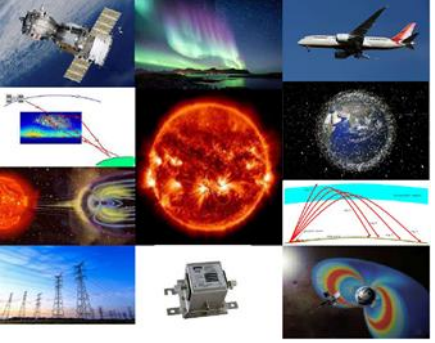
- *"MOSWOC capability for aviation risk forecasting"*
- Provide a global nowcast model (MAIRE+) and a research model (MAIRE-R)
- Test and validate the new models
- Provide improved insight/methods to forecast radiation increases



<u>Status:</u>

- Operational model for aviation MAIRE+ delivered to Met Office
- Validated with historic data – new data from S1 and S5 to come
- Already used in some joint exercises with US and European partners
- Research version (MAIRE-R) delivered as a development model
- Supplemented by energetic particle model (SPARX) from UCLan





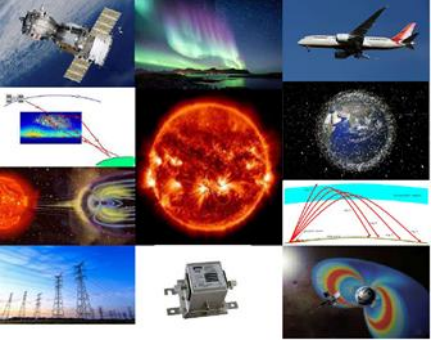
Aviation Radiation Modelling

UK Research and Innovation

SWIMMR N2 - Radiation Modelling for Aviation (University of Surrey, BGS, MSSL and UCLan)

How did it go?

- All objectives achieved
- Delivered a well-documented model
- Already being used at MOSWOC
- Used in exercises with international partners
- Research version also delivered
- (Needs validation data from other SWIMMR projects)



Ionosphere and Thermosphere

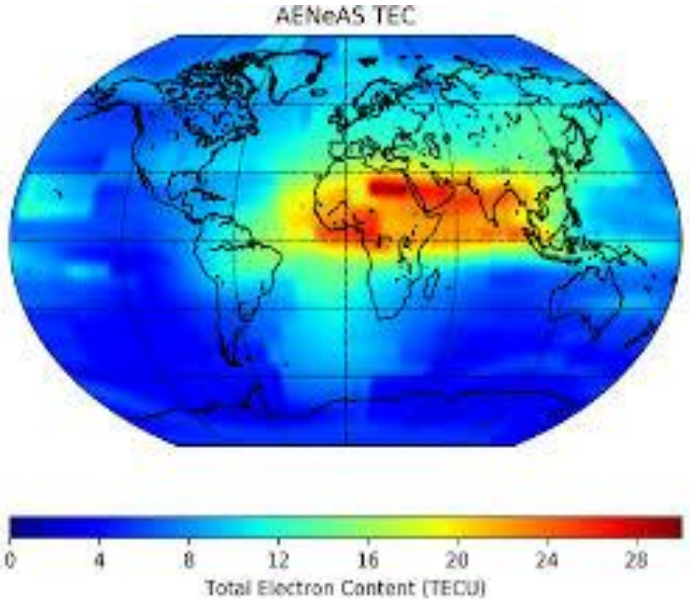
UK Research and Innovation

SWIMMR N3 and SWIMMR N5 – Assimilative modelling of the ionosphere and thermosphere

(University of Birmingham)

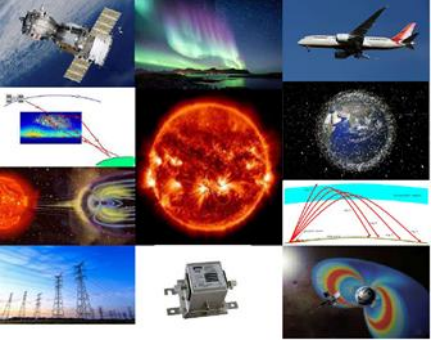
Objectives:

- Improved MOSWOC prediction for GNSS and trans-ionospheric effects
- Improved MOSWOC capability for satellite drag and orbit perturbation forecasting
- Enhance the AENeAS assimilative tool for ionospheric and thermospheric forecasting
- Provide new tools for forecasting ionospheric absorption, scintillation and gradients
- Nowcast and forecast GNSS and HF performance for aviation applications
- Investigate effects of Joule heating and radiative cooling on satellite and space debris orbits



Status:

- Two self-consistent models using same assimilation scheme (AENeAS)
- Model needs to be run on Met Office operational HPC, because of large data traffic
- Met Office operational HPC is a secure system, so approval process is long
- Expect deployment to operational HPC in summer 2025
- Initial deployment to Met Office parallel HPC, so that porting is as easy as possible, ended March 2025



Ionosphere and Thermosphere

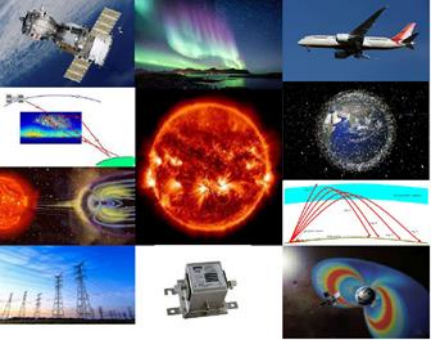
UK Research and Innovation

SWIMMR N3 and SWIMMR N5 – Assimilative modelling of the ionosphere and thermosphere

(University of Birmingham)

How did it go?:

- We will get there, but initial plan to deploy on AWS was flawed
- We learned a lot about limits of AWS for data assimilation models
- New strategy to deploy on HPC was more time-consuming
- Some compromises needed on how input data are provided
- As a result, final deployment will happen in summer 2025
- First model products will be online by year end
- There are lots of use cases for these models – more still becoming evident
- Including potential uses for NSpOC, ideas of assimilating tracking data



Ground Effects Forecasts

UK Research and Innovation

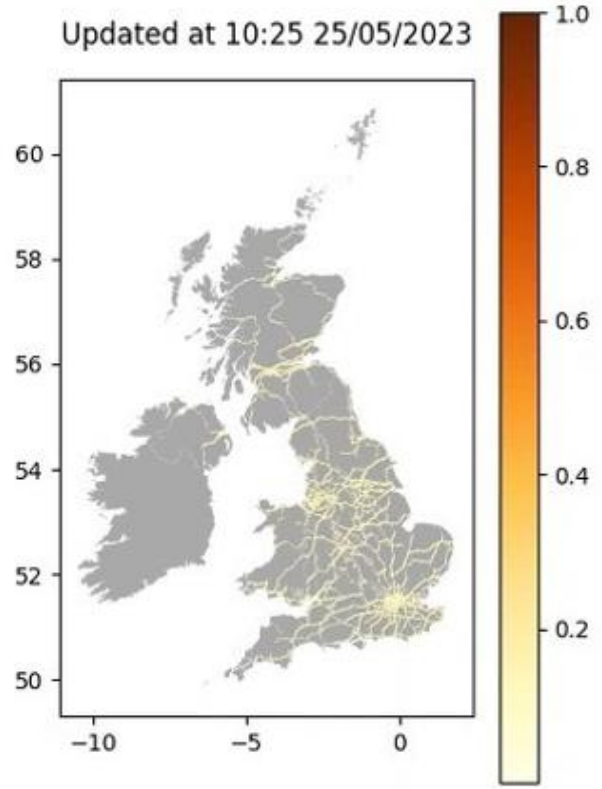
<u>SWIMMR N4 - Ground Effects Forecasting</u> (GICs) (British Geological Survey, BAS, UCL, Imperial)

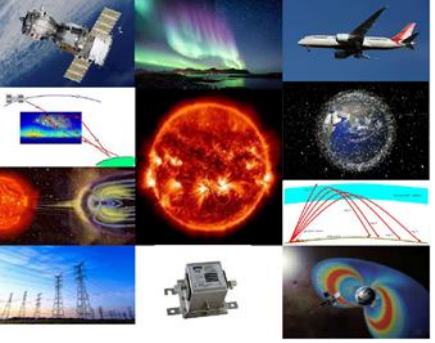
<u>Objective:</u>

- *MOSWOC capability for power grid and pipeline forecasting*
- Model and tools for nowcast/forecast of GIC impacts on UK grid, pipeline and rail system
- Conduct fieldwork to develop an improved ground conductivity model for UK
- Deploy new variometers to support UK magnetic modelling

<u>Status</u>:

- Nowcasting and forecasting code now running at UKMO
- GORGON model running on Met Office MONSOON system
- Fieldwork finished and new conductivity model complete
- New variometers installed (Enniskillen, Herstmonceux, Market Harborough)
- Will supplement data from existing UK magnetometers





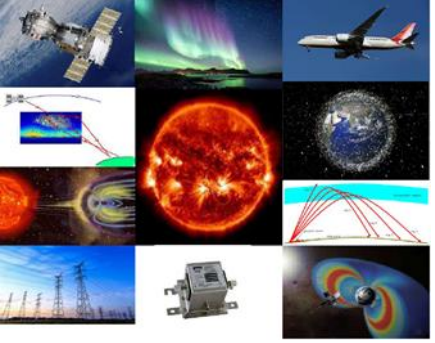
Ground Effects Forecasts

UK Research and Innovation

SWIMMR N4 - Ground Effects Forecasting (GICs) (British Geological Survey, BAS, UCL, Imperial)

How did it go?

- Mission accomplished
- Survey completed and well-documented model delivered to MOSWOC
- Added rail network capability, which was not in the original plan
- Model already used to simulate the May 2024 storm
- Join between the GORGON and SAGE elements could be better
- GORGON running on MONSOON "on-demand" HPC, not operational HPC



Space and Airborne Monitoring

UK Research and Innovation

SWIMMR S1 - Space and Airborne Radiation Monitoring

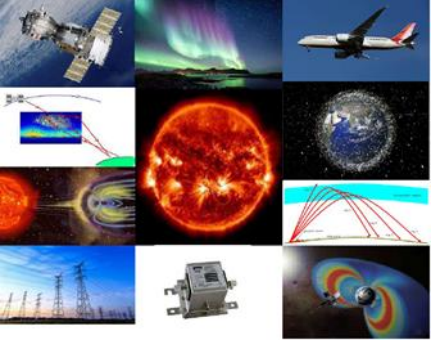
(RAL Space, D-Orbit, Surrey, CVUT)

Objectives:

- Two trusted satellite monitors in key orbits, ten airborne sensors on North Atlantic routes, improved, miniaturised monitoring technology
- To fly space-borne radiation monitors to 645km and 1200km orbits (OneWeb altitudes)
- To fly airborne radiation monitors on commercial aircraft and balloons, with data supplied to Met Office.
- To design UK miniaturised sensors for multiple spacecraft applications.

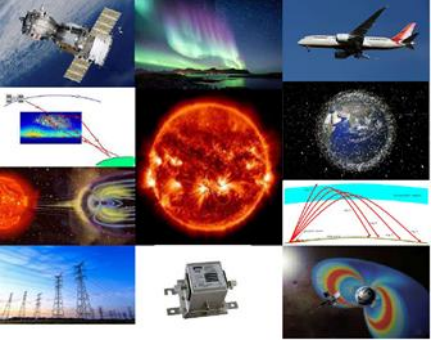
Status:

- First Hardpix space sensor (645 km) launched in June 2023, second in February 2025
- Wanted to get to 1200km circular orbit, but will only got to 1200km x 330km (April 2025) – still delivering data
- First airborne and balloon units delivered from June 2024, commercial flights started December 2024
- Clearances for flights took quite a long time, not all sensors get allocated (and some allocated sensors not yet flying)



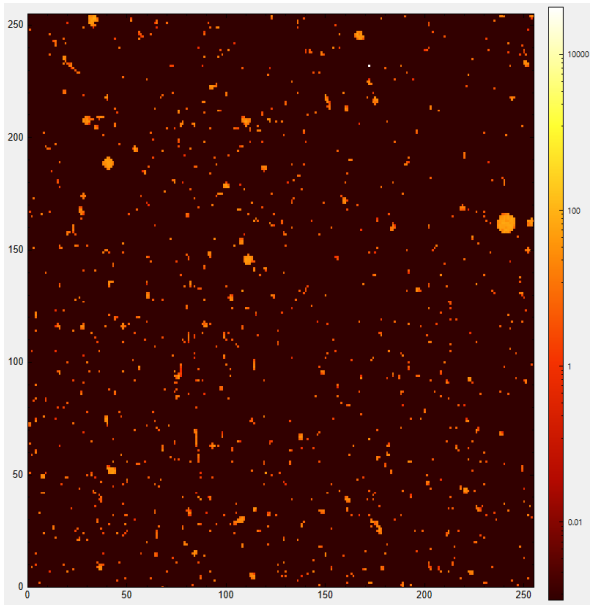
First SWIMMR S1 Mission

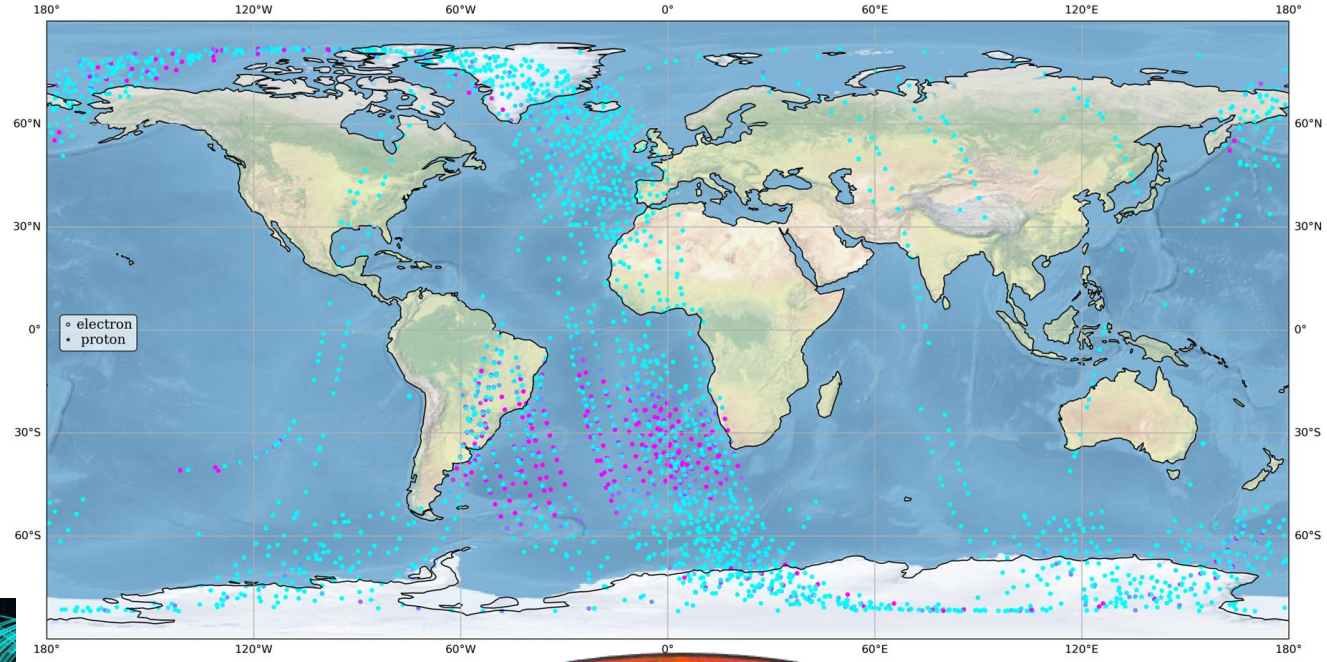
UK Research and Innovation

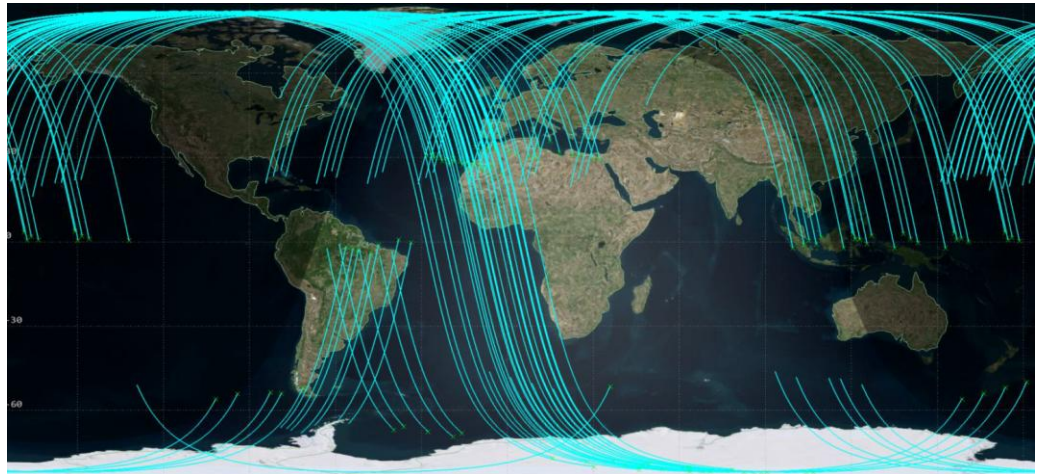


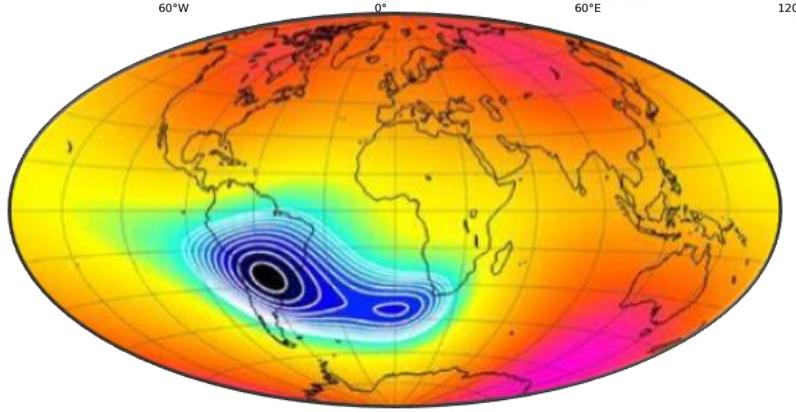
First SWIMMR S1 Mission

UK Research and Innovation

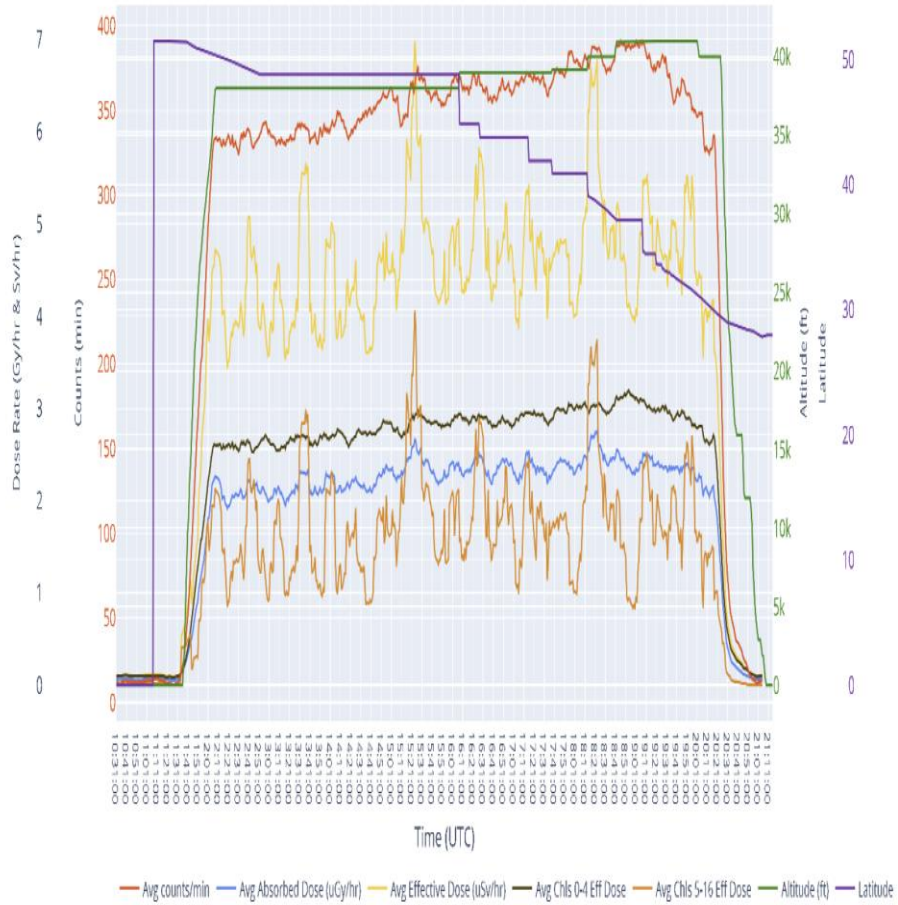




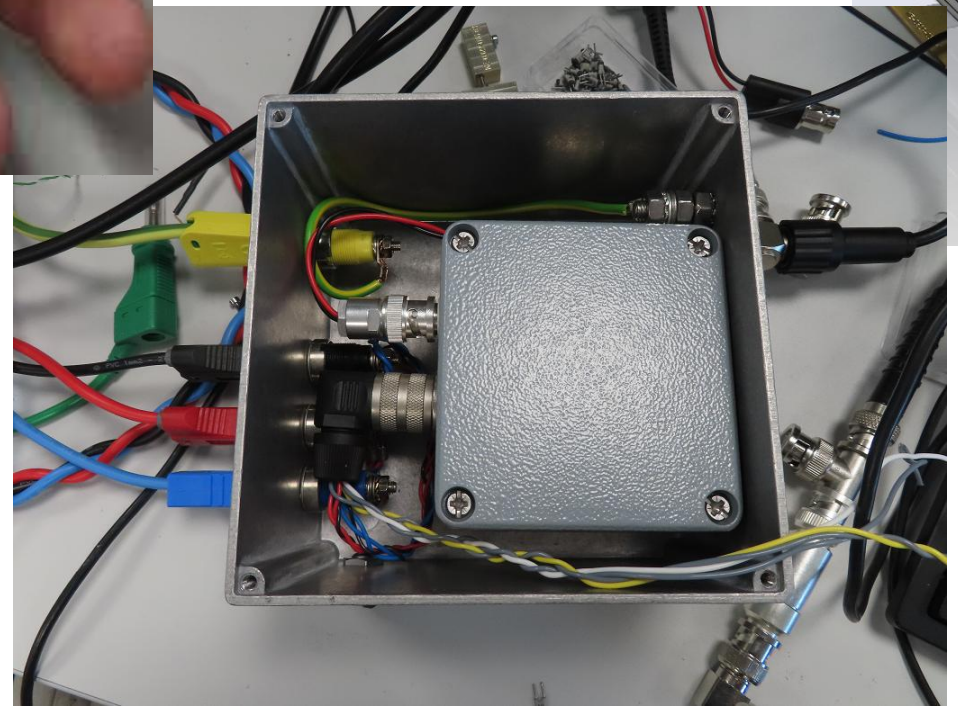


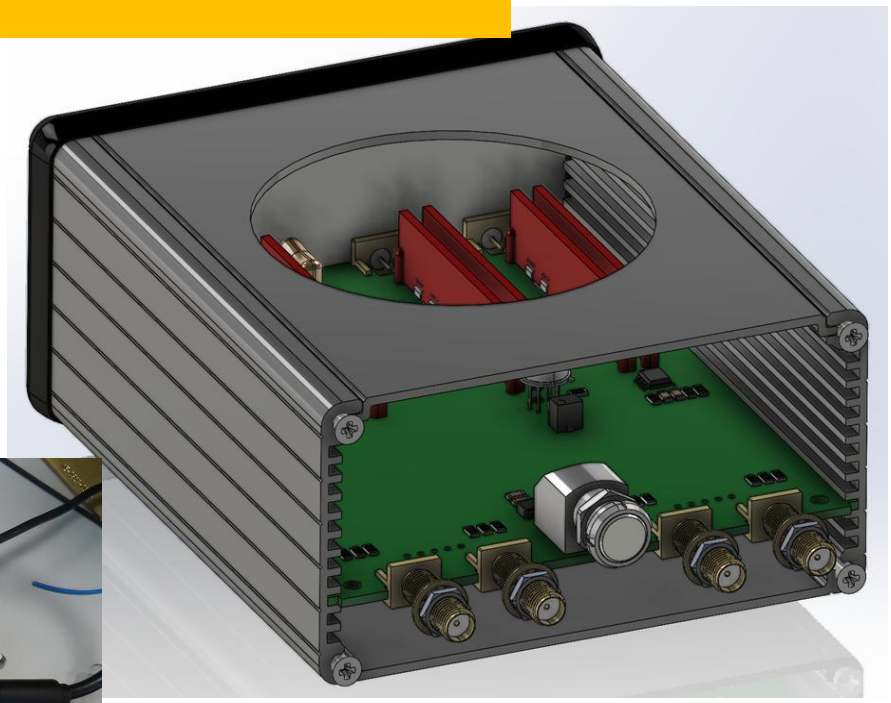


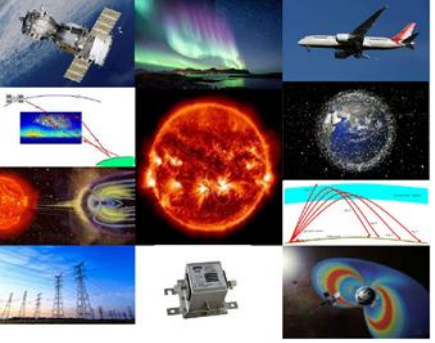
SWIMMR S1 Airborne Sensors



SWIMMR Miniaturised Instruments







Space and Airborne Monitoring

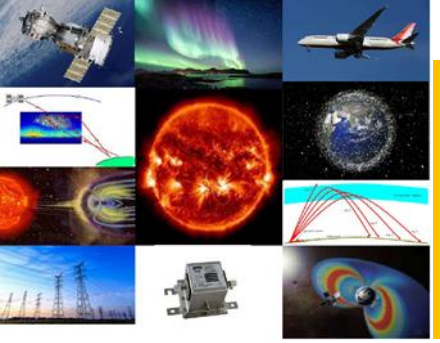
UK Research and Innovation

SWIMMR S1 - Space and Airborne Radiation Monitoring

(RAL Space, D-Orbit, Surrey, CVUT)

How did it go?:

- We will achieve most aims, but underestimated complexity/cost
- Only one space launch/platform provider combination available at our price point
- However, we did manage to secure two launches
- Proof of concept using "newspace"missions was successful
  - Has established a useful precedent, and OneWeb will start flying their own monitors
- Some unexpected effects of Covid
  - Getting detectors onto planes was much slower than anticipated
  - Lots of interest in these detectors, however
  - Likewise miniaturised instrument development has been quite slow
  - A long time was taken to sort out requirements for miniaturised instruments



Technology Testing and Modelling

UK Research and Innovation

SWIMMR S2 - Testing facilities for radiation resilience (STFC)

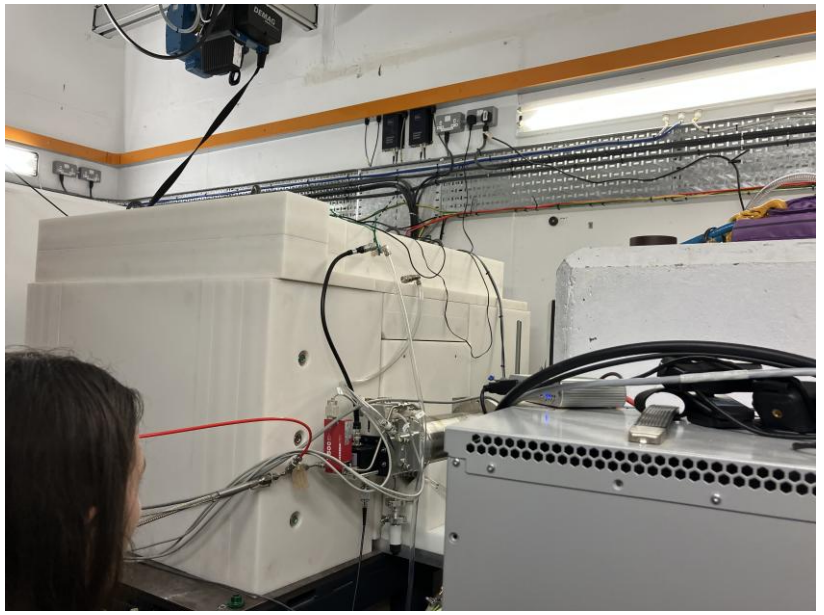
Objective:

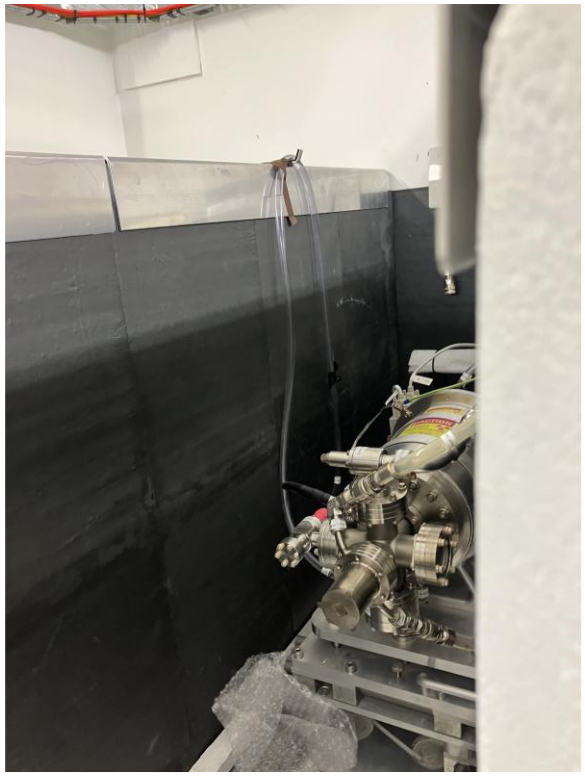
- Subsidised technology testing programme
- Upgrade the ChipIr neutron testing facility at RAL
- Add additional small sources for stand-alone operations
- Advertise the ChipIr facility better and more widely, subsidise new users

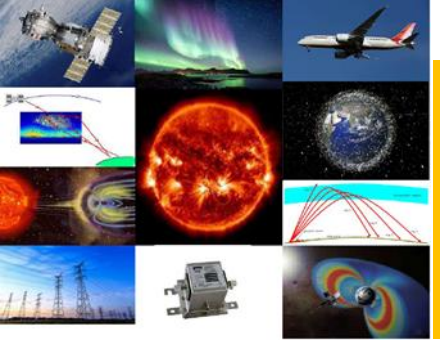
Status:

- Upgrades made to ChipIr facility at Harwell (ISIS) and new small source facilities purchased
- Promoted ChipIr testing for several space weather industry users
- Helped test SWIMMR S5 project kit and helped internationalise design

ChipIR and NILE







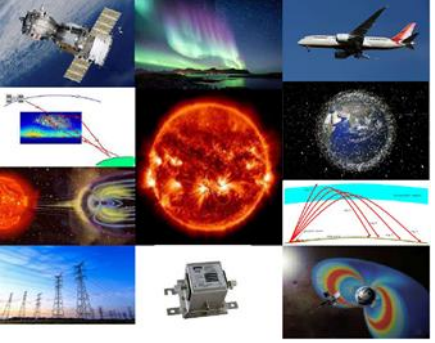
Technology Testing and Modelling

UK Research and Innovation

SWIMMR S2 - Testing facilities for radiation resilience (STFC)

How did it go?:

- Able to deliver some upgrades to ChipIr
- Co-funded a new low-energy neutron source facility (NILE)
- Established a subsidised testing programme
- Number of new users was somewhat less than anticipated
  - Timing, during and immediately after Covid, was not ideal
  - Useful publicity for ChipIr and hope that take-up will continue to increase
  - Some very useful synergy with S5 neutron monitoring project
  - Able to unlock some international opportunities by tapping into ISIS user base



SWIMMR R2O Portal

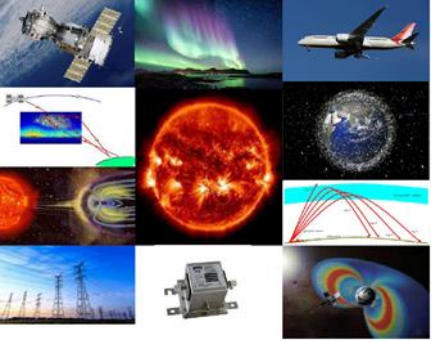
UK Research and Innovation

SWIMMR S3 - Research to Operations Platform for model migration

(Met Office, CACI/BJSS, RAL)

Objective:

- The S3 Research to Operations Project aimed to develop an IT infrastructure to facilitate research partners making their models operational in the forecasting environment used by MOSWOC
- The goal was to enable academics and other stakeholders to collaborate on the operational mitigation of space weather effects.
- This IT framework will allow model developers to perform verification, validation and reliability testing in their own institutions using a common environment, which is available to Met Office Forecasters
- This will allow more rapid prototyping of forecast models, and facilitate strong interaction between the Met Office and UK research community



SWIMMR R2O Portal

UK Research and Innovation

SWIMMR S3 - Research to Operations Platform for model migration

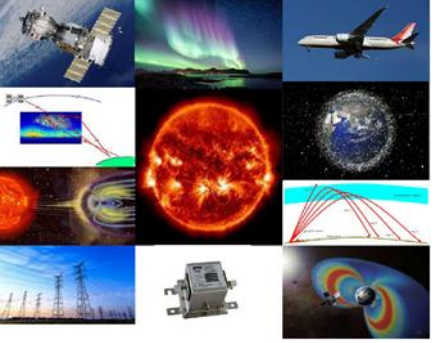
(Met Office, CACI/BJSS, RAL)

Status:

- Framework completed on time and has implemented N1, N2, N4, and parts of S4 models in Met Office AWS environment
- Opened up several new APIs for datasets to drive models
- Will continue to be used as future models arrive

How did it go?

- Mission accomplished!
- Expect for AENeAS models, which can't run on AWS
- Some new requirements appeared along the way, not initially expected



Solar Wind Modelling

UK Research and Innovation

SWIMMR S4 - Solar Wind Empirical Ensemble Package

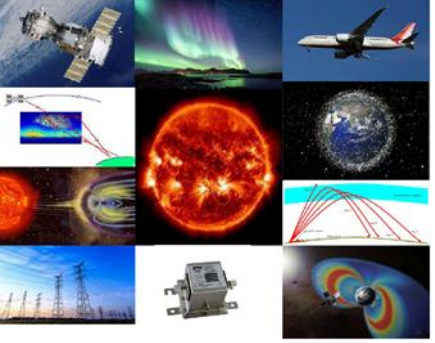
(University of Aberystwyth plus Reading and Durham)

Objective:

- Supply Met Office with a suite of solar coronal and solar wind models to complement and improve current forecast capabilities, especially through ensemble modelling
- Explore potential for advanced forecasting of IMF orientation during CME arrival.

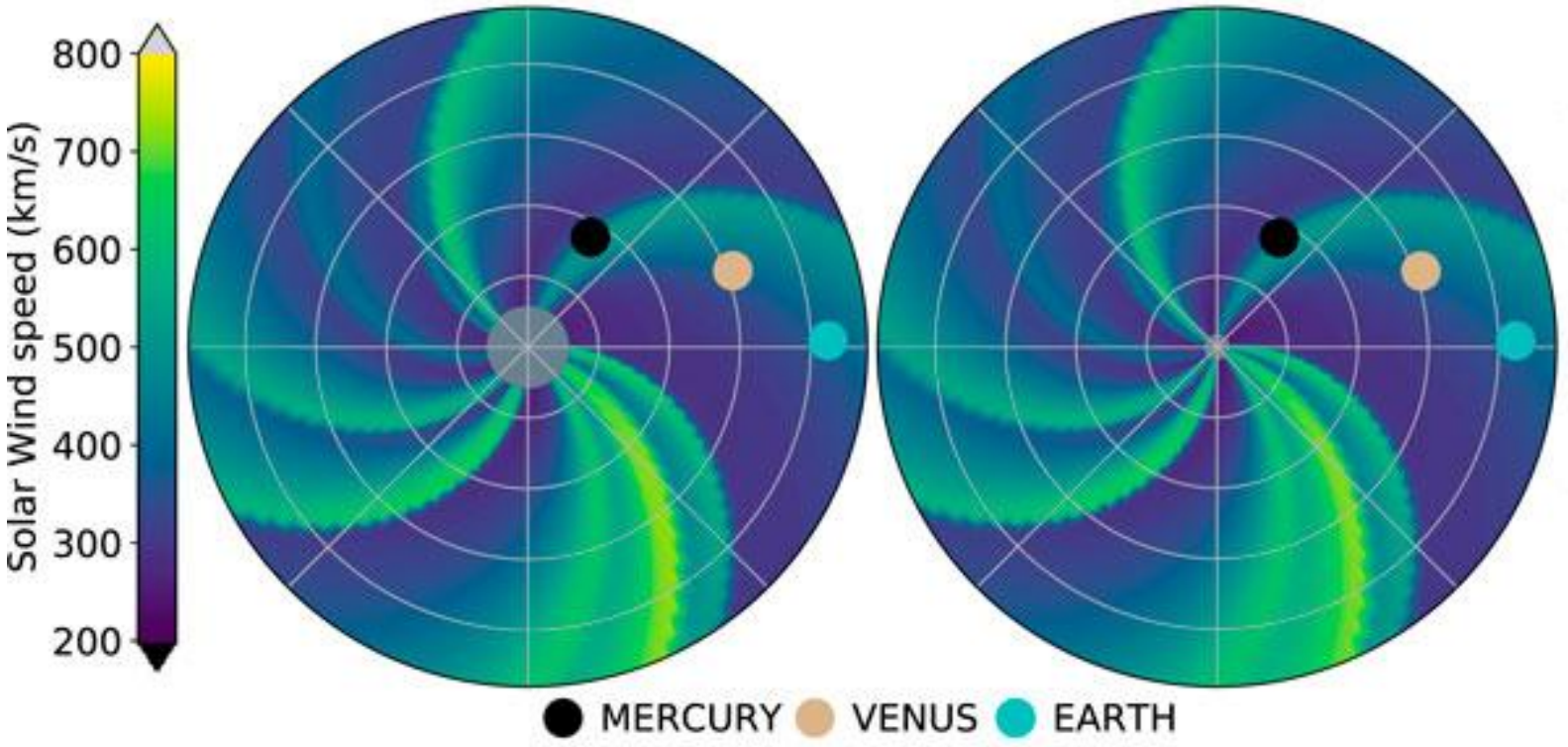
Status:

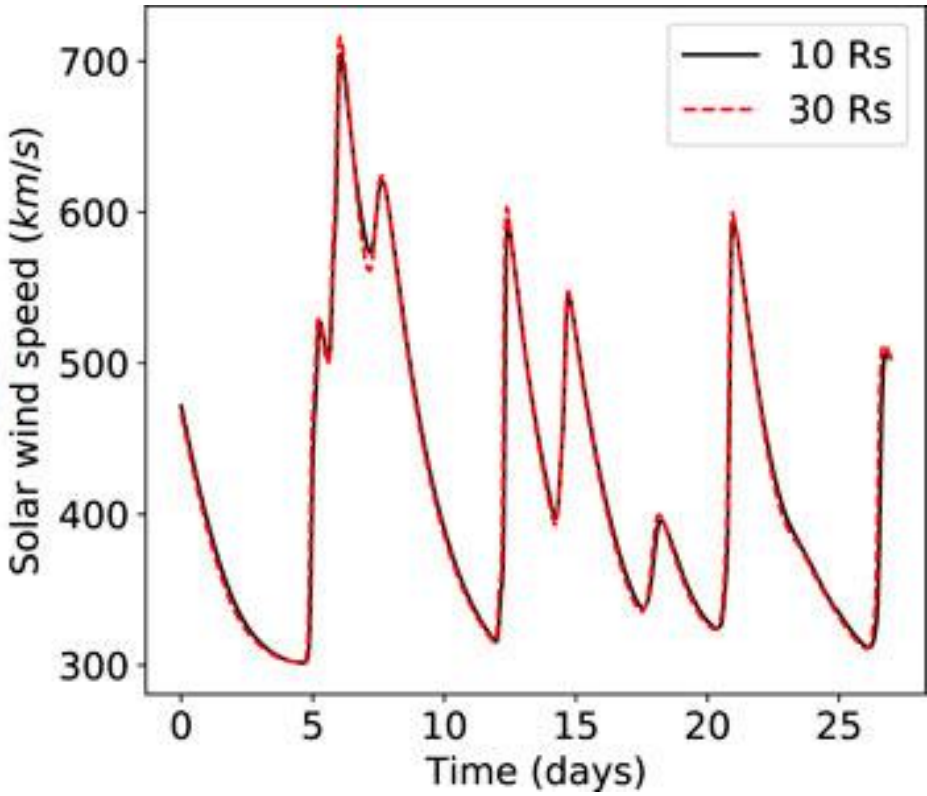
- SWIMMR grant has finished, some outstanding tasks ongoing
- Most of the planned component modules (CORTOM, DUMFRIC HUXt and PFSS) in place at the Met Office. Some final upgrades/updates to models ongoing
- The missing module is the Automated CME Tracker (ACT) which is being recoded into Python at Aberystwyth before delivery to the Met Office and data agreement needs to be signed
- Some documentation to be delivered to MOSWOC

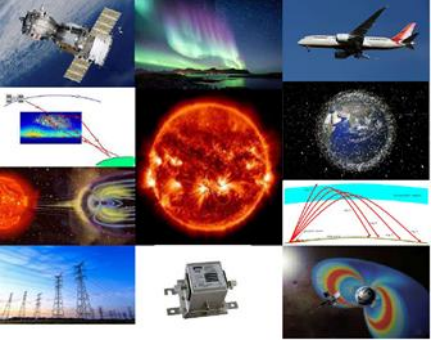


Solar Wind Modelling

UK Research and Innovation







Solar Wind Modelling

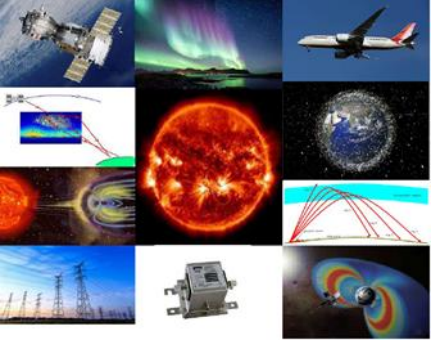
UK Research and Innovation

SWIMMR S4 - Solar Wind Empirical Ensemble Package

(University of Aberystwyth plus Reading and Durham)

How did it go?:

- Almost all elements successfully delivered to MOSWOC
- One module needs recoding to Python as IDL is not operational at MOSWOC
- Multiple modules, will take some time to optimise their use
- Some work on documentation and licence agreements still needed
- Project maybe slightly too ambitious for available time and effort



Ground-Based Neutrons

UK Research and Innovation

SWIMMR S5 - Ground-Based Neutron Monitoring Network

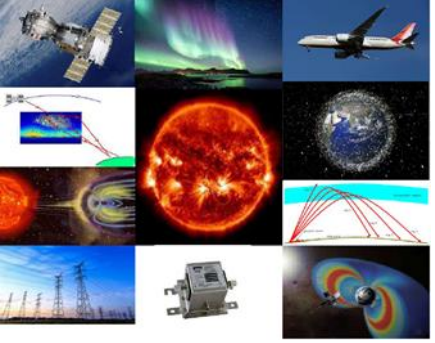
(Lancaster, Mirion Systems, UKAEA)

Objective:

- Design, construct and deploy a network of ground-based UK neutron monitors
- Use these to supply real-time data to UK Met Office.

Status:

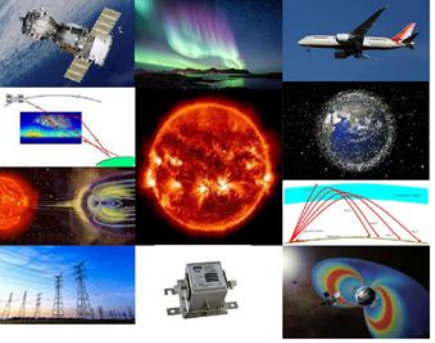
- Assembled contact neutron monitor for deployment in Camborne
- Containerised neutron monitor deployed to Camborne in December
- Smaller monitor for Lancaster complete, commissioned in February
- University of Surrey developed a monitor for Lerwick, accepted in March, deployed in April



Ground-Based Neutrons

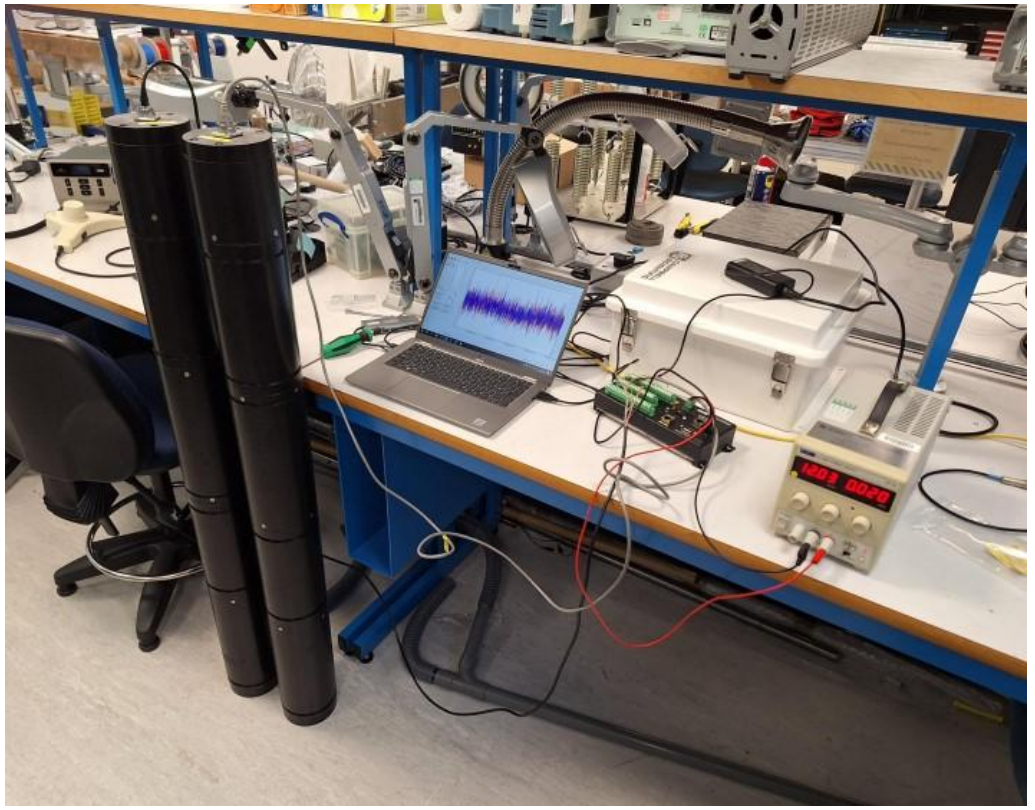
UK Research and Innovation

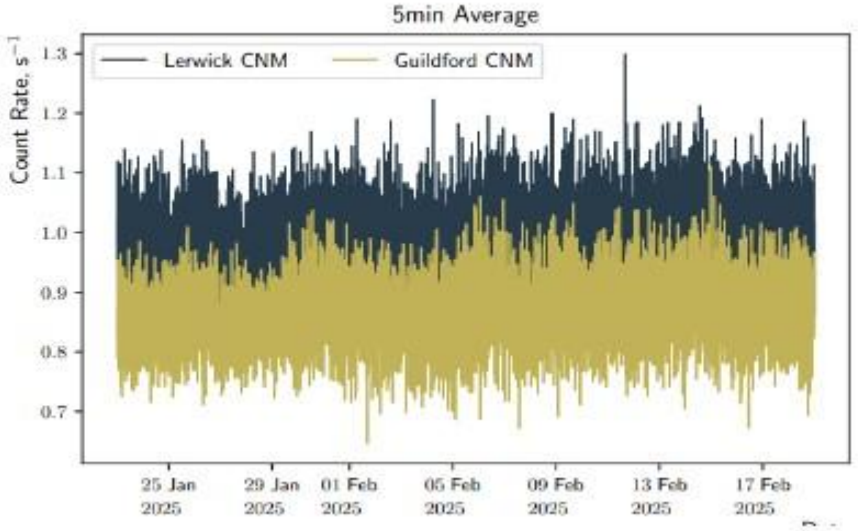
Camborne and Lancaster Monitors

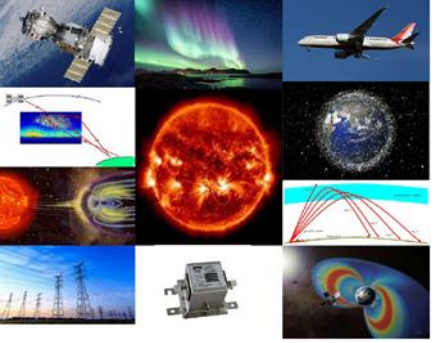


Lerwick Monitor

- Lerwick monitor commissioned from University of Surrey - £69.3k contract
- Uses two Boron Trifluoride tubes
- First powered up in Surrey January 9th
- Ran in test mode until March 11th
- Compared with Surrey Group monitor in Guildford
- Deployment happened last week in April
- MOSWOC has accepted this instrument on behalf of Met Office
- We have paid Surrey, based on Met Office accepting the risk of installation







Ground-Based Neutrons

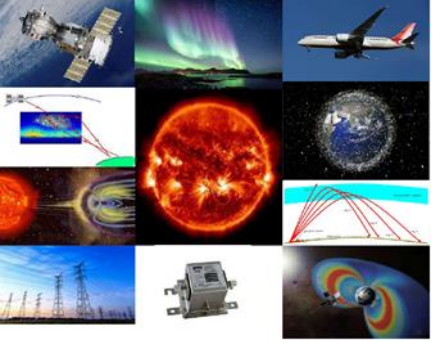
UK Research and Innovation

SWIMMR S5 - Ground-Based Neutron Monitoring Network

(Lancaster, Mirion Systems, UKAEA)

How did it go?:

- Had a major change of design philosophy part-way through
  - From Boron-Coated Straw detectors to Helium-3 tubes
- Ambitious for available budget!
- Difficulty of getting deployments approved was underestimated
- In the end, UK has its first neutron monitors since the 1970s
- International interest in new design was unexpected bonus



Impacts and Policy

UK Research and Innovation

SWIMMR S6: An updated space weather impact study

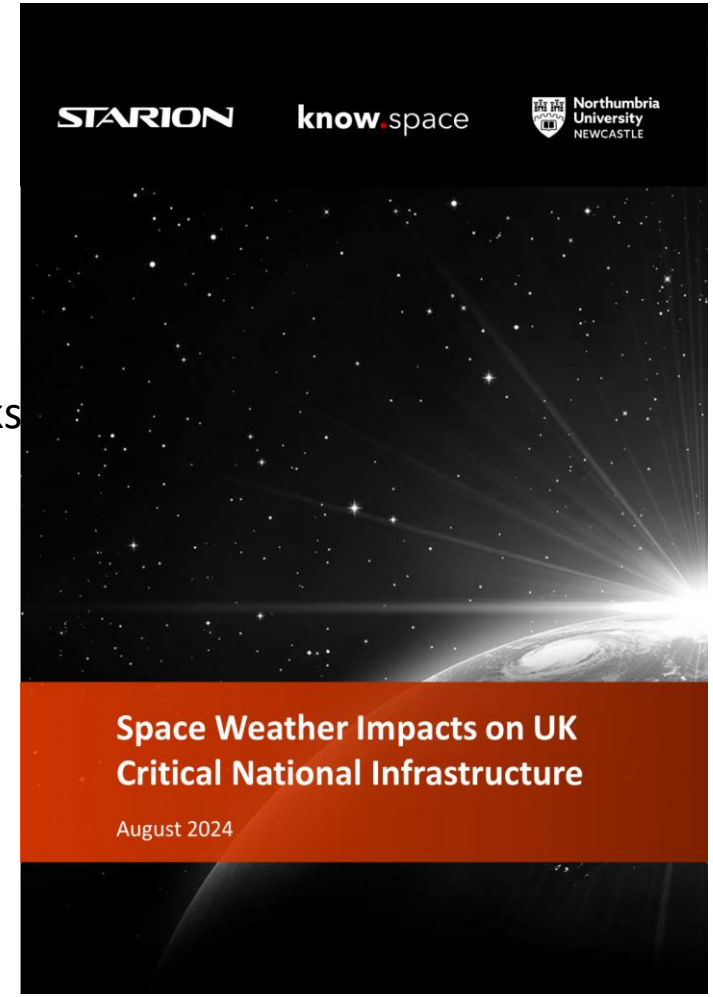
(Rhea-UK, Know.Space, University of Northumbria)

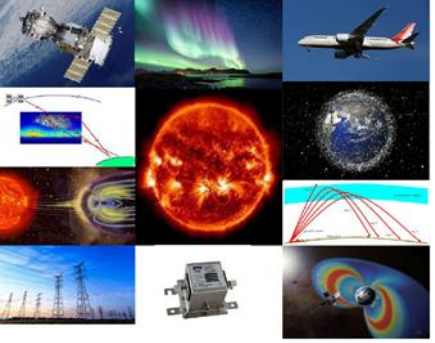
Objective:

- Produce a space weather impact study building on the 2013 Royal Academy of Engineering report, covering national strategic/economic factors, emerging risks and new technology areas.
- Ensure peer review, publication and dissemination of the above.

Status:

- Final report produced December 2025, but not endorsed by SEIEG
- Presented at a public workshop at the RAS in October
- Recommendations to government have been discussed with ministries
- Published as an STFC report in February 2025, plus supporting annex





Impacts and Policy

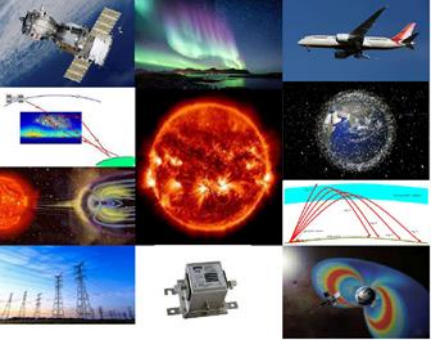
UK Research and Innovation

SWIMMR S6: An updated space weather impact study

(Rhea-UK, Know.Space, University of Northumbria)

How did it go?

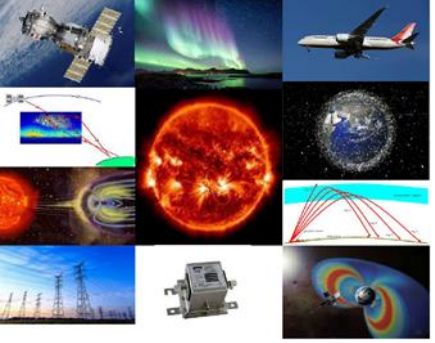
- Probably underestimated the amount of work and resources needed to ensure coverage of all sectors
- Sectoral and cross-sectoral workshops were a very positive experience
- Enthusiastic engagement of the expert community and community forums
- Great engagement from ministries, very helpful pointers on advice to government
- However, we underestimated the difficulties of peer review and could not get the conclusions endorsed by SEIEG
- Beneficial to the participants, will lead to new opportunities



So how was it overall?

UK Research and Innovation

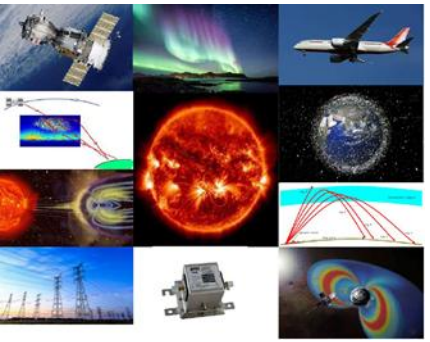
- A very interesting and rewarding experience!
- High quality, wonderfully committed and enthusiastic teams
- We were probably a bit overambitious, as almost every project fully used its budget (and many went way more than the extra mile!)
- Fantastic support and engagement from the teams at MOSWOC (including BJSS and CACI), e.g. to get models up to AUL 8
- We have exemplified the role that UK Reseach Councils can have in supporting and managing development of strategic science
- We have not achieved everything we wanted – but we got very close
- Hopefully SWIMMR has created a paradigm which can be repeated
- “SWIMMR has set a new global standard for how research should be done to support operations.”
    - Clint Wallace, Director of NOAA Space Weather Prediction Center, Boulder, Colorado, USA



SWIMMR Lessons Learned

UK Research and Innovation

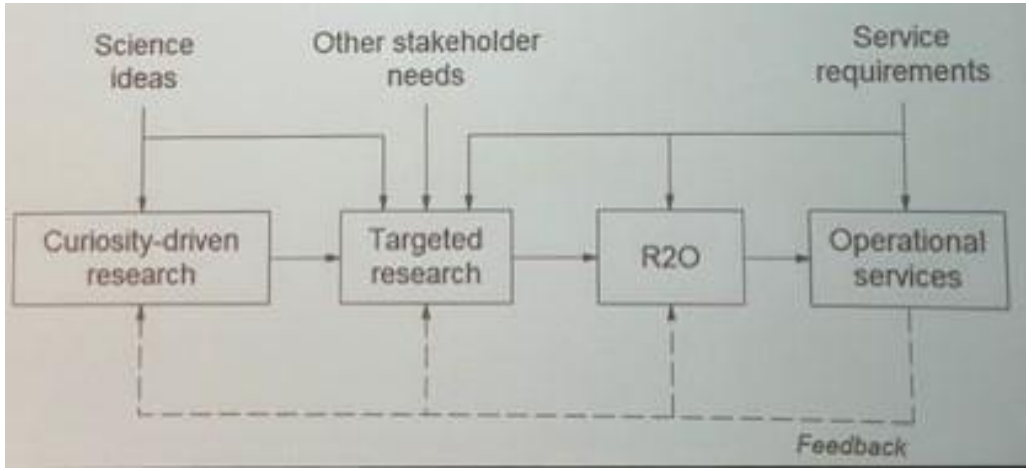
- Much of what happened was good:
  - Our scope and costings were broadly correct
  - Project teams were highly motivated and very committed
  - Programme managers (Mila, Catherine and Elise) were all excellent
  - The Governance model worked well
  - We got exceptional support from Met Office (much more than funded for)
  - Good support from STFC Procurement, Finance and Legal
  - Grant teams in STFC and NERC were magnificent (even during Covid)
  - Our annual SWIMMR Symposium has now become an independent meeting
- Some things were outside of our control
  - Covid caused a significant delay in activities needing labs,
  - Covid also delayed BGS fieldwork and caused a reduction in testing at ISIS
  - Some key personnel moved on during the projects
  - We do not have management authority for people outside of STFC funded on grants
  - Russian invasion of Ukraine reduced options for cheap space launches
  - Problems starting up our first space sensor when in orbit

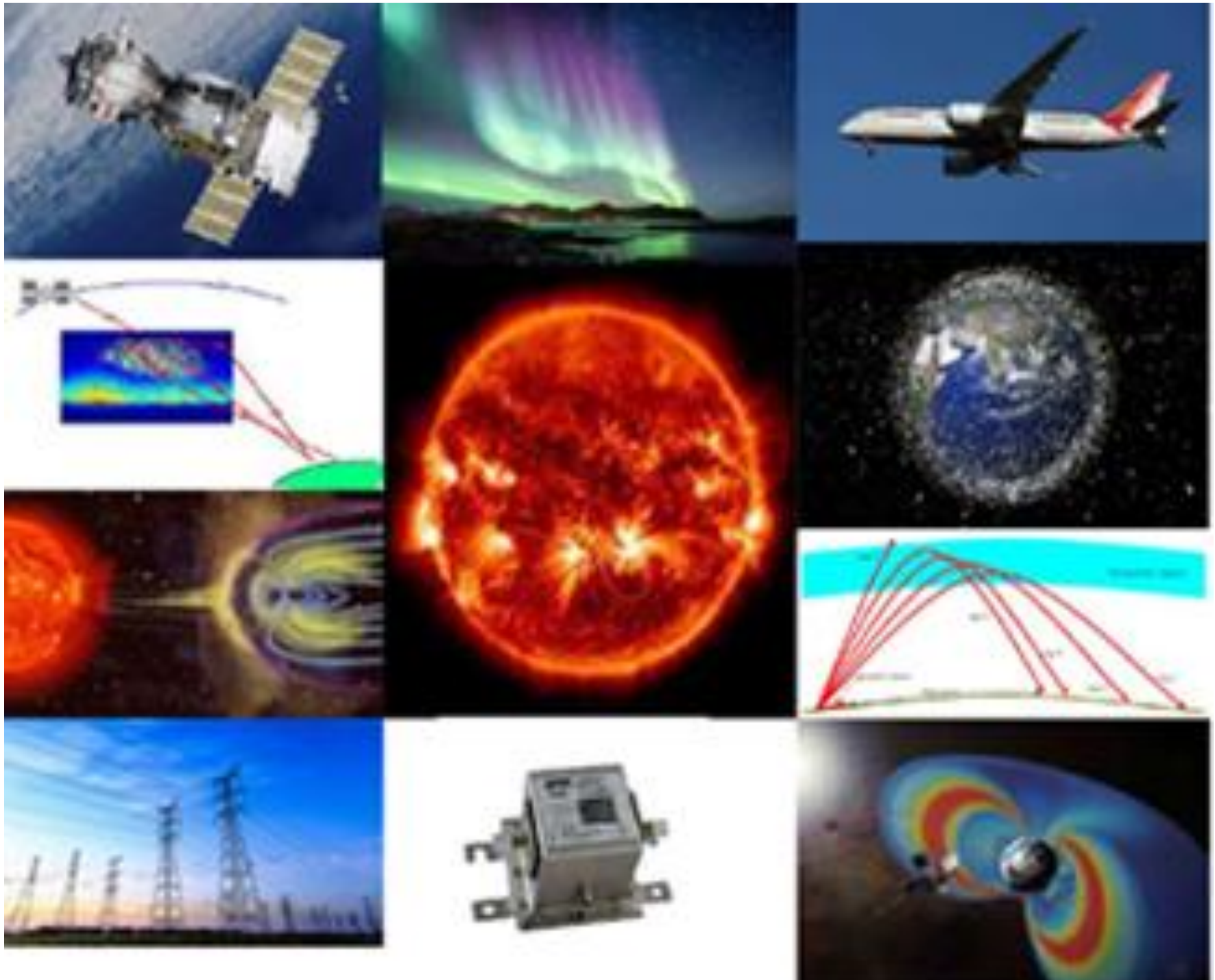


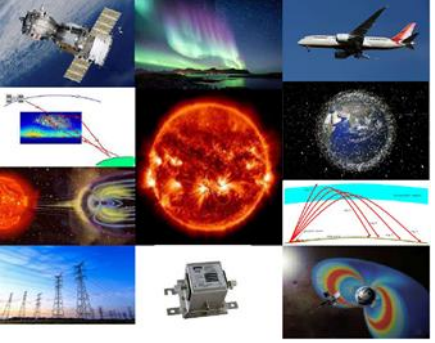
What comes next?

UK Research and Innovation

- We have to realise that SWIMMR has been R2O, not R202R
- SWIMMR deliverables will keep MOSWOC busy for a long time!
- Several more cycles are needed based on user engagement and service improvement
- There will be a legacy of continuing activities between MOSWOC and modelling groups, hopefully extending into the coming CSR periods
- A new, smaller successor programme to SWIMMR will start this autumn, with two aims
  - Tidying up the loose ends of previous projects
  - Laying the foundations for a new larger programme based on R2O2R and greater international collaboration







What is still to do?

UK Research and Innovation

NERC side of SWIMMR Programme:

SWIMMR N1

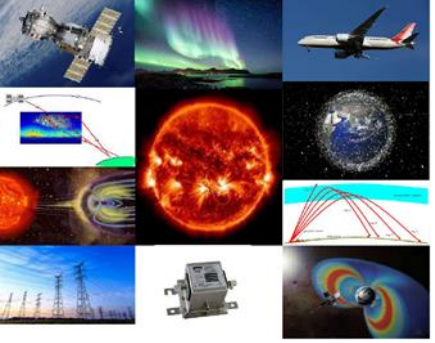
- Tools (MULASSES, SHIELDOSE) to be integrated
- BAS-PRO model to be got working at MOSWOC
- Inner Belt Extension to be done

SWIMMR N2

- Model validation to be done using SWIMMR S1 aviation and SWIMMR S5 data

SWIMMR N3/N5

- Security checks and full implementation on Met Office operational HPC to be done
- Model usage agreement to be completed
- Last grant payment is at end of Q1 of FY26/27



What is still to do?

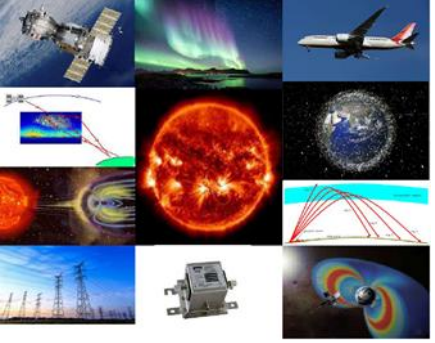
UK Research and Innovation

SWIMMR S1: Trusted Space:

- D-Orbit to confirm that satellite and instrument successfully commissioned
- We expect nominal orbit to be reached by 28/04 and data thereafter
- Pre-payment for the first four months of data will be done by year end
- Will offer these data out to academia as a possible collaboration
- Data format may change slightly, compared to first mission

SWIMMR S1: Trusted Aviation

- BA need to start flying sensors – maybe happened already?
- They will get four further sensors when they start flying the six they have
- BA operations MoU runs to the end of the calendar year
- Virgin operations paid until end of July
- Two sensor units are at Surrey for repair, one more is with Virgin still to be upgraded
- Transfer of ownership for two sensors needs to be done with DSTL
- .....and we will give them two sensors to give to the RAF
- Meeting on 27/03 with Honeywell and Boeing
- Can we progress things with Canadian Air Force, or Voltitude?
- Battery chargers from Accutronics still have to arrive
- Balloon sensors need to go to the Met Office



What is still to do?

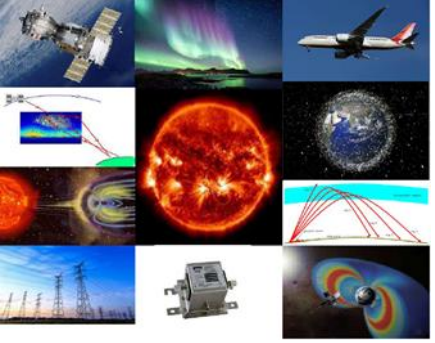
UK Research and Innovation

SWIMMR S1 Instrument Management Facility

- Met Office (and Surrey) to verify that aviation data files are as expected
- We will continue to accumulate data at RAL for the time being
- Surrey support contract extended to the end of May
- FR24 contract extended for a year
- MOSWOC to put in place a service going forward (using DfT funding?)
- D-Orbit have indicated a possible change in file format with respect to first mission

SWIMMR S1: Miniaturised Instruments

- Did not fully get to prototype stage on our three instruments
- However, components have been tested and looking for a way to continue
- SAM board for Hardpix data analysis partially complete
- LEES Low Energy Electron Spectrometer partially built
- Also developed electron gun and vacuum harness for testing
- Board developed for SURF+, shows good linearity for low currents
- Test rig for SURF+ developed (REEF), but has only just begun to be used
- Looking for alternative funding to continue



What is still to do?

UK Research and Innovation

SWIMMR S4

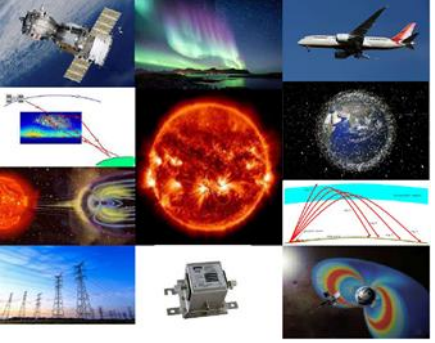
- ☐ ACME recoding (IDL to Python) to be done
- ☐ Model usage agreement to be concluded

SWIMMR S5

- ☐ Lancaster data feed to NMDB and MOSWOC to be completed
- ☐ Lerwick installation target date is week beginning 21/04, or following week
- ☐ We have receipted final payment to Surrey, so this is done from the STFC side
- ☐ Met Office has accepted the risks in installation
- ☐ Need to do transfer of ownership to Met Office (nominal £1 invoice has been raised)

SWIMMR S6

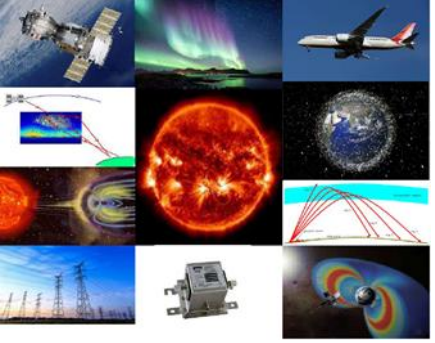
- ☐ We still owe £8k to Starion
- ☐ A credit note seems to be lost somewhere in the finance syste,



Monitoring and Evaluation

UK Research and Innovation

- Two studies are running
- STFC-funded post-programme evaluation of SWMMR
  - Contract awarded to Fraser Nash in January
  - Waiting to hear about the NDA that they will put in place
  - Will interview project leaders and SWIMMR PIs
  - They expect to be done by mid-Summer
- UKRI-funded evaluation of the Strategic Priorities Fund
  - Being conducted by Technopolis, fourth in a series of evaluations
  - SWIMMR is one of eight programmes selected for a "deeper dive"
  - Surveys and questionnaires to be done over Spring and early Summer
  - Will pick up findings of the Fraser Nash study
  - First findings presented in September, final report in December

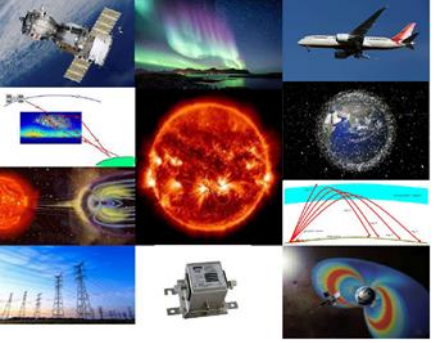


Final Financial Position

UK Research and Innovation

- Final reconciliation will take some time, into the new FY
- Using PRISM (in-house finance tool) to estimate shows that we are currently underspending by about £350k
  - £20k on SWIMMR Management
  - £330k on SWIMMR S1
- Underspend may reduce somewhat by/beyond year end
- Somewhat galling, as we would have carried this money forward
- However, £350k is 1.75% of the programme funding

STFC Projects	FY19/20	FY20/21	FY21/22	FY22/23	FY23/24	FY24/25	TOTAL
Management	199.28	123.56	157.28	143.58	172.26	164.06 (145.76)	**960.00**
SWIMMR S1	53.86	330.28	821.69	807.96	980.10	2,472.49 (2,142.59)	**5465.36**
SWIMMR S2	213.98	61.91	90.63	87.65	98.60		**553.07**
SWIMMR S3	118.00	222.81	418.36	322.40	132.60		**1096.28**
SWIMMR S4		75.00	150.00	150.00	75.00		**450.0**
SWIMMR S5			99.00	485.00	673.00	143.00	**1400.00**
SWIMMR S6				90.00	168.25	51.42	**309.67**
STFC OpEx	60.00	36.00	38.00	78.00	78.00		**290.00**
TOTALS	527.24	849.56	1775.25	2164.59	2520.81	2687.97	**10525.42**
NERC Projects	FY19/20	FY20/21	FY21/22	FY22/23	FY23/24	FY24/25	**TOTAL**
SWIMMR N1		581.06	774.75	774.75	79.82	113.89	**2324.27**
SWIMMR N2		405.87	541.17	541.17	135.29		**1623.51**
SWIMMR N3		501.61	668.84	668.84	167.21		**2006.50**
SWIMMR N4		493.03	657.36	657.36	66.36		**1874.11**
SWIMMR N5		270.18	360.23	360.23	90.06		**1080.70**
Data Mngmt.		63.00	67.00	67.00	9.00		**206.00**
NERC OpEx	60.00	80.00	90.00	70.00			**300.00**
TOTALS	60.00	2394.75	3159.35	3139.35	547.74	113.89	**9415.08**



What did we get wrong?

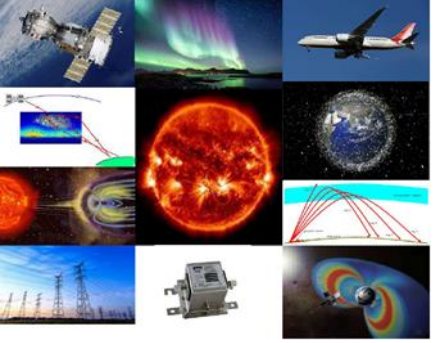
UK Research and Innovation

- Should have started earlier on the Business Case
  - Even before we knew we would be allowed to submit it.
- Underestimated how long some key things would take:
  - Regulatory approvals, getting contracts and MoUs in place, review processes
- Getting sufficiently clear external expert advice was not always easy
  - SWIMMR S1 Mini requirements, SWIMMR S6 report review
- Some initially attractive technologies proved to be unfeasible
  - e.g. move from BCS to Helium-3 detectors in neutron monitors
- Some technical mistakes, due to not understanding the AWS model
  - Data assimilation models (e.g. N3, N5) could only have been run on HPC

Space Strategy Progress

UK Research and Innovation

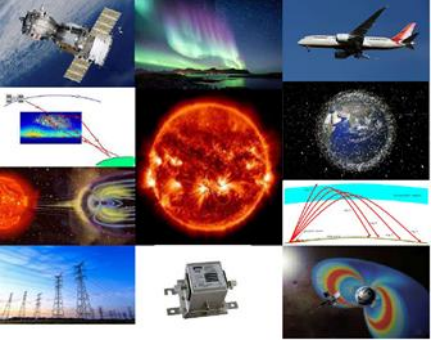
- Implementation process for National Space Strategy has moved on to the writing of Space Capability Goals and Strategic Summaries
- Required for government to see the totality of what is required to deliver the NSS national capability
- Very well received at National Space Board
- How this translates into CSR settlements is less obvious, however
- Space Domain Awareness is one of the five (now six?) categories being prioritised for implementation
  - Space Domain Awareness, PNT, SatCom, IOASM, Space Data Architecture
- Some agreement on priorities for SDA, includes NSpOC and Vigil
  - R202R approach for space weather capability development is still in the discussion
- Moves in progress to establish cross-government working group for space(?)



The Business Case Process

UK Research and Innovation

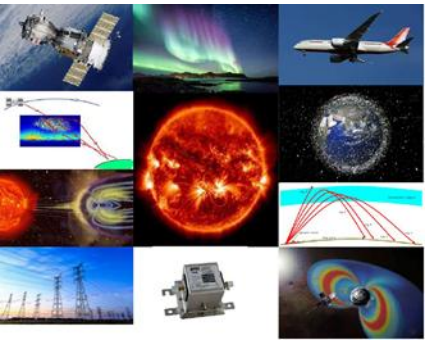
- The BEIS "three part" business case seemed an overwhelming endeavour
- Especially because we had quite little time to write it (two months including the Christmas break) once we got approval to submit
- A lot of work on the technical case was done at the American Geophysical Union Meeting in Washington in December 2018
- Great support from Andy Sawko and team, especially from Lucy Broomfield on the economics side, since this was the one part that I had no clue how to write.
- Also, fantastic support from Tom Madden at BEIS, who made the cross-government links needed to get us support letters from MoD and DfT
- Support from the Met Office and the US Space Weather Prediction Center was vital to us getting approval from Patrick Vallance (then GCSA), otherwise UKRI would not have approved the programme



SWIMMR Governance Model

UK Research and Innovation

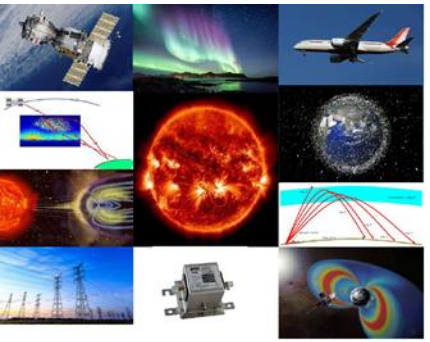
- The Governance model was needed for the business case and this was strongly suggested to us by BEIS, who had used it for other programmes
- The key components were:
  - Programme Management Board - of major stakeholders, chaired by the SRO at STFC, meeting monthly – this makes the detailed decisions needed to steer the project
  - Strategic Advisory Group – of community experts, meeting quarterly, which should oversee alignment of the programme with the external landscape
  - Governing Board – combination of the PMB and SAG, chaired by BEIS (then by DESNZ) meeting at least twice a year. Only this board could end projects and start new ones (though we never actually had to do this)
- Other things we added were:
  - A Programme Manager, to help me run the programme (either from STFC or Met Office)
  - A weekly "drop-in" session, for all PMB stakeholders
  - A monthly telecon, involving the Met Office and all the project PIs



What might the future look like?

UK Research and Innovation

- Strategic Priorities Fund, which supported SWIMMR, will expire at the end of this financial year
- Post SWIMMR, the worry is that we will go back to small individual pieces of research funded by individual grants, not necessarily aligned to strategic needs
- SWIMMR has shown that UKRI can deliver strategic science programmes, joined up across multiple Councils, and SPF was a great vehicle for doing this
- In the short term, we don't have any similar UKRI funding mechanism
  - At least not one with unallocated resources
- But we do now have the National Space Strategy and the SIP, with an emphasis on Space Domain Awareness, and a need for long-term directed development
- Post CSR, we really need a new mandate and a long-term mechanism for doing strategic science and delivering the goals of the NSS within UKRI
- Ideally that mechanism should help us combine efforts across the whole DSIT family



The SWOpPER Proposal

UK Research and Innovation

- Space Weather Operations and External Relationships
- Submitted to STFC Visions January 2023, approved by Visions Board 25/04/23
  - Validation of the new SWIMMR models
  - R2O2R against existing (and emerging) user requirements
  - Identification and improvements to increase skill
  - Comparison with international models and techniques
  - Potentially plugging data gaps
- Approval by Visions Board opens way to a thematic funding opportunity
  - If there was a scheme available (currently not the case)
- Little prospect of new schemes in 25/26 due to one-year CSR
  - Continue to try for an opportunity when multi-year funding becomes available