Date: Monday, November 02, 2026

Session Info: HEL2 COSMIC RAYS IN THE HELIOSPHERE

SPECTRAL ANALYSIS OF THE DELAYED RESPONSE OF COSMIC RAYS TO VARIATIONS IN SOLAR ACTIVITY

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Investigating the relationship between galactic cosmic rays (GCRs) and solar activity is fundamental for understanding the physical mechanisms governing particle transport in the heliosphere.
A well-known effect is the delayed relationship between solar activity and the GCR flux measured at Earth, due to the propagation time of the solar wind and the diffusive transport of cosmic rays. This time lag presents both temporal and rigidity-dependent features, which we investigated using different complementary approaches.
We used multi-channel GCR flux data, such as that from ACE and neutron monitor observations, together with several solar activity proxies, including sunspot number (SSN) and open solar flux.
By combining cross-correlation techniques with refined wavelet analyses, we derived and validated a global effective formulation suitable for implementation in solar modulation models, focused on forecasting GCR fluxes, thereby improving long-term radiation-risk assessments for future human space exploration.
Given the intrinsic non-linearity and non-stationarity of the data, we also adopted a Hilbert spectral analysis approach to estimate the time lag even from relatively short time series, such as those provided by the AMS-02 experiment. These techniques allow us to investigate phase coherence and extract time-dependent spectral features from cosmic-ray observations and solar proxies.
Using the latest antiproton flux measurements from AMS-02, we qualitatively demonstrate the charge-sign dependence of the time lag, as predicted by solar modulation models. This behavior is associated with the different trajectories followed by charged particles in the heliosphere as a consequence of drift effects.

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LINKING 3 DIMENSIONAL CME STRUCTURE AND FORBUSH DECREASES

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Forbush decreases are caused when a transient magnetic structure in the solar wind, such as a coronal mass ejection (CME), inhibits the flow of galactic cosmic rays, causing a local decrease in energetic particle flux. Studies of Forbush decreases in conjunction with CMEs have linked substructures in their profiles with CME properties, such as different decrease gradients for the shock and sheath, and greater magnitudes associated with faster CMEs. However, individual profiles of Forbush decreases, like in-situ measurements of coronal mass ejections, are highly varied in their structure and do not always follow these trends, and it is debated in what causes these complex profiles. Current models have been able to reproduce simple Forbush decrease profiles, but studies disagree on the importance of drifts and particle scattering in causing decreases associated with a sheath and magnetic cloud, and no model has included the full 3D spatial variation inherent in a CME. We model Forbush decreases with full-orbit test particles and 3 different 3D models of magnetized CMEs, to model the full profile of Forbush decreases. We also compare the profiles both between different models, different scattering regimes, and within the same simulation, in order to shed light on the particle transport processes and properties of CME substructures that drive Forbush decreases and explain the variability in Forbush decreases recorded in in-situ measurements.

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EXAMINING THE Q/M DEPENDENCE OF SEP HEAVY ION ABUNDANCES WITH IMAP

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Mason et al. (2012) showed that the apparent time dependence of heavy-ion abundance ratios in SEP events may be caused by how particles propagate through space, rather than by changes at the source. When they compared ions by rigidity instead of energy per nucleon, the abundance ratios became more stable. However, that approach required assuming charge states as a key limiting factor.

The Interstellar Mapping and Acceleration Probe's (IMAP) energetic particle instruments now allow this test to be revisited with measured charge-state information. CoDICE-Lo provides suprathermal charge-state measurements that can be used to estimate Q/M in the pre-accelerated seed population, while CoDICE-Hi and HIT provide the higher-energy composition needed to compare abundance ratios such as Fe/O as a function of both energy per nucleon and rigidity.

Using early IMAP SEP events, we examine whether Fe/O, C/O, or He/O smoothly vary across the suprathermal to SEP transition, and whether they are more constant when organized by rigidity or by energy per nucleon. By utilizing measured suprathermal charge-states rather than assuming values, this work better examines the degree to which interplanetary transport affects SEP abundances at 1 AU.

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GROUND LEVEL ENHANCEMENT GLE 77 ON 11 NOVEMBER 2025 AND ITS SPACE WEATHER SIGNATURES, STUDY BASED ON NEUTRON MONITOR RECORDS ANALYSIS

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A new strong solar energetic particle event was observed on 11-Nov-2025, registered by space probes and the worldwide network of neutron monitors (NMs) as a ground-level enhancement (GLE) 77. The event is among the strongest measured GLEs during the NM era, with peak integral intensities reached about 125 (165) % and 600 (800) %*hr, respectively, for standard (bare) NMs. The event was analysed using state-of-the-art modelling and experimental space probes and NM records. It revealed a complicated, multi-component anisotropy with two distinct components: a short impulsive phase (during 10:10 -- 10:50 UT), and a long gradual phase lasting until 17:00 UT.
In this work, we present a summary of observations and report the derived spectral and angular distribution of GLE-causing solar ions. We also present some space weather signatures, namely the impact of this event on the radiation environment in the Earth's atmosphere.

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HIGH-ENERGY PROTON ACCELERATION ON THE 21ST NOVEMBER 2024 (GLE76)

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Solar energetic particles (SEPs) accelerated during eruptive solar events can occasionally reach relativistic energies and produce Ground Level Enhancements (GLEs) detectable by neutron monitors at Earth. The event of 21 November 2024 (GLE76) provides an opportunity to investigate the acceleration and release of very high-energy protons using observations from Earth, STEREO-A, and Solar Orbiter.
We combine remote-sensing observations, radio measurements, and in situ particle data to study the origin and evolution of the energetic proton population associated with GLE76. We reconstruct the three-dimensional evolution of the CME-driven shock and derive its properties along the magnetic field lines connected to the different observers, including shock geometry and Mach number.
We also reconstruct the associated radio burst sources and compare their locations and timing with the shock structure, other electromagnetic signatures, and the relativistic proton population. Proton intensities and spectra measured at STEREO-A, Solar Orbiter, and near-Earth spacecraft are analysed together with the effect of magnetic connectivity on the observed particle profiles.
These results provide constraints on the acceleration and release processes operating during extreme SEP events.

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CHARACTERIZING THE TIME-DEPENDENT LONGITUDINAL DISTRIBUTION OF SOLAR ENERGETIC PARTICLES USING MULTI-SPACECRAFT OBSERVATIONS

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The two main sources for accelerating solar energetic particles (SEPs) are magnetic reconnection regions in solar flares or shock waves driven by coronal mass ejections (CMEs). Especially during large events, both potential acceleration regions are present. To infer which is the dominant acceleration mechanism for specific particle populations in a single event, we study the time-dependent longitudinal distribution of particle intensities using multiple heliospheric observers.
We analyse the 28 May 2021 SEP event using well-separated observations from Solar Orbiter, Parker Solar Probe, STEREO A, and near-Earth observers: SOHO & Wind. Gaussian curves are fitted to particle intensities as a function of the observer's location at regular time intervals. These fits are applied to 100 keV & 1 MeV electrons, as well as 14 MeV & 32 MeV protons, to infer the time evolution of the particle distribution centre and width.
Our results indicate that, for this event, the characteristics of higher-energy particle distribution are consistent with acceleration by an outward-moving source, like a CME-driven shock, whereas 100 keV electrons display characteristics in line with acceleration mainly by the flare. Our investigation demonstrates a useful technique for inferring acceleration mechanisms in solar events, and the methodology has been developed into a publicly available tool through the SOLER project.

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Session Info: HEL2 COSMIC RAYS IN THE HELIOSPHERE

COSMIC-RAY MODULATION BY HELIOSPHERIC TRANSIENTS: INSIGHTS FROM FORBUSH DECREASES

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Galactic cosmic rays (GCRs) continuously permeate the heliosphere and can be detected by both space-borne detectors and ground-based neutron monitors. As GCRs propagate through the turbulent interplanetary magnetic field, the low-energy part of their spectrum undergoes significant modulation and exhibits rapid variations on timescales ranging from hours to days, associated with heliospheric transient structures - e.g., stream interaction regions, interplanetary coronal mass ejections (ICMEs), etc. These disturbances frequently generate abrupt depressions in the observed cosmic-ray intensity known as Forbush decreases (FDs). The physical mechanisms underlying FDs involve particle scattering and transport within interplanetary shocks, turbulence, and magnetic flux ropes embedded in ICMEs. Due to their sensitivity to large-scale heliospheric structures, GCRs constitute an important diagnostic for investigating particle transport processes in the heliosphere and the magnetic topology of heliospheric transients. The combined availability of multipoint spacecraft observations and the global neutron monitor network now enables detailed investigations of FD properties, including their temporal evolution, energy dependence, and directional anisotropies. In this work, we model the neutron monitor response to the GCR spectrum variation and then we use ground-based observations to retrieve proton spectra and anisotropy during illustrative cases, like the November 3, 2021 FD event caused by the passage of an intense ICME. Outcomes are tested against spacecraft observations and the possible associations between FD anisotropy and the global magnetic configuration of the ICME is discussed.

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Session Info: MIT2 CROSS-SCALE GNSS-BASED MONITORING OF IONOSPHERIC IRREGULARITIES: FROM PHYSICS TO OPERATIONAL SPACE WEATHER SERVICES

PREDICTING SOLAR ENERGETIC PARTICLES: SOLAR STORM WATCH - PREPARING FOR SPACE ODYSSEY

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Space Weather effects produced by Solar Energetic Particles (SEPs) present a direct radiation hazard to crew and spacecraft equipment, first in interplanetary space, and then, due to secondary effects, within the Earth's magnetosphere and atmosphere. Being able to predict and/or forecast SEP events is of particular importance for the near-future planned manned missions to the Moon and Mars, as well as for our unimpeded daily living. We present key findings that have been utilized and/or explored by the scientific community over the last few decades to establish prediction schemes of SEP events. We discuss empirical models where parameters related to the parent solar events (i.e. solar flares and coronal mass ejections) can be used to estimate both the probability of occurrence and critical properties (i.e. peak proton flux and/or fluence) of SEP events in the near-Earth environment and beyond. Moreover, we present physics-based modeling efforts of SEP events that are geared towards operational prediction, particularly focusing on SEP transport effects and multi-spacecraft observations. We furthermore explore the applicability of higher order multivariate, machine learning, and artificial intelligence methods and highlight the particular value and limitations of such advances. Finally, the most current operational approaches in the prediction of SEP events, together with future challenges that need to be addressed by the scientific community, are presented and discussed.

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Session Info: MIT2 CROSS-SCALE GNSS-BASED MONITORING OF IONOSPHERIC IRREGULARITIES: FROM PHYSICS TO OPERATIONAL SPACE WEATHER SERVICES

UNRAVELING STORM-TIME EQUATORIAL PLASMA BUBBLE DYNAMICS: MULTI-SOURCE DATA FUSION AND COUPLED GITM-SAMI3 MODELING

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Equatorial Plasma Bubbles (EPBs) are a primary source of GNSS signal degradation. However, their dynamics during geomagnetic disturbances are not yet fully understood, which prohibits reliable forecasting. This study presents a comprehensive analysis of storm-time EPB evolution using a combination of multi-source data fusion, integrating TEC from ground-based GNSS receivers, GOLD and LEO satellites, and the DORIS system, and high-resolution simulations from the coupled GITM-SAMI3 model driven by the Space Weather Modeling Framework (SWMF) Geospace suite.

We focus on the morphological evolution of storm-time EPBs by tracking their initiation, development, and suppression in relation to large-scale neutral wind surges and electric fields. The numerical model is utilized to perform a quantitative diagnostic of the generalized Rayleigh-Taylor (RT) instability growth rate, evaluating the relative contributions of individual terms during different storm phases. Our findings reveal storm-time mechanisms shaping the low-latitude ionosphere under extreme conditions and advance understanding crucial for space weather prediction. Detailed investigation of EPB growth and suppression during the sheath and magnetic cloud periods highlights the controlling influence of external drivers. Notably, we identify an externally triggered EPB seeding mechanism linked to enhanced vertical velocity shear at the convergence of zonal eastward and westward prompt penetration electric fields in a longitudinally confined region. These results provide key new insights into storm-time EPB evolution and pave the way for improved EPB forecast capability.

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INVESTIGATING THE LEPTOKURTOTIC NATURE OF LOW LATITUDE GNSS SCINTILLATIONS WITH A MULTISCALE APPROACH

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We investigate the statistical nature of Global Navigation Satellite System (GNSS) signal fluctuations through multiscale analysis of a strong scintillation event recorded at the Ionospheric Observatory of the Luigi Broglio Space Center in Malindi, Kenya. By applying the Fast Iterative Filtering (FIF) technique, raw 50 Hz amplitude, phase and Ionosphere-Free Linear Combination (IFLC) signals were decomposed into Intrinsic Mode Components (IMCs), enabling a rigorous examination of scale-dependent properties. The analysis reveals that low-latitude scintillation is inherently non-Gaussian and intermittent, with statistical characteristics that evolve distinctively across frequency scales.

Specifically, these modes exhibit pronounced leptokurtotic behaviour, reflecting the combined effects of fine-scale ionospheric turbulence and non-linear signal propagation. In the higher-frequency range, the Probability Density Functions (PDFs) of the IMCs deviate significantly from a Gaussian distribution and are accurately modelled by Castaing-family distributions. Strong intermittency begins above the Fresnel frequency and, crucially, extends into the high-frequency range where standard spectral analysis suggests the signal is dominated by noise.

We demonstrate that non-Gaussian signatures persist in this regime, showing that meaningful physical information is preserved in the heavy tails of the distribution despite Gaussian dilution from thermal receiver noise. Similar behaviour is observed in phase and IFLC signals, where excess kurtosis increases with frequency beyond the Fresnel scale. This multiscale approach demonstrates that advanced statistical models are necessary to characterize the fine-scale structures impacting GNSS and provides a powerful framework for superstatistical modelling.

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PLASMA BUBBLE DETECTION USING DUAL AND SINGLE-FREQUENCY GNSS OBSERVATIONS FROM COSMIC-2

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Equatorial Plasma Bubbles (EPBs) are large-scale plasma depletion structures that can disrupt Global Navigation Satellite Systems (GNSS) and other space-based technologies. Ground-based GNSS observations provide important insights into EPB dynamics; however, their spatial coverage is limited, particularly over oceanic regions. This highlights the importance of Low Earth Orbit (LEO) satellite missions such as COSMIC-2, designed to analyze the Earth's ionospheric plasma from a topside perspective with large coverage even over oceanic regions. In this study, we investigate the capability of GNSS-based indices derived from dual- and single-frequency topside Total Electron Content (TEC) observations to detect EPBs. First, we evaluate the capability of the Rate of TEC Index (ROTI), computed from dual-frequency carrier-phase measurements, to detect and map EPB signatures during the ascending and maximum phases of Solar Cycle 25 (2020-2025). Climatological analyses are performed considering local time, seasonal, longitudinal, and latitudinal variabilities. The results show that topside ROTI captures the spatial and temporal evolution of EPBs, in agreement with ground-based GNSS observations and previous studies. In addition, we introduce the Rate of Single Difference Index (RoSDI), a metric computed from the single difference of carrier-phase measurements between two consecutive epochs using single-frequency GNSS observations. The performance of RoSDI is evaluated through comparisons with ROTI and in-situ Ion Velocity Meter (IVM) measurements. The results show a strong correlation with IVM-derived EPB occurrence rates ($R = 0.89$), demonstrating that single-frequency GNSS observations can be effectively used to monitor EPBs in the topside ionosphere. These results open new opportunities for global ionospheric monitoring using miniaturized GNSS payloads.

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Session Info: OTH3 MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

NOWCASTING OF EQUATORIAL TEC GRADIENTS BY ASSIMILATION OF MULTI-CONSTELLATION GPS DATA INTO AN IONOSPHERIC MODEL: APPLICATION TO THE MAY 10, 2024 GEOMAGNETIC STORM

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Equatorial plasma bubbles remain one of the most difficult ionospheric phenomena to predict. After sunset, the ionosphere over South America and the Pacific can develop sharp TEC gradients, sometimes exceeding 1 TECU/km within a few tens of kilometers, that render centimeter-level GNSS positioning unreliable. During intense geomagnetic storms, this problem is dramatically amplified.

The May 10, 2024 storm, one of the strongest events of solar cycle 25 (Kp~9), provided an excellent case study to test a near-real-time gradient mapping approach under extreme conditions. We assimilated multi constellation VTEC observations from five equatorial IGS stations (AREQ, ASPA, BOGT, GLPS, MANA) into an IRI background model using Optimal Interpolation on a 0.25x0.25 degree grid. Ionospheric Pierce Point coordinates were derived from GPS broadcast ephemerides. The entire pipeline, from raw RINEX ingestion to gradient maps, is executed in near-real-time.

Three distinct disturbed periods emerged from the 24-hour analysis: 00:30, 04:30, and 21:30 UTC, all exceeding the 0.5 TECU/km GNSS alert threshold. Peak gradients reached 1.08 TECU/km, consistent with active plasma bubble signatures. ROTI validation confirmed both the spatial localization and temporal phasing of these structures. Daytime hours, by contrast, showed remarkably quiet gradient fields below 0.2 TECU/km.

The approach is operationally deployable. Extending it to denser station networks or shorter assimilation windows requires no fundamental redesign, making it a credible candidate for a dedicated nowcasting service for equatorial GNSS users. Results are directly interpretable as space weather alerts for aviation and geodetic applications.

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Session Info: SOL1 MAGNETIC FIELDS IN THE LOWER SOLAR ATMOSPHERE - THE ENGINE BEHIND SOLAR WIND AND ERUPTIVE EVENTS

STUDYING ACTIVE REGION FLUX EVOLUTION THROUGH MULTI-VIEW OBSERVATIONS

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The magnetic flux distribution on the solar surface is commonly reconstructed from Earth-based observations collected over one Carrington rotation. However, the resulting synoptic maps cannot directly capture the magnetic field on the far side of the Sun, introducing uncertainties in global magnetic field reconstructions and space-weather models. We combine near-Earth observations from the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory with far-side magnetic field measurements from the Full Disk Telescope (FDT) of the Polarimetric and Helioseismic Imager (SO/PHI) onboard Solar Orbiter to assess how accurately synoptic maps represent the true magnetic flux on the hidden hemisphere.
Solar Orbiter has been operating for more than five years and has passed through five superior conjunctions, providing repeated far-side coverage during the rising phase of Solar Cycle 25. We identify active regions observed by SO/PHI-FDT on the far side, determine their magnetic field characteristics and compare these properties with the corresponding regions in HMI synoptic maps for the same Carrington rotations. This allows us to quantify systematic under- and over-estimation of magnetic properties (e.g. magnetic flux) that are not fully represented in standard synoptic reconstructions.
In addition, we track the temporal evolution of active regions over their full observable lifetime, from emergence to decay, by combining SO/PHI-FDT far-side observations with subsequent HMI measurements on the Earth-facing side. This enables us to follow the persistence and transport of magnetic flux across multiple rotations and to investigate the contribution of long-lived active regions to large-scale magnetic structures. Our results provide a quantitative estimate of magnetic flux missing from synoptic maps and demonstrate the importance of Solar Orbiter's unique viewpoint for improving global solar magnetic field models.

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CHROMOSPHERES AS THERMODYNAMIC GATEKEEPERS OF SOLAR MAGNETIC COUPLING

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The chromosphere forms the magnetic and thermodynamic interface between the solar interior and the corona, regulating how mass and energy are transferred into the heliosphere. Yet, despite its central role in solar-wind formation and coronal structuring, chromospheric thermodynamics remain poorly constrained in both local and global coronal models, where lower-boundary conditions and magnetic driving are often treated through simplified, homogeneous or weakly constrained prescriptions.

Using the radiative-MHD Bifrost code, we perform a parametric study of quiet-Sun atmospheres experiencing different levels of small-scale magnetic flux emergence, producing magnetic topologies ranging from nearly vertical coronal-hole-like configurations to strongly inclined loop-dominated structures. We quantify how these changes in magnetic amplitude and connectivity modify chromospheric heating and atmospheric coupling. Increasing magnetic flux progressively redistributes heating from shocks toward magnetic reconnection, and produces hotter chromospheres. However, despite enhanced magnetic heating, the thermodynamic response at the coronal base becomes non-monotonic and can even lead to reduced coronal-base temperatures, an effect that we will detail and discuss.

Our results demonstrate that lower-atmosphere magnetic topology strongly controls thermodynamic coupling into the corona and therefore cannot be neglected in large-scale coronal and heliospheric modelling. We discuss how radiative-MHD simulations and chromospheric diagnostics can provide quantitative constraints toward physically motivated lower-boundary parameterisations for future Sun-to-heliosphere models.

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HE I 1083 NM SPECTROPOLARIMETRY AS A PROBE OF PROMINENCE ERUPTION MAGNETIC STRUCTURE

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Space-weather forecasting requires knowledge of the CME magnetic field strength, orientation, and topology before they reach Earth. However, coronal fields are weak, and Zeeman-induced circular polarization in the corona is often too small for routine CME magnetometry. The He I 1083 nm triplet provides a promising alternative, as cool prominence material entrained in CMEs remains observable while its linear polarization is sensitive to magnetic fields through the unsaturated Hanle effect. We investigate He I 1083 nm spectropolarimetry as a diagnostic of CME magnetic structure using forward modeling from realistic MHD prominence-eruption simulations The models show that the He I 1083 nm linear-polarization morphology is linked to the topology of the erupting flux rope, while multi-vantage observations can help reduce some of the Hanle ambiguities. Recent UCoMP results demonstrate the observational feasibility of this approach, detecting eruptive prominence material to nearly 2 solar radii and providing complementary line-of-sight velocity information. These results support He I 1083 nm spectropolarimetry as a path toward earlier, magnetically informed CME characterization for space-weather forecasting.

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Session Info: SOL1 MAGNETIC FIELDS IN THE LOWER SOLAR ATMOSPHERE - THE ENGINE BEHIND SOLAR WIND AND ERUPTIVE EVENTS

TWO-STAGE INSTABILITY MODEL FOR EXPLAINING AND PREDICTING THE GENERATION OF CORONAL MASS EJECTIONS

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Coronal mass ejections (CMEs) are explosive events that suddenly release large amounts of magnetized plasma from the solar corona into interplanetary space. CMEs are a major source of space weather disturbances, but their generation mechanisms remain only partially understood, making prediction difficult. Recently, Muhamad and Kusano (2025) demonstrated that, based on observational data analysis, the ratio between the critical height where torus instability can grow and the electric current non-neutrality of the active region can effectively distinguish active regions that produce eruptive and non-eruptive solar flares, which in turn generate CMEs or not. In this study, we introduce a new theoretical model, the two-stage instability (TSI) model, to explain CME generation and conduct a simulation study to verify it. The simulation results align well with the TSI model and demonstrate that the double-arc instability (Ishiguro and Kusano, 2017) grows in the low corona and triggers flare reconnection in the first stage. As a result, torus instability grows in the second stage, leading to CME formation. The simulation also shows that if the twisted flux rope, formed by flare reconnection, cannot reach the critical height for torus instability due to another reconnection with the external field, it results in a non-eruptive (confined) flare. Based on these findings, we propose a new approach for forecasting CME occurrence.

Date: Monday, November 02, 2026

Session Info: SOL1 MAGNETIC FIELDS IN THE LOWER SOLAR ATMOSPHERE - THE ENGINE BEHIND SOLAR WIND AND ERUPTIVE EVENTS

ES-MAGNAR:A MULTI-HEIGHTNARX-BASEDFORECASTINGMODEL FOR PREDICTINGTHEERUPTIVESTATEOFSOLARACTIVEREGIONS,ARETHEMAINSOURCESOFFLARES AND CORONAL MASS EJECTIONSYET ONLY FRACTION OFMAGNETICALLYCOMPLEXREGIONS

Marianna Korsos [1]

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Solar active regions are the main sources of flares and coronal mass ejections, yet only a small fraction of magnetically complex regions produce major eruptions. In this work, we focus on how magnetic diagnostics of the lower solar atmosphere can improve the identification of eruptive active regions.

Building on our recent finding that flare-predictive parameters become more informative when extended from the photosphere into the lower solar atmosphere, we introduce ES-MAGNAR: the Eruptive State - MAGnetic Nonlinear AutoRegressive prediction model. ES-MAGNAR is based on a NARX-type architecture and uses the temporal evolution of ten magnetic morphological parameters measured at multiple atmospheric heights, from the photosphere to the lower corona, up to approximately 7 Mm.

The model predicts the eruptive state of active regions 24 hours in advance. By combining multi-height magnetic information with time-dependent active-region evolution, ES-MAGNAR provides a physics-informed machine-learning framework for assessing whether an active region is likely to produce a major eruption. Our results show that diagnostics rooted in the lower solar atmosphere can play a key role in improving solar eruption prediction.

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Session Info: SOL1 MAGNETIC FIELDS IN THE LOWER SOLAR ATMOSPHERE - THE ENGINE BEHIND SOLAR WIND AND ERUPTIVE EVENTS

UNVEILING THE GLOBAL MAGNETIC TOPOLOGY WITH PHYSICS-INFORMED NEURAL NETWORKS

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The 3D coronal magnetic field is a key quantity for understanding the formation, stability, and eruption of magnetic flux ropes in the solar corona. Nonlinear force-free magnetic-field extrapolations are widely used to estimate the coronal magnetic field from photospheric vector magnetograms, but they are typically restricted to local Cartesian domains and therefore cannot capture global magnetic connectivity.
We present a physics-informed neural network approach for nonlinear force-free extrapolations of the global solar magnetic field. The method uses full-disk vector magnetograms from SDO/HMI and directly models highly twisted quiet-Sun filaments, coronal holes, and complex active-region fields, consistent with extreme-ultraviolet observations from SDO/AIA.
We apply the method to the eruption of a trans-equatorial filament on 5 February 2016 and its possible connection to a quiet-Sun filament eruption. The global extrapolation reveals magnetic connectivity across the solar equator, interactions with neighboring open-flux regions, and a connection to flux emergence that leads to a change in global connectivity. These results highlight the importance of global magnetic topology for both localized reconnection and large-scale coronal reconfiguration.
We conclude with an outlook on using global extrapolations to estimate open magnetic flux and investigate the role of highly twisted field configurations in the formation of open-flux regions.

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PHOTOSPHERIC MAGNETIC ORGANIZATION IN CORONAL HOLES AND ITS ROLE IN FAST SOLAR WIND ORIGINS

Matteo Cantoresi [1], Michele Berretti [1,3], Francesco Berrilli [1], Fabio Lepreti [2]

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Coronal holes are regions of the solar corona that appear as areas of reduced extreme-ultraviolet emission and are widely recognized as the main sources of the fast solar wind. A key characteristic of these regions is a pronounced imbalance in the polarity of the underlying photospheric magnetic field.
In our study we investigate the nature of this imbalance and the spatial scales at which it develops, combining observational data with synthetic magnetograms. We apply the signed measure technique to examine the scaling properties of fluctuating magnetic fields, showing that CHs systematically exhibit strong polarity asymmetries, especially at scales comparable to supergranulation. Numerical experiments using synthetic data confirm these results, indicating that configurations where one polarity is preferentially organized along supergranular boundaries reproduce the observed cancellation functions. Further analysis of magnetic flux diffusion in CHs reinforces this picture.
Our results support a scenario in which CHs are structured by magnetic flux concentrations rooted in the supergranular network, where polarity imbalance naturally arises. In this framework, dominant-polarity photospheric fields are the footpoints of open magnetic funnels that guide the fast solar wind into interplanetary space. This interpretation is consistent with recent Parker Solar Probe observations, which indicate that signatures of the supergranular pattern are preserved in the solar wind, offering new constraints on its origin and acceleration mechanisms.

Date: Monday, November 02, 2026

Session Info: OPS OPEN SESSION

GLOBAL SOLAR DYNAMO AND WIND COUPLING IN AN MHD SIMULATION

Allan Sacha Brun [1], Barbara Perri [1], Antoine Strugarek [1]

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We will discuss solar MHD simulations of the coupling between a cyclic dynamo and a wind. We use the PLUTO code in 2.5D MHD mode and develop a setup that follow both the evolution of the internal solar magnetic field via a mean field dynamo model and couple it to the generation of a polytropic solar wind. This is realize by developing special boundary conditions for the solar dynamo and for impacting the magneto-thermal coronal wind. The global time varying poloidal field is used to make the wind velocity and magnetic field evolve leading to a original dynamo solutions . We can observe the time it takes for the global polarity reversal to propagate into the corona and how this restructure the solar wind streams. We further compare this simulation to more classical dynamo solutions and vary the cycle period to see how the wind respond. We find that the injection of magnetic helicity into the wind leads to more time depend solutions that are more realistic than steady solutions.

Date: Monday, November 02, 2026

Session Info: IOM3 OPERATIONAL AND PROTOTYPE DATA PRODUCTS DERIVED FROM LOW-EARTH ORBIT, NEAR-EARTH, AND UPSTREAM OBSERVATIONS

GLOBAL NEUTRAL DENSITY ESTIMATES USING THE CTIPE MODEL AND DATA ASSIMILATION

Catalin Negrea [1], Mihail Codrescu [1,2], Stefan Codrescu [2], Daniel Dumitru [1], Marius Mihai Echim [1,3]

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Accurate estimation of thermospheric neutral density is vital for atmospheric drag compensation, Actual measurements are difficult to make, limited in number and coverage, and often suffer from large and poorly specified uncertainties. Numerical models are often used as a substitute, sometimes in conjunction with data assimilation schemes. During geomagnetic storms, having an accurate representation of the thermosphere-ionosphere (TI) is vital, since climatological models cannot accurately reproduce the system response. The physics-based Coupled Thermosphere Ionosphere Plasmasphere electrodynamics (CTIPe) model has been shown to provide accurate global estimates of neutral density when used in together with the Thermosphere Ionosphere Data Assimilation scheme (TIDA).
This approach adds the model inputs to the state vector and better accounts for the strongly forced nature of the TI. In this study, we expand on previous work by demonstrating the use of TIDA-CTIPe for neutral density estimation over a much broader time interval, covering multiple geomagnetic events. We demonstrate the capability to improve global estimates of neutral density by assimilating measurements in a narrow altitude range, from the CHAMP, GRACE and SWARM missions. Additionally, we discuss the need for near-real-time data for potential forecasting applications.

Date: Monday, November 02, 2026

Session Info: IOM3 OPERATIONAL AND PROTOTYPE DATA PRODUCTS DERIVED FROM LOW-EARTH ORBIT, NEAR-EARTH, AND UPSTREAM OBSERVATIONS

FROM UPSTREAM DRIVERS TO DOWNSTREAM IMPACTS: OPERATIONAL DATA PRODUCT INTEGRATION DURING THE MAY 2024 STORM IN EUROPE

Alfredo Micera [1], de Patoul Judith [1], O'Hara Jennifer [1], Andries Jesse [1], Dom Elisabeth [1], Millas Dimitrios [1], Maneva Yana [1], Shukhobods Daria [1]

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The May 2024 "Mother's Day" geomagnetic storm was one of the most severe space weather events of Solar Cycle 25 and provided a major test case for operational space weather monitoring in Europe. This contribution examines how European operational data products, including those available through the ESA Space Weather Service Network, can be used to reconstruct a major Sun-Earth event chain and assess how different product domains support situational awareness, interpretation, and user-relevant analysis. The study follows the event from its solar origin and heliospheric evolution to upstream and near-Earth observations, geomagnetic response, ionospheric disturbances, and impact-relevant indicators. The focus is not only on describing the storm, but on evaluating how operational and near-real-time products helped link upstream drivers and observations with downstream geospace responses and potential consequences for European user sectors, including navigation, aviation, radio communication, satellite operations, and ground infrastructure. Particular attention is given to the integration of heterogeneous products across service domains, including their complementarity, interpretation limits, uncertainty, timeliness, and usefulness for retrospective assessment. The event is used to identify where operational products provided clear added value, where gaps or ambiguities remained, and how product chains could better support severe-event analysis in future operational contexts. Using the May 2024 storm as a concrete case study, this work highlights the importance of coordinated, low-latency, multi-domain data products for operational space weather services. It contributes to the discussion on how upstream observations and near-Earth measurements can be connected more effectively to support monitoring, forecasting, service assessment, and communication during severe space weather events.

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Session Info: IOM3 OPERATIONAL AND PROTOTYPE DATA PRODUCTS DERIVED FROM LOW-EARTH ORBIT, NEAR-EARTH, AND UPSTREAM OBSERVATIONS

AVAILABLE AND UPCOMING DATA SETS OF ESA'S DISTRIBUTED SPACE WEATHER SENSOR SYSTEM

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ESA's Distributed Space Weather Sensor System (D3S) is being developed to enhance space weather monitoring through a fleet of coordinated small satellites hosting complementary instrumentation. By distributing measurements across multiple platforms and orbital regimes, D3S aims to provide improved spatial and temporal coverage of key region, including the solar wind, magnetosphere, and ionosphere.

This contribution presents an overview of the data sets that are currently available from Hosted Payload mission and those expected from upcoming D3S missions, including SWING, which is planned to launch in 2027. The talk will highlight the measurement capabilities of the different missions, the anticipated data products, and their relevance for scientific investigation and real-time space weather applications. Particular focus is placed on the harmonisation of data across missions, ensuring consistency in formatting, and accessibility to support multi-point analyses.

In addition, the contribution will address related upcoming activities on D3S end-to-end simulation and data utilisation studies.

By providing a consolidated view of available and forthcoming data, this presentation aims to facilitate data user engagement and maximise the scientific and operational exploitation of ESA's observation system.

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Session Info: IOM3 OPERATIONAL AND PROTOTYPE DATA PRODUCTS DERIVED FROM LOW-EARTH ORBIT, NEAR-EARTH, AND UPSTREAM OBSERVATIONS

TURBULENT DYNAMICS OF THE UPPER IONOSPHERE OBSERVED BY SWARM MAGNETIC FIELD RECORDS AND ITS IMPLICATIONS FOR SPACE WEATHER

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Small-scale plasma irregularities are ubiquitous in the upper ionosphere and can severely distort GNSS radio signals, causing loss of lock events and ground scintillations. We characterize the magnetic signatures of these irregularities using the high-frequency (50 Hz) vector field magnetometer (VFM) records of the ESA Swarm mission triplet.

We investigate ionospheric turbulent dynamics through intermittent fluctuations in sliding-window segments of the Swarm magnetic field records. Intermittency is measured via a flatness-based proxy derived from probability density function (PDF) analysis of magnetic field increments, which quantifies deviations from Gaussian statistics. Besides, multifractal spectrum (MFS) analysis is also applied to provide Hölder exponent ranges and the multifractal P-model parameter of fluctuations along the orbits of the Swarm spacecraft. We extend this framework with automated spectral analysis — yielding power-law scaling ranges, exponents, and transverse–compressional anisotropy.

In the presentation we show that the strongest transverse intermittency appears in two oval-shaped regions around the geomagnetic poles, consistent with auroral oval boundaries and the ionospheric footprint of the plasmapause. Besides, we also find compressional and transverse intermittent fluctuations near ±10° dip latitude, which are linked to equatorial plasma bubble (EPB) events. Regarding space weather impact, equatorial IMI anomalies correlate with on-board GNSS loss-of-lock events and are also associated with amplitude scintillation events recorded at ground GNSS stations.

The new spectral and MFS databases, compiled for the full Swarm record (2014–present), are being developed within the SWIFT project, supported by ESA.

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Session Info: IOM3 OPERATIONAL AND PROTOTYPE DATA PRODUCTS DERIVED FROM LOW-EARTH ORBIT, NEAR-EARTH, AND UPSTREAM OBSERVATIONS

ESA'S SMOS MISSION FOR SPACE WEATHER

Roberta Forte [1], Federica Guarnaccia [1], Lorenzo Trenchi [1], Consuelo Cid [2], Manuel Flores-Soriano [2], Veronica Gonzalez Gambau [3], Arnau Ruiz [3], Nuria Duffo [4], Roger Oliva Balague [5], Raffaele Crapolicchio [1]

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SMOS is an ESA Earth Explorer missions, launched in 2009 and operational since 2010, to monitor the Soil Moisture and Ocean Salinity using L-band (1.4 GHz) passive microwave radiometry.
In 2026 a new Data, Innovation, and Science Cluster (DISC) contractual phase has started, where all SMOS partners, scientific and industrial, gather in a consortium of experts and collaborators with the purpose of developing an ecosystem of products and services, enhancing the return on scientific results.
In this frame, SMOS has demonstrated a significant added value in the Space Weather, a domain beyond its core scientific objectives, and a Space Weather Expert Support Laboratory (ESL) has been built, to exploit SMOS potentialities in this field.
For example, SMOS full-polarimetric measurements allow deriving solar brightness temperature, solar flux, and solar radio bursts occurrences, including the degree of circular polarization of the signal, potentially interesting to investigate the impact of solar radio bursts and L-band emissions on Global Navigation Satellite Systems (GNSS) signal degradation.
Furthermore, the exploitation of SMOS data has opened new applications for ionospheric monitoring, including the retrieval of vertical total electron content (VTEC) and the analysis of its variability during geomagnetic disturbances.
These innovative products have enabled synergies with other ESA EO missions (among which, but not limited to, Swarm). Moreover, they expand the mission's scientific objective, together with areas of interest and coverage, allowing to enlarge users' community and to provide visibility in new scientific environments.
This work intends to present an overview of the various activities carried out in the SMOS environment in the field of Space Weather, together with the upcoming activities, including products and services. And it aims at positioning SMOS, with these capabilities, as a valuable complementary asset within the Space Weather observational framework.

Date: Monday, November 02, 2026

Session Info: OTH2 OPERATIONAL SPACE WEATHER FORECASTING: SYSTEMS, WORKFLOWS, AND COORDINATION ACROSS FORECAST CENTRES

OPERATIONAL IMPROVEMENTS TO ACFJ'S GNSS ADVISORIES

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Since 2019, the International Civil Aviation Organization (ICAO) space weather service has been providing advisories for the aviation industry. The service comprises of 4 global centres: ACFJ (Australia, Canada, France, and Japan), PECASUS, SWPC, and CRC who rotate on-duty responsibilities every 2 weeks. Within ACFJ, GNSS advisories are issued by the SPECTRA consortium of ESSP, CLS and Meteo-France. Advisories are validated when total electron content (TEC) or scintillation data reach critical ICAO-defined thresholds. At ESSP, the operational chain automatically generates advisories when the TEC or scintillation thresholds are breached. These advisories are quality checked then validated or rejected by a team of forecasters before being disseminated.
ICAO centres abide by strict guidelines relating to the advisories. This guidance is regularly updated, based upon user feedback and technical discussions between centres. Recently, each centre was required to enhance the spatial resolution of the grid over which advisories are prepared, and to switch to using 5-point polygons to display advisory areas, rather than latitude bands that were used previously. For GNSS advisories, ESSP have played an important role in the definition of guidance to all ICAO centres, including the criteria needing to be fulfilled in order to allow the creation of a polygon and how to deal with complicated scenarios with multiple or severe-level polygons. In this presentation, we discuss these developments to the GNSS advisory process. We assess the impact that the changes have had on the precision and frequency of the advisories disseminated. An example of the advisory process is provided for the geomagnetic storm of 20th January 2026. Finally, we outline future evolutions to further improve the service, including the harmonisation of GNSS advisories between global warning centres.

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Session Info: OTH2 OPERATIONAL SPACE WEATHER FORECASTING: SYSTEMS, WORKFLOWS, AND COORDINATION ACROSS FORECAST CENTRES

FROM OPERATIONAL FORECASTING TO RESILIENT SYSTEM ARCHITECTURE: STRUCTURING THE SIDC/SWOP FORECASTING ENVIRONMENT

Daria Shukhobodskaia [1], Judith de Patoul [1], Lukas Vinoelst [1], Freek Verstringe [1], Veronique Delouille [1], Pavai Valliappan Senthamizh [1], Jesse Andries [1]

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Operational space weather forecasting relies on the continuous integration of observations, models, expert interpretation, products, communication channels, and service interfaces. At the Solar Influences Data Analysis Center and the Belgian Space Weather Operational Centre, SIDC/SWOP, this operational capability has progressively evolved from a science-driven monitoring activity into a structured forecasting environment supporting national, European, and international users.

This presentation describes the forecasting system from an operational-centre perspective, with emphasis on workflows rather than individual space weather events. We present the main components of the daily forecasting chain, including observation and data acquisition, detection and monitoring, modelling and forecasting, expert interpretation, alerting, and dissemination. Attention is given to how heterogeneous data sources, models, operational tools, and human expertise are combined under real-time constraints to provide continuous situational awareness and actionable information.

The talk will addresses the organisational and technical challenges involved in sustaining such a system. These include the maintenance of operational chains, dependency on external data, traceability of forecast decisions, harmonisation of thresholds and product definitions, and the need for robust fallback procedures.

Finally, we discuss ongoing efforts to structure the SIDC/SWOP environment through a clearer service-chain approach, linking assets, gaps, validation needs, and development priorities. This provides a practical framework for improving reproducibility, interoperability, and long-term sustainability, while supporting coordination with the ESA Space Weather Service Network, international forecasting centres, and user-oriented services such as aviation. It illustrates how operational centres can move from expert-based forecasting toward more transparent, resilient, and interoperable forecasting systems.

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OPERATIONAL FRAMEWORK FOR SPACE WEATHER ANALYSIS AND PREDICTION BY NASA GSFC'S MOON TO MARS SPACE WEATHER ANALYSIS OFFICE (M2M SWAO)

Michelangelo Romano [1], Teresa Nieves-Chinchilla [1], Mary Aronne [2], Carina Alden [3], Madeleine Anastopulos [2], Anna Chulaki [3], Francesca Di Mare [3], Anthony Iampietro [3], Elizabeth Juelfs [2], Melissa Kane [3], Robert Loper [4], Mary Pasanen [5], Norberto Romanelli [6], C Alex Young [1]

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The Moon to Mars Space Weather Analysis Office (M2M SWAO), located within the Heliophysics Science Division (HSD) at NASA Goddard Space Flight Center (GSFC), provides real-time, human-in-the-loop space weather analysis and prediction to safeguard NASA's robotic and human exploration missions. To deliver timely and actionable information for missions operating throughout the heliosphere, M2M SWAO continues to develop and maintain operational workflows that integrate heterogeneous observational data streams with advanced modeling capabilities. This presentation outlines the continued development of a cohesive operational framework supporting M2M SWAO's daily activities. Specifically, we detail how we maintain an adaptable framework to implement newer capabilities without compromising maintainability. We highlight the requirements, methodologies, and best practices supporting this framework and identify key challenges encountered when planning for continuity of operations. We also share updates about ongoing coordination with partners to provide space weather assessments which bridge existing gaps between solar, heliospheric, and planetary environments to demonstrate the importance of collaboration in support of space exploration to the Moon, Mars, and beyond.

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Session Info: OTH2 OPERATIONAL SPACE WEATHER FORECASTING: SYSTEMS, WORKFLOWS, AND COORDINATION ACROSS FORECAST CENTRES

THE SOLAR WIND SCOREBOARD HOSTED BY NASA'S CCMC

Martin Reiss [1], Leila Mays [1], Masha Kuznetsova [1], Barbara Perri [2], Tinatin Baratashvili [3], Edmund Henley [4], Igor Sokolov [5], Gergely Koban [5]

[1] NASA CCMC, Greenbelt, USA, [2] Astronome-Adjointe au CNAP, OSUPS, Paris, FRANCE, [3] KU Leuven, Leuven, BELGIUM, [4] Met Office, Exeter, UNITED KINGDOM, [5] University of Michigan, Michigan, USA

We present the Solar Wind Scoreboard, which is hosted by NASA's Community Coordinated Modeling Center (CCMC) and developed with the community as part of the COSPAR ISWAT initiative. The Solar Wind Scoreboard will serve the space weather and science community as a hub for real-time solar wind predictions at Earth, Mars, and other locations of interest. It will allow users to view the ensemble of community-contributed models and compare their performance during space weather events. Our overarching objective is to build an open platform that allows us to identify science models that show potential to improve operational services. In this presentation, we will share our progress from the COSPAR ISWAT Workshop in Cape Canaveral, FL, USA, focusing on the open information architecture, including metadata standards, automated prediction submissions, and front-end development. Additionally, we will discuss how the Solar Wind Scoreboard integrates with existing CCMC Scoreboards and feeds into the new Geospace Scoreboard. We will share lessons learned from running models like AWSoM (University of Michigan) and ICARUS (KU Leuven) in real-time, and how we integrate their results into the Scoreboard. Finally, we will outline future plans and how we envision broader community engagement in line with an open science approach.

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Session Info: OTH2 OPERATIONAL SPACE WEATHER FORECASTING: SYSTEMS, WORKFLOWS, AND COORDINATION ACROSS FORECAST CENTRES

ARCHITECTURE AND SERVICE WORKFLOW OF THE SPANISH SPACE WEATHER SERVICE (SENMES)

Pablo Muñoz [1], Consuelo Cid [1], Manuel Flores-Soriano [1], Armando Collado-Villaverde [1], Carlos Larrodera [1], Iván Maseda-Zurdo [1], Mario Cobos-Maestre [1], David F. Barrero [1]

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The Spanish Space Weather Service (SeNMEs) is a platform designed to provide continuous monitoring and forecasting of space weather conditions across the full Sun-to-Earth chain. The platform integrates heterogeneous observational and model-based products into a unified environment that supports both expert forecasters and end users requiring timely and actionable information.

SeNMEs is built around a modular orchestration framework that automates the acquisition, processing and publication of data products from multiple sources, including the NOAA Space Weather Prediction Center (SWPC), INTERMAGNET, the World Data Center for Geomagnetism, Kyoto, and instruments from the University of Alcala. The platform combines real-time observations with forecasting tools covering solar activity, solar wind conditions, radiation environment and geomagnetic disturbances indicators. Product outputs are presented through web dashboards featuring traffic-light indicators that summarize the current level of disturbance in different domains of the Sun-Earth system. In addition, SeNMEs generates user-oriented alert products based on configurable subsets of products tailored to specific applications and stakeholder needs. Automated email notifications are issued whenever predefined thresholds are exceeded, enabling rapid dissemination of warnings and updates.

The service architecture emphasizes automation, reproducibility, maintainability, and scalability, allowing new products to be incorporated with minimal operational overhead. By integrating diverse data streams and forecast products into a coherent workflow, SeNMEs provides a robust framework for space weather service and demonstrates an effective approach aiming to transition research developments into sustainable operational capabilities.

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Session Info: OTH2 OPERATIONAL SPACE WEATHER FORECASTING: SYSTEMS, WORKFLOWS, AND COORDINATION ACROSS FORECAST CENTRES

DEVELOPMENT OF OPERATIONAL SPACE WEATHER CAPABILITIES IN KENYA: INTEGRATING MONITORING AND FORECASTING SYSTEMS

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This work presents the development of operational space weather capabilities through the integration of multi-instrument monitoring and forecasting systems deployed on a Docker-containerised architecture, configured for near real-time data ingestion from a national network of space weather sensors. The network comprises GNSS receivers, an ionosonde station, magnetometers, and the Transient Array Radio Telescope (TART), with all observations streaming to a central monitoring system. Operational results from 2025 to 2026 demonstrate the system's capability to monitor ionospheric irregularities and associated variability in GNSS signal quality and HF propagation conditions under both quiet and disturbed ionospheric states. Frequent post-sunset scintillation occurrence was observed, consistent with expectations for a solar maximum period. Measurable inter-constellation differences in TEC and scintillation indices were identified, reflecting constellation-dependent sensitivity to ionospheric irregularities. TART correlated power measurements, representing the first reported observations from the Kenya deployment, revealed recurring diurnal enhancements consistent with solar transit and transient signatures of ionospheric structure, demonstrating its potential as an independent ionospheric monitor within the network. Variations in solar X-ray flux were observed to be associated with corresponding changes in HF propagation conditions as measured by the ionosonde. Positioning error monitoring integrated into the system reveals significantly elevated vertical errors above 5 m on days where S4 exceeds 0.3, directly quantifying the operational impact of scintillation on GNSS accuracy. This work demonstrates Kenya's progress toward establishing a fully operational Space Weather Monitoring and Forecasting Centre, contributing to regional space weather service infrastructure and supporting broader Space Weather Service Network initiatives.

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FIELDNOTES FROM AN ACADEMIC RESEARCHER TRANSITIONING TO OPERATIONAL FORECASTER

Elizabeth Butler [1]

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The transition of tools, models, and understanding from the research community to an operational environment (R2O) is riddled with many obstacles and gaps, some of which arise from cultural differences between the two communities, e.g. operations focusing on the 'big picture' of the entire space weather and human system whereas (basic) research tends to be more narrowly focused on specific phenomena. Based on a recently accepted paper, this talk presents a case study of my experiences transitioning from a career in academic research to space weather forecasting operations, supplemented with first-hand accounts from other forecasters and trainers. Topics highlighted in this talk are: (1) differences in prioritization arising from community goals; (2) how the operational environment dictates skills; (3) how forecasters interact with models; and (4) differences in mental frameworks and paradigms. Due to being predicated on my experience and background in academia and training at NOAA's Space Weather Prediction Center, there are gaps in the topics discussed and while it is largely aimed at the academic/basic research community, anyone is welcome, so that the topics discussed can spark a wider and ongoing conversation. Some recommendations for transition projects based on this discussion are also presented.

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IMPROVING THE PATHWAY FROM RESEARCH TO OPERATIONS FOR SPACE WEATHER SERVICES

François-Xavier Bocquet [1], Suzy Bingham [1], Edmund Henley [1], Mike Marsh [1], Harriet Turner [1], Siegfried Gonzi [1], David Jackson [1], Richard Mace [1], Wilf Wilson [1], Ander Englyst [1], Alan Wood [1], Gemma Creed [1]

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Transitioning research models into sustained operational use remains a complex, multi-faceted challenge, encompassing scientific, technical, and operational considerations. The Met Office's Research to Operations (R2O) programme addresses these challenges by providing a structured pathway that supports models as they mature from research prototypes to operationally supported systems underpinning vital space weather services.

A central element of this approach is the development of research models on shared, cloud-based infrastructure. This enables researchers and software engineers to adopt modern software development practices (including those required for operations) from an early stage, improving code quality, reproducibility, and robustness, whilst supporting progression towards the desired Application Usability Level (AUL). Embedding good engineering practice early in the life-cycle helps to reduce technical debt that can hinder later transition to operations.

A second critical element is the provision of a dedicated portal that allows users (currently MOSWOC forecasters) to interact with these models, for example through model visualisations. This supports user-centered development by facilitating testbed exercises, used to fine-tune the development of products and services to meet end-user needs. Early forecaster engagement through this portal is key to allowing quick iterations in the development of these services.

The final element is the transition to full operational status. Differences in assurance requirements, and operational constraints mean that movement from a flexible research environment to a production operational system is not yet fully seamless and requires close coordination across science and technology teams.

This process will be illustrated by presenting the R2O journey of the BAS radiation belt model and the associated satellite risk products, alongside a discussion of how lessons learned will further refine the R2O process.

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THE R2O2R APPROACH AT THE AUSTRIAN SPACE WEATHER OFFICE

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The Austrian Space Weather Office (ASWO) was established as the Austrian Space Weather Service in 2022, as part of the Austrian federal meteorological, geological and geophysical service GeoSphere Austria. At ASWO, we focus on improving hyperfast models for the solar wind and CMEs to advance their basic understanding and to provide real-time forecasts. We hereby focus on a research-to-operations-to-research (R2O2R) approach and aim at interpreting our model results with respect to impact based forecasts, focusing on effects of mid-latitude aurora, enhanced geomagnetically induced currents in the Austrian power grid, and GNSS errors.

We provide forecasts of solar storms and aurora for the public in Austria, which we distribute mainly via social media, and via press releases for newspapers and TV stations. We also provide alerts for all Austrian stakeholders in the case of a significant space weather event.

The ASWO is part of the Austrian Multi-Hazard impact-based Advice Service (AMAS) for the Ministry of Interior in Austria, where we meet twice a week to assess the potential overlaps of current space weather impacts with other natural hazards. Our participation in a European-level multi-hazard system is currently in a planning stage.

Our research program focuses on the establishment of ICME catalogs with all current spacecraft operating in the solar wind, tracking CMEs in heliospheric imagers for the Vigil mission, improving ambient wind modeling, combining physics based forecast approaches with AI based automatic detections, and evaluating how sub-L1 monitors need to be designed to be able to provide accurate CME forecasts with strongly enhanced lead times. We present an overview of our research program, forecasting pipeline, operational workflow, and dissemination strategies, as well as the main challenges we face.

Date: Monday, November 02, 2026

Session Info: PL1 PLENARY 1 - INSIGHTS FROM AN OPERATIONAL PERSPECTIVE: CHALLENGES AND LESSONS LEARNED FROM SEVERE EVENTS IN SOLAR CYCLE 25

RESPONSE TO SEVERE EVENTS DURING SC 25: END-USER PERSPECTIVE

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Severe events in Solar Cycle 25 have revealed important operational challenges in monitoring and mitigating space weather impacts across Canada's high-latitude regions, where GNSS scintillation, HF communication absorption, and geomagnetic disturbances affect critical systems. This presentation highlights how recent high-impact events, including those in May 2024, disrupted northern aviation, degraded HF communications, and posed risks to power grid operations and other key infrastructure. These examples highlight persistent challenges in real-time situational awareness-particularly in data-sparse regions-and the translation of complex observations into actionable guidance for users. Lessons learned are guiding efforts to expand ground-based monitoring networks, improve the spatial and temporal resolution of key measurements, and advance auroral imaging capabilities intended for highly elliptical orbit. These developments are essential to strengthening national resilience as infrastructure and operations continue to expand across the Arctic. This work provides a Canadian operational perspective on preparing for future solar cycle maxima, during which critical infrastructure is expected to expand significantly across northern regions while becoming increasingly interconnected and reliant on space weather-sensitive technologies. As this interdependence grows, so does the potential for cascading impacts across systems. Addressing this evolving risk will require not only enhanced monitoring and forecasting capabilities, but also deeper integration of space weather intelligence into operational decision-making.

Date: Monday, November 02, 2026

Session Info: PL1 PLENARY 1 - INSIGHTS FROM AN OPERATIONAL PERSPECTIVE: CHALLENGES AND LESSONS LEARNED FROM SEVERE EVENTS IN SOLAR CYCLE 25

SEVERE EVENTS DURING SC 25 SO FAR: AN OVERVIEW OF DETECTIONS, MODELLING AND DISSEMINATION

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The Solar Influences Data Analysis Center (SIDC) at the Royal Observatory of Belgium has been operating space weather services for several decades, progressively evolving from a scientific monitoring center toward an operational, end-to-end 24/7 space weather service provider supporting national, European, and international users. Solar Cycle 25 has provided a unique opportunity to assess the strengths and limitations of operational space weather forecasting, particularly during periods of elevated solar activity and severe geomagnetic disturbances.

During this plenary discussion, the SIDC perspective will provide an overview of some of the most significant events observed during Solar Cycle 25, focusing on lessons learned from real-time operational experience. The discussion will address practical challenges associated with monitoring, forecasting, communication, coordination, and decision support during severe space weather events.

Particular attention will be given to operational constraints encountered during high-impact periods, including forecaster workload, escalation procedures, and operational bottlenecks. Current limitations in forecasting extreme events will also be examined, including model discrepancies, data reliability issues, and the difficulty of translating evolving scientific information into operationally actionable guidance for end-users.

The panel contribution will further highlight broader system-level challenges, particularly under high operational pressure, including communication of uncertainty and risk, user interpretation of warnings, international coordination, consistency between operational centers, data sharing, and governance. Through these examples, the contribution aims to provide a realistic operational perspective on current capabilities and limitations of space weather services, reflecting on how these have evolved and identifying priorities for more robust, interoperable, and user-oriented operational frameworks.

Date: Tuesday, November 03, 2026

Session Info: HEL1 ADVANCING CROSS-SCALE SPACE WEATHER AT THE MOON, MARS, AND BEYOND IN SUPPORT OF SCIENCE, OPERATIONS, AND EXPLORATION

SOLAR WIND HIGH SPEED STREAM FORECASTS AT MARS IMPROVED BY DATA ASSIMILATION

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It is important to forecast space weather to help mitigate the potential impacts it can have on modern technology and humans in space. Forecasting at Mars is becoming increasingly important with the planning of crewed missions and it also offers an independent location at which to verify forecasts. Current space weather modelling methods combine a model for the corona close to the Sun and a model for the heliosphere. Here, we use the Wang-Sheeley-Arge (WSA) model for the corona and the Heliospheric Upwind Extrapolation with time-dependence (HUXt) model for the heliosphere, combined into the WSA-HUXt framework. In this work, we show that the Burger Radius Variational Data Assimilation (BRaVDA) scheme, which assimilates in situ solar wind observations, can be used to improve solar wind speed forecasting at Mars. BRaVDA is used to modify the output from the WSA model with information from observations taken near-Earth, with the updated output then being used in HUXt. This produces the WSA-BRaVDA-HUXt framework. When predicting solar wind high speed streams (HSSs), we find that using WSA-BRaVDA-HUXt reduces the number of false alarms by approximately half when compared to WSA-HUXt. Furthermore, using WSA-BRaVDA-HUXt improves the arrival time error and peak speed prediction of the HSSs. This shows that BRaVDA can be a useful forecasting tool for locations at other locations in the heliosphere.

Date: Tuesday, November 03, 2026

Session Info: HEL1 ADVANCING CROSS-SCALE SPACE WEATHER AT THE MOON, MARS, AND BEYOND IN SUPPORT OF SCIENCE, OPERATIONS, AND EXPLORATION

SOLAR EVENTS AND COSMIC RAY ENVIRONMENT AT THE LUNAR SURFACE

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With upcoming long-duration human missions to the Moon, accurately assessing environmental hazards is essential, with radiation exposure representing one of the most critical risks for surface operations.

This work investigates the interaction of high-energy charged particles with the lunar surface, with particular focus on solar energetic particles and galactic cosmic rays. Using Monte Carlo simulations of particle transport and interactions within the lunar regolith, we characterize the production of secondary particles emerging from the surface, commonly referred to as lunar albedo.

For a selected subset of Solar Particle Events, whose energy spectra are described by power laws with exponential cutoffs, simulations indicate systematic production of secondary particles. Among these, neutrons are of particular interest because of their high penetration capability and relatively low interaction probability, which make them a significant contributor to radiation risk for future lunar exploration. Galactic cosmic rays, characterized by even higher energies and an approximately isotropic flux modulated by the 11-year solar cycle, may further enhance this radiation hazard.

We also investigate the relationship between secondary particle production and the spectral properties of incident particles. Preliminary results suggest that variations in the primary spectra can significantly affect both the intensity and energy distribution of the produced secondary particles. These findings contribute to a broader understanding of particle interactions in planetary environments and may support future studies related to radiation characterization and mitigation strategies.

Date: Tuesday, November 03, 2026

Session Info: HEL1: ADVANCING CROSS-SCALE SPACE WEATHER AT THE MOON, MARS, AND BEYOND IN SUPPORT OF SCIENCE, OPERATIONS, AND EXPLORATION

UNCERTAINTY QUANTIFICATION FOR SUN-TO-MARS SPACE WEATHER PREDICTION

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Space weather at Mars presents a coupled science and exploration challenge: solar transients evolve substantially beyond 1 AU, while Mars lacks a continuous upstream solar wind monitor comparable to Sun-Earth L1 assets. This gap limits both physical interpretation of Mars plasma and radiation observations and the development of operational forecasting capabilities needed for future human exploration. We present an uncertainty quantification framework for evaluating how well current heliophysics observations, models, and data-driven methods can characterize the space weather environment from the Sun to Mars. The effort integrates existing observations from Earth L1 assets, heliospheric imagers, Mars missions, and model outputs to examine how uncertainty propagates through key parts of the Sun-to-Mars prediction chain, including ambient solar wind propagation, CME/SEP arrival, and Mars upstream conditions. Rather than treating uncertainty as an after-the-fact error bar, we use it as a mission design metric: identifying where predictions diverge, which observables most reduce forecast uncertainty, and what measurements may require a dedicated Mars L1 capability. Preliminary work focuses on mapping available data products, model interfaces, and uncertainty sources, with forthcoming analysis aimed at ranking measurement priorities, cadence needs, and operational data products. This approach supports a future Earth-independent Mars space weather architecture while advancing planetary space weather science across the inner heliosphere.

Date: Tuesday, November 03, 2026

Session Info: HEL1: ADVANCING CROSS-SCALE SPACE WEATHER AT THE MOON, MARS, AND BEYOND IN SUPPORT OF SCIENCE, OPERATIONS, AND EXPLORATION

A COMPREHENSIVE ANALYSIS OF THE EFFECTS OF SPACE WEATHER ON THE LUNAR SODIUM EXOSPHERE AND THE EXTENDED LUNAR SODIUM TAIL UTILIZING GROUND-BASED OPTICAL, RADIO, AND SATELLITE OBSERVATION METHODS

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The Lunar Exosphere is highly variable, surface-bounded system, where the regolith acts as the primary source of species released via external forcing. Among the principal mechanisms involved in atmospheric loss and the release of atoms from the Lunar surface are drivers depending on space weather effects, such as Photon-Stimulated Desorption (PSD), Solar wind interactions, and meteoroid impacts. Distinguishing the effects of these drivers requires careful control of observational geometry and event timing. In this study, the variability of Lunar Exospheric Sodium (Na) is investigated using a combined dataset. This includes orbital observations from the Lunar Atmosphere and Dust Environment Explorer (LADEE/UVS), converted into daily mean Na abundance, and ground-based all-sky imaging of the Lunar Sodium Spot (LSS) extended tail. These are analyzed alongside meteor radar counts and Solar wind parameters derived from OMNIWeb data. The LADEE analysis indicates that Na abundance is not only dependent of Lunar phase geometry-dependent but also High-Speed Streams (HSS)/Coronal Mass Ejection (CME). The reduced Na abundance in the Lunar exosphere shows clear decreases, with an average depletion of approximately ~26-31 %. Superposed analysis further suggests a cumulative and delayed depletion pattern following HSS/CME onset. Meteoroid activity alone, in contrast, does not show a comparable enhancement in daily mean Na abundance. Ground-based imaging shows that LSS brightness is higher during HSS/CME intervals. Taken together, these results indicate that Lunar Sodium variability is controlled by multiple interacting processes, with the Solar wind playing an important role not only in the atmospheric abundance of planetary bodies like the Moon, but also in the subsequent chemistry and dynamics of their exospheres.

Date: Tuesday, November 03, 2026

Session Info: HEL1: ADVANCING CROSS-SCALE SPACE WEATHER AT THE MOON, MARS, AND BEYOND IN SUPPORT OF SCIENCE, OPERATIONS, AND EXPLORATION

SPACE WEATHER AT THE MOON: CURRENT STATE AND CHALLENGES

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The Moon during most part of its orbit around the Earth is directly exposed to the interplanetary medium. Solar wind and solar energetic particles (SEPs) arrive almost without any deviation or absorption and impact directly on its surface, interacting with the lunar regolith and the tenuous lunar exosphere. The same phenomenon occurs also with the galactic cosmic rays (GCRs). Energetic particles arriving at the Moon's surface can be absorbed, or scattered, or produce albedo energetic particles, including electrons, protons, heavy ions and neutrons, which in their turn contribute to the generation of a unique space weather environment. During 5 - 6 days every orbit, however, the Moon crosses the tail of the Earth's magnetosphere, getting exposed to terrestrial origin plasma and energetic particles. Electrostatic surface charging, dust levitation, meteoritic flux and the tenuous lunar exosphere are additional components of the lunar and cis-lunar space weather environment, which is a complex, multi-scale interacting system. Understanding this system and developing the capability to predict its response to space weather events is of paramount importance, in view of the forthcoming robotic and human missions. Characterisation and monitoring of the lunar environment is also essential in order to asses the environmental impacts that human and robotic activity can have on the pristine Moon and to gain a better understanding of how this natural laboratory works.

Date: Tuesday, November 03, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

NASA SPACE WEATHER PROGRAM COORDINATED EXPLORATION STRATEGY FOR MOON, MARS, AND BEYOND

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The NASA Space Weather Program is strategically supporting and leveraging robotic and human exploration across the solar system. Driven by the revitalization of crewed space missions under the Artemis program and beyond, the strategy addresses the critical need to predict, monitor, and model harsh radiation, plasma, and dust environments to ensure astronaut safety and protect supporting infrastructure. In alignment with these goals, the Program's initiatives emphasize that understanding space weather throughout the inner heliosphere is essential for both robotic and human exploration. We will discuss the NASA Space Weather Program's Exploration pursuits along with the data and observation gaps that have been identified in coordination with the Moon to Mars Architecture facilitators as critically relevant to human space exploration initiatives.

Date: Tuesday, November 03, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

THE CURRENT STATUS OF SOLAR WIND PHYSICS AND THE GROUND STATE OF SPACE WEATHER

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Aspects of the physical mechanisms involved in energizing the solar atmosphere and generating the solar wind continue to elude scientists. Questions remain because the solar-inner heliosphere system is enormous, both in terms of volume and the range of different physical regimes. Thus, observations and simulations are necessarily limited to narrow aspects of physics and/or system, and are only just beginning to capture cross-scale and cross-region coupling. The pathway of solar wind formation, starting with coronal heating, then solar wind release and lastly solar wind acceleration, leaves imprints in mesoscale solar wind structures that survive through the inner heliosphere. Mesoscale structures form the ground state of space weather, driving Geospace dynamics including ultralow frequency waves, dynamics of the ultra-relativistic radiation belt particles, and GICs, even during times when there are no large space weather events. Additionally, mesoscale solar wind structures are the structure through which larger space weather events propagate, as they funnel and scatter energetic particles, and affect the propagation of CMEs and formation of CME sheath regions. Furthermore, mesoscale solar wind structures 'precondition' Geospace, determining the state of the magnetosphere and radiation belts when large space weather events impact Earth. We discuss progress and prospects with recent and upcoming observations with the Polarimeter to Unify the Corona and Heliosphere (PUNCH) mission, ASPIICS/PROBA-3, COronal Diagnostic EXperiment (CODEX), Metis on Solar Orbiter, and Joint EUV coronal Diagnostic Investigation (JEDI). Together, they provide measurements of density, speed, and temperature of the corona and its structures. Combined with models, these new data provide new understanding of the source, release, acceleration and evolution of the solar wind and its mesoscale structures and the ground state of space weather.

Date: Tuesday, November 03, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

LONG-LIVED MAGNETIC SWITCHBACKS TRACKED ACROSS 0.32 AU THROUGH BEPICOLOMBO-SOLAR ORBITER RADIAL ALIGNMENT

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Magnetic switchbacks, often observed in the near-Sun solar wind, have received increased interest in recent years due to their potential role in mediating the heating and acceleration of the solar wind, but their origin remains debated.
In this work, we present a coordinated observation of a switchbacks cluster by BepiColombo (0.35 au) and Solar Orbiter (0.67 au), obtained during the alignment between 6-8th October 2021, which enabled the direct investigation of switchbacks evolution across heliocentric distances. In particular, the stream observed by the spacecraft can be tracked back to the boundary of an equatorial coronal hole. Plasma and magnetic field data measured in-situ exhibit remarkable similarities at both locations. In particular, larger-scale switchbacks exhibit strong sub-linear expansion, thus appearing almost unevolved in morphology during the propagation when the spacecraft cutting-angle effect is taken into account. The stable magnetic configuration of the analyzed switchbacks suggests that they can be identified as small-scale flux ropes. Indeed, for shear-driven instabilities triggered by stream interaction with the background slow wind, short-living (one eddy turnover time, ~ 1hr) switchbacks would be expected compared to the travel time from BepiColombo to Solar Orbiter (~38hr). These findings provide critical insights on switchbacks origin and evolution, potentially constraining future phenomenologies on their formation. A useful consequence of our observations is that statistical analyses on switchbacks evolution should always account for the cutting-angle effect.

Date: Tuesday, November 03, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

PROBING SOLAR WIND ORIGINS AND CORONAL PLASMA PARAMETERS THROUGH COORDINATED MULTI-SPACECRAFT OBSERVATIONS

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Understanding the origin and acceleration of the solar wind in the inner heliosphere
requires probing the plasma close to the Sun, where heat and momentum deposition occurs. In this study, we exploit a near-quadrature configuration between Solar Orbiter (SolO) and Parker Solar Probe (PSP), while the latter is in co-rotation with the Sun at about 30 solar radii, enabling the simultaneous sampling of coronal source regions and their heliospheric extensions.
Using high-resolution ultraviolet (UV) and polarized visible-light (pB) observations from the SolO/Metis coronagraph, we derive the coronal electron density and the plane-of-sky distribution of the solar wind speed. The latter is obtained using the Doppler Dimming Tool (DDT), which yields uncertainties of about 20-40% because of the different possible assumptions on the unmeasured coronal temperatures, which can vary by about 1 MK.
To improve the accuracy of velocity measurements in the acceleration region, we use
a 1D solar wind model to extrapolate PSP proton and electron temperatures back to the Sun. These temperatures are used to update the DDT velocity estimates,
and the procedure is iterated until the solar wind solution matches density and
velocity measurements from 2 to 30 solar radii. The resulting data-constrained solar wind solution depends on the peak and locations of the proton and electron temperatures. We discuss the properties of this solution and its implications
for the heating and acceleration of the solar wind in this particular stream.

Date: Tuesday, November 03, 2026

Session Info: SCL1: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS

PERIODIC DENSITY STRUCTURES AND THEIR RADIAL EVOLUTION FROM SOLAR ORBITER DATA

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The quasi-periodic density structures (PDSs) are quasiperiodic variations of solar wind density ranging from a few minutes to a few hours. They are trains of advected density structures with radial length scales LR~100-10,000 Mm, thus belonging to the class of solar wind mesoscale structures. Even though PDS at L1 have been extensively studied both through statistical and event analysis, their investigation at distances closer to the Sun is limited. This study performs a statistical investigation of PDS at various distances from the Sun between 0.3 and 1 AU by exploiting Solar Orbiter data. We compiled and made publicly available an extensive list of PDSs following a well-established methodology that combines the Multitaper method as well as wavelet analysis to reveal the distribution of PDS radial length scales and how they vary with respect to the radial distance. Our results indicate that PDS advected with the ambient slow solar wind are expanded, while PDS detected during fast solar wind segments show compression indicative of their interaction with stream interaction regions. We further applied a wavelet analysis technique to obtain the reduced magnetic helicity, cross helicity, and residual energy. Our results indicate that small flux ropes are a constituent of PDS events, while the occurrence probability of helical Alfvenic structures is similar within and outside the PDSs. These results are consistent with the scenario in which PDSs are formed by processes involving magnetic reconnection.

Date: Tuesday, November 03, 2026

Session Info: SCL12: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS - EXTREME SOLAR EVENTS: FROM SOLAR ORIGIN TO COSMOGENIC ISOTOPE SIGNATURES

THE IMPACT OF SPACE WEATHER ON EARTH'S ATMOSPHERIC CHEMISTRY AND CLIMATE: IS N2O A SOLUTION TO THE FAINT YOUNG SUN PARADOX?

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Space weather could have a profound impact on Earth's climate. Compared to the present-day Sun, the young Sun would have been more magnetically active and should have experienced more frequent extreme space weather events, in the form of coronal mass ejections and solar energetic particles, which steadily bombarded Earth's upper atmosphere. These particles enhanced atmospheric chemistry, potentially resulting in large amounts of kinetically produced greenhouse gases, such as CO, H2, N2O, and HCN. In this work, to explore whether the Sun-Earth interaction could address the faint young Sun paradox (FYSP), we use a chain of three models: (i) an Earth-like planet surface temperature model, (ii) a radiative-convective model (EOS), and (iii) a thermochemical and photochemical kinetic model. We also apply this modeling pipeline to the present-day Earth atmosphere to assess the potential impact of a prolonged period of intense solar activity. Our main results can be summarized as follows. First, we find that, for an Archean Earth-like atmosphere of 90% N2, 10% CO2, and trace amounts of either CH4 or H2, the surface temperature increase due to space weather-produced greenhouse species is no larger than 0.3 K, which makes this solution to the FYSP unviable. Second, we find that the contribution of nitrogen species (N2O and HCN) to this temperature increase is negligible and that the main greenhouse contributors are instead CO and H2. Third, on present-day conditions, the cumulative effects of a prolonged period of intense solar activity would decrease the surface temperature by about 3 K. This work has recently been published in The Astrophysical Journal (ApJ).

Date: Tuesday, November 03, 2026

Session Info: SCL12: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS - EXTREME SOLAR EVENTS: FROM SOLAR ORIGIN TO COSMOGENIC ISOTOPE SIGNATURES

DATA-DRIVEN IDENTIFICATION OF SOLAR ACTIVITY SIGNATURES USING EMPIRICAL MODE DECOMPOSITION AND HILBERT SPECTRAL ANALYSIS

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Understanding and analyzing solar activity is essential for characterizing the variability of the Sun and its impact on the near-Earth environment. Solar phenomena such as flares, coronal mass ejections, and associated solar energetic particle (SEP) events can significantly affect the planetary and circumplanetary environment. Extending our knowledge beyond the instrumental era requires the study of indirect proxies, such as cosmogenic isotopes, whose variability reflects changes in solar magnetic activity and particle fluxes over long timescales. In this context, robust data analysis techniques are crucial for extracting meaningful signals from complex and often non-stationary datasets.

Unlike traditional spectral methods, Empirical Mode Decomposition (EMD) and its extensions provide an adaptive decomposition of signals into intrinsic mode functions, enabling the isolation of transient, scale-dependent features without requiring prior assumptions about stationarity or linearity. Coupled with Hilbert Spectral Analysis, this approach enables the extraction of phase, amplitude, and frequency for each time-dependent component, yielding a time-frequency-energy representation of the data and enhancing the identification of time-localized anomalies.

A key advantage of this framework is its flexibility across a wide range of datasets, from short to long time series, allowing a targeted focus on specific timescales of interest. We present results from the application of this method to selected solar-related signals, including quantities inferred from cosmogenic isotope measurements, such as the open solar magnetic field.

Date: Tuesday, November 03, 2026
Session Info: SCL12: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS - EXTREME SOLAR EVENTS: FROM SOLAR ORIGIN TO COSMOGENIC ISOTOPE SIGNATURES

FROM CALIBRATION TO RECONSTRUCTION: EVALUATING SNV2 AND BUILDING THE NEXT SUNSPOT NUMBER (SNV3)

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The International Sunspot Number (SN) is of major scientific importance, as its accuracy directly impacts solar physics, space weather, and space climate studies, as well as a broad spectrum of related fields, including climate and atmospheric science, geomagnetism, ionospheric and magnetospheric physics, cosmic ray modulation, astrophysics, and Earth system science.

The current index was originally established in 1849 by Rudolf Wolf at the Zurich Observatory, although the series itself extends back to the early 1600s. Prior to 2015, the Sunspot Number had never undergone revision bar an alternative group sunspot number series developed in 1995 by Hoyt and Schatten. With the introduction of a formal versioning system in 2015, it became essential to continuously monitor and refine the Sunspot Number.

In this work, we present a multiparameter analysis of version 2 of the Sunspot Number (SNV2), based on comparisons with multiple proxy datasets, in order to assess the quality of the produced index since its release in 2015. We also outline our plans for the next version of the index.

Our analysis indicates that SNV2 shows no significant deviations or long-term drifts in its production. The observed excursions are largely attributable to intrinsic solar variability.

We are currently undertaking a complete reconstruction of the Sunspot Number that will be called SNV3, from raw observational data, moving beyond the calibration approach implemented in 2015. This effort has required the collection and extraction of additional historical documents, all of which are being consolidated into a comprehensive database. We will present the source data and the first tentative reconstructions.

Date: Tuesday, November 03, 2026

Session Info: SCL12: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS - EXTREME SOLAR EVENTS: FROM SOLAR ORIGIN TO COSMOGENIC ISOTOPE SIGNATURES

UNDERSTANDING WHY SOLAR CYCLES RISE DIFFERENTLY BUT DECAY IN A SIMILAR WAY: IMPLICATIONS FOR SPACE WEATHER AND CYCLE PREDICTION

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Sunspots are an obvious observable manifestation of the toroidal magnetic field generated through the dynamo in the convection zone. They appear in different sizes, having a wide distribution in their area. We analyse the sunspot group area of the past 13 cycles and the Bipolar Magnetic Region (BMR) flux for Cycles 23 and 24 to explore their area and flux distributions and connect with the theory. We find that, in general, the group area and BMR flux are statistically larger in the rising phase than in the declining phase of the solar cycle. This implies that the rising phase of the solar cycle is more prone to drive space weather. We further show that the mean and median of the area distribution during the rising phase are dependent on cycle strength. However, the distribution mean and median are cycle strength-independent or weakly dependent during the decline phases of the solar cycles, particularly during the last three years when the latitudinal bands of all cycles migrate towards the equator along the same trajectory. These results support the theoretical dynamo model of nonlinear flux loss due to flux emergence, which explains why solar cycles rise differently but decay similarly. Further, the results provide a physical basis for early solar-cycle prediction.

Date: Tuesday, November 03, 2026

Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

COSMOGENIC ISOTOPES SIGNATURES OF EXTREME SOLAR PARTICLE EVENTS IN THE TALOS DOME ICE CORE (EAST ANTARCTICA)

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Extreme solar particle events (ESPEs) represent some of the most energetic manifestations of solar activity, with direct consequences for the near-Earth radiation environment. Their signatures, preserved as anomalies in 14C in tree rings and in other cosmogenic radionuclides (10Be, 36Cl) in ice cores,provide a unique opportunity to extend our knowledge of extreme solar events well beyond the instrumental era. In particular, the 36Cl/10Be ratio enables assessment of the spectral hardness of SEP events.

We present new high-resolution 10Be and 36Cl concentration profiles from the Talos Dome ice core (East Antarctica), including the first Antarctic 36Cl measurements covering extreme SEP events. Talos Dome represents a particularly suitable site for this purpose, as its relatively high snow accumulation rate ensures well-preserved 36Cl signals compared to other low-accumulation Antarctic sites.

Our measurements cover different ESPEs, including the 9,125 BP event, which is considered one of the spectrally hardest events currently known. The signal retrieved in TALDICE is consistent with previous studies, confirming the global coherence of this event signature. Our study provides new insight into the physical differences among ESPEs of different magnitude and into their possible origins.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

MACHINE LEARNING CLASSIFICATION OF SOLAR ENERGETIC PARTICLE INTERVALS USING SOLAR ORBITER ENERGETIC PARTICLE OBSERVATIONS

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The inner heliosphere is affected by transient increases in energetic electron and proton fluxes generated by different acceleration processes. Among these phenomena, solar energetic particle (SEP) events associated with solar flares and coronal mass ejections (CMEs) constitute a major radiation hazard for spacecraft and human exploration. Distinguishing solar-origin energetic particles from particles accelerated locally by interplanetary processes remains a significant challenge for machine learning applications in Space Weather.

We investigate the automatic identification of energetic particle events using in situ Solar Orbiter observations from 2020-2025. We use measurements from the Energetic Particle Detector (EPD), including the Electron Proton Telescope (EPT) and High Energy Telescope (HET). The dataset includes electron fluxes in the 35-53 keV range and proton fluxes covering 0.5-100 MeV. Positive samples correspond to intervals containing Solar Energetic Electrons and Particles (SEE/SEP) linked to eruptive solar activity, while the negative class (NO_SEE/NO_SEP) includes quiet background intervals and energetic storm particle (ESP) events related to interplanetary shocks and local acceleration processes in the solar wind.

The objective is to distinguish energetic particles of solar origin from flux enhancements generated by local interplanetary acceleration mechanisms. Electron and proton fluxes are represented as time-energy matrices and analysed using 2D convolutional neural networks (2D-CNNs), enabling the binary classifier models to learn temporal and spectral structures directly from the particle measurements.

Model performance is evaluated with metrics commonly used in Space Weather studies, including accuracy, F1 score, ROC AUC, Heidke Skill Score (HSS), and True Skill Statistic (TSS). Preliminary results indicate that the proposed methodology achieves performance comparable to current state of the art approaches for SEP and SEE classification.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

BRIDGING GAPS IN GLOBAL MAGNETIC FIELD DATA WITH HELIOSEISMIC RECONSTRUCTION OF FAR SIDE MAGNETOGRAMS

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Magnetic activity on the solar surface is fundamental for constructing global magnetic field models and improving space weather forecasting. While Earth facing magnetograms are routinely obtained from ground based and space borne observatories, direct measurements of the far side magnetic field became possible with the launch of Solar Orbiter (SO) in 2020. Its Polarimetric and Helioseismic Imager (SO/PHI) provides intermittent full disk magnetograms from vantage points that vary with orbital geometry, yielding partial or complete far side coverage. Combining front side and far side magnetograms enables continuous tracking of active region evolution - an essential input for forecasting coronal mass ejections, solar wind streams, flares, and solar energetic particle events.

For more than two decades, far side helioseismic maps have served as reliable early indicators of active regions, detecting them days before they rotate into Earth's view. These maps are valuable for locating far side activity, but their lack of quantitative information - such as magnetic field strength, polarity structure, and tilt angle - limits their use in full Sun magnetic field modeling.

We present a physics informed machine learning framework for generating signed far side magnetograms. Previous efforts have relied solely on indirect seismic proxies to infer magnetic field strength, leading to substantial uncertainties in the resulting data products. Our approach overcomes this limitation by calibrating helioseismic phase shift maps with direct magnetic field measurements from SO/PHI. Because SO/PHI provides far side observations only intermittently, the framework is designed to produce robust magnetograms even in the absence of contemporaneous direct data. By integrating seismic diagnostics with direct magnetic observations, this method enables more accurate and comprehensive reconstructions of the Sun's global magnetic field, ultimately strengthening space weather forecasting capabilities.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

PREDICTING 3D CORONAL MASS EJECTION PARAMETERS FROM MULTI-SPACECRAFT CORONAGRAPH OBSERVATIONS USING DOMAIN-ADAPTED DEEP LEARNING

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Reliable and timely characterisation of coronal mass ejections (CMEs) is essential for operational space weather forecasting. Automated CME parameter estimation from coronagraph images remains challenging due to fragmented fronts, diffuse boundaries, missing structures, data gaps, and viewpoint-dependent morphology. Supervised deep learning models are limited by the lack of labelled real CME datasets with reliable 3D ground-truth parameters. Synthetic CMEs provide known labels, but models trained only on idealised masks may not generalise to real observations. Building on Gandhi et al. (2025), we investigate one of the first domain-adaptation frameworks using synthetic-to-real image translation for supervised 3D CME parameter prediction from multi-viewpoint coronagraph sequences.

Synthetic CME events are generated for SOHO/LASCO C3, STEREO-A/COR2, and STEREO-B/COR2 using a croissant-like model, converted to binary polar masks, and labelled with longitude, latitude, tilt, angular width, speed, and acceleration. To reduce the domain gap, a CycleGAN model is implemented that translates clean synthetic masks into realistic masks using NRGF-DST processed real CME masks as the target domain. These masks qualitatively reproduce domain gaps. A key focus is to assess whether they preserve the underlying CME geometry associated with their synthetic labels.

As an initial diagnostic, we apply a CNN trained only on clean synthetic masks to both clean and CycleGAN-translated validation events. The resulting prediction shifts quantify sensitivity to realistic mask degradation and provide a baseline for domain-adapted training. Next, a CNN will be trained on CycleGAN-translated and combined datasets to test whether realistic masks improve robustness on real CMEs. This work demonstrates the potential of CycleGAN-based synthetic-to-real adaptation to generate labelled training datasets for automated 3D CME characterisation, supporting progress toward robust operational CME forecasting.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

ADVANCING SPACE WEATHER DATA-DRIVEN AND MACHINE LEARNING APPLICATIONS FOR OPERATIONS USING THE SPACE WEATHER ANALYST

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Transitioning data-driven and ML space weather forecast and tool capabilities across the research-to-operations (R2O) 'valley of death' to realize effective capabilities to mitigate risk from critical infrastructure and spaceflight operations continues to be a significant challenge.
The Space Weather Analyst (SWA) is a technology specifically made to address space weather data-driven and R2O challenges. SWA's infrastructure and artifacts including data, models, and decision support tools span the entire R2O lifecycle. SWA's technologies, methods, and techniques can revolutionize space weather forecasting and risk mitigation.
SWA's data-driven and MLOps development, testing, validation, deployment, and operational environments are supported by NextGen's Space Radiation Intelligence System (SPRINTS) technology. SPRINTS is a modular framework for forecasting solar-driven events using empirical, ML, and physics-based models and relevant datasets. SWA's Spacecraft Anomaly Resolution Knowledgebase (SPARK) NextGen technology enables critical infrastructure and human and robotic spaceflight analysts and operators to have secure environments to develop data-driven insights by fusing space environment and forecast data to impacted data. SWA's ReadiChatTM technology is a mission AI platform using GenAI for analyzing live sensor data, coordinating specialized agents, and deploying trusted workflows. ReadiChat is integrated into the Space Weather Analyst providing users from model developers to industry operators high fidelity tools and information to rapidly develop and validate models and gain insight into space weather impacts and how to manage risk. This talk highlights SWA's analytical and modeling features across its data-driven and ML R2O product lifecycles.

Date: Tuesday, November 03, 2026

Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

IDENTIFYING FLARE PRECURSORS WITH WEAKLY SUPERVISED CONTRASTIVE REPRESENTATIONS FOR SOLAR FLARE FORECASTING

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Reliable solar flare forecasting is limited by two forms of class imbalance in active region time series: the dominance of quiet, non-flaring states over eruptive states, and the weak separability between common, physically similar flare classes, such as C- and M-class events. Empirical parameters derived from the photospheric vector magnetic field (VMF), including SDO/HMI SHARP quantities, capture aspects of magnetic complexity and free-energy buildup, but often evolve smoothly and overlap across flare classes. As a result, models may distinguish flaring from non-flaring regions reasonably well, while still struggling to separate flare magnitude or association with eruptive phenomena such as CMEs from photospheric information alone. Improved flare-class separation therefore requires a clearer definition of similarity between pre-flare states and a parametrization that emphasizes flare-relevant structure rather than common active region morphology. We investigate a weakly supervised contrastive parametrization of SDO/HMI SHARP VMF cutouts using a β-VAE trained with label triplets. The weak supervision is introduced through flare-relevant, physics-informed thresholding of selected SHARP magnetic-field parameters, which act as proxies for elevated flare likelihood and magnetic complexity. These labels define similar and dissimilar active-region states, allowing the β-VAE loss to include a Siamese-like contrastive logic alongside the standard reconstruction and regularization terms. The resulting latent space is therefore encouraged to capture active-region morphology while organizing images according to flare-relevant magnetic structure. We evaluate whether this latent geometry improves neighborhood consistency, class-conditional clustering, and probabilistic forecasting across multiple horizons using empirical parameters, β-VAE latents, and their combined representations.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

A PHYSICS-BASED MACHINE LEARNING APPROACH FOR A LONG TERM GCR FORECASTING TOOL

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Galactic cosmic rays (GCRs) are affected by solar modulation as they propagate through the heliosphere. The temporal variation of GCR spectra is driven by several physical processes, including advection, diffusion, particle drifts, and adiabatic energy losses, whose relative contributions vary throughout the solar cycle. Here, we present preliminary efforts toward the development of a physics-and Machine Learning based, long-term GCR forecasting tool. First, we constrain the GCR transport parameters using a neural surrogate of a 3D numerical model, trained on precise measurements from PAMELA and AMS-02. We then relate these parameters to solar and heliospheric quantities using a mixture density network (MDN) routed through a mixture-of-experts gating mechanism, enabling the estimation of proper probability distribution functions for the predicted GCR spectra.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

FORECASTING POLAR IONOSPHERIC ELECTROSTATIC POTENTIALS PATTERNS USING SCORE-BASED DIFFUSION MODELS AND SOLAR WIND DRIVERS

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We present a preliminary study on forecasting electrostatic potential maps in the polar ionosphere using external drivers, including the interplanetary magnetic field (IMF) and solar wind velocity (SWV). We employ advanced machine learning techniques, focusing on score-based diffusion models, which are capable of generating realistic data by reversing a noise-corruption process and are well suited for capturing complex spatial patterns.
The model is trained on a dataset of two-dimensional ionospheric potential maps derived from SuperDARN observations in the Southern Hemisphere (years 2020-2025, 2-minute cadence), combined with corresponding IMF and SWV measurements. Using a 30-minute input window, the model directly predicts future map sequences while enforcing physical consistency through the inclusion of solar wind conditions.
Results show high predictive accuracy on short timescales (a few minutes), successfully reproducing both spatial structures and global indicators such as the Cross Polar Cap Potential. Performance degrades beyond 10-20 minutes, reflecting the intrinsic dependence of ionospheric dynamics on future external conditions. However, by incorporating upstream measurements at L1 and accounting for propagation delays, the model enables forecasts with up to ~1 hour lead time.
These findings demonstrate the potential of diffusion models for ionospheric prediction, while highlighting fundamental limits in system predictability and the need for improved solar input characterization and expanded training datasets.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

VARIATIONAL DATA ASSIMILATION FOR IMPROVED 3D GLOBAL MHD FORECASTING OF THE AMBIENT SOLAR WIND

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Space weather can adversely impact human infrastructure, activity, as well as health. As a consequence, there is a requirement for accurate and reliable space weather forecasting capabilities. Successful space weather forecasting requires precise knowledge of the ambient solar wind as this is the medium through which solar disturbances propagate to Earth. For example, the ambient solar wind strongly influences the transit time of interplanetary coronal mass ejections and contributes to significant near-Earth space weather effects through the formation of stream interaction regions. State-of-the-art predictions of the ambient solar wind are today based on three-dimensional, global, magnetohydrodynamic (MHD) models. Despite their sophistication and fidelity, the full potential of these models is not yet fully realized and solar wind forecasts often fail to accurately match observations. While the global MHD models are data-driven and estimate boundary data at the inner inflow heliospheric boundary for the simulations by combining observations of the solar magnetic field and empirical estimates of the plasma properties, the models are typically also `free-running' and unconstrained by in-situ spacecraft observations. Thus, uncertainties and/or errors arising from inflow boundary conditions can pollute or contaminate predictions. To overcome these limitations, a novel variational data assimilation framework is proposed that optimally combines in-situ observations with the predicted solutions of a global MHD model. A Bayesian inverse MHD problem is solved to obtain the most probable solar wind inflow boundary data for a given set of observations. An overview of the data assimilation approach and results for observing system simulation experiments conducted using both ACE and STEREO spacecraft data are presented. The substantially improved predictions of the near-Earth solar wind afforded by the proposed data assimilation approach are fully demonstrated.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

USING CAUSAL DIAGNOSTICS FOR INTERPRETABILITY IN AI-BASED MODELS

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Space weather forecasting is increasingly driven by artificial intelligence, with modern models capable of integrating diverse, multi-modal data sources to potentially deliver more informed predictions. However, this growing complexity introduces a fundamental challenge: the loss of interpretability.
A central question in explainable AI is the quantification of feature importance—specifically, understanding the contribution of both physically meaningful variables and additional, potentially non-physical features within a forecasting model. In this work, we address precisely this challenge.
As a proof-of-principle playground, we examine the solar flare index and it's variations with geomagnetic activity. We compare between conventional attribution techniques, such as SHAP, and causality-based measures of feature importance and association with indices of geomagnetic disturbance and the interplanetary magnetic field. This includes quantifying "joint importance" of combination of features. Our initial findings indicate that causal approaches and measures yield insights that are more consistent with intuitive, physical picture. These results suggest that incorporating causal diagnostics (measures) into AI-based models may offer a more reliable pathway towards trustworthy and physically grounded models in space weather forecasting.

Date: Tuesday, November 03, 2026

Session Info: HEL3: RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

RECONSTRUCTION OF THE INNER-BOUNDARY SOLAR WIND SPEED FROM SATELLITE OBSERVATIONS USING A DIFFERENTIABLE SOLVER

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Prescribing inner boundary conditions for solar wind models (at 21.5 solar radii) remains a bottleneck for space weather forecasting. While data assimilation can reconstruct these conditions using 1 AU observations, methods suffer from severe overfitting. If the optimization has too much flexibility, models can 'memorize' sparse satellite measurements by introducing unphysical boundary artifacts, effectively ignoring actual solar imagery.

To solve this, we present a data-driven pipeline featuring a Time-Distributed Spatial Encoder that structurally prevents overfitting. The pipeline ingests single-disk extreme ultraviolet (EUV) imagery from SDO/AIA reprojected into Carrington coordinates. Instead of processing the entire time series globally, the network evaluates each temporal slice independently. The model is forbidden from mixing information across time, forcing it to learn a robust mapping from instantaneous solar structures-such as coronal holes-to corresponding boundary wind speeds.

The output is re-assembled into a 360-degree boundary and fed into a differentiable ballistic solar wind forward model. The loss function evaluates the mismatch between simulated wind and in-situ observations along the precise orbital tracks of a multi-spacecraft fleet, including ACE, STEREO, and Parker Solar Probe. Crucially, because the entire pipeline is end-to-end differentiable, gradients flow from the 1 AU observational loss backward through the fluid propagation dynamics to update the solar-to-boundary mapping.

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Session Info: SOL2: SOLAR ORBITER CROSS-SCALE OBSERVATIONS OF THE ORIGINS OF SPACE WEATHER

MULTI-INSTRUMENT KINEMATIC ANALYSIS AND MHD MODELING OF A SOLAR FILAMENT ERUPTION

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This study presents a comprehensive analysis of a major filament eruption and subsequent Coronal Mass Ejection (CME) observed on March 14, 2024, utilizing the remote sensing suite aboard Solar Orbiter. The investigation integrates data from the Polarimetric and Helioseismic Imager (PHI), the Extreme Ultraviolet Imager (EUI), and the dual-channel (VL and UV) Metis coronagraph.

The eruption was initially identified on the solar disk by EUI and subsequently tracked through the corona using both Metis channels. The synergy between EUI and Metis allows for a continuous tracking of the filament from the inner corona into the Metis field of view (FOV), revealing a persistent acceleration phase as the structure transitions between the two instruments. Notably, the simultaneous dual-channel observations from Metis allow for discrimination of distinct CME components: the cold plasma visible in the UV (likely originating from the erupting filament), the CME core, and the CME front visible in the VL images, which is associated with the shock.

To bridge the gap between remote-sensing observations and the underlying magnetic drivers, we present a preliminary 3D MHD simulation of the erupting flux rope. Utilizing PHI synoptic maps of the photospheric magnetic field, we reconstruct the pre-eruptive magnetic configuration through magneto-frictional models and we use it to model the eruption. This modeling effort aims to replicate the observed morphology and trajectory, providing insights into the balance of forces governing CME initiation.

By linking multi-perspective observations with physical models, this work aims to advance our understanding of how small-scale magnetic structures evolve into large-scale space weather drivers.

Date: Tuesday, November 03, 2026

Session Info: SOL2: SOLAR ORBITER CROSS-SCALE OBSERVATIONS OF THE ORIGINS OF SPACE WEATHER

BEYOND THE EARTH-SUN LINE: MULTI-VIEWPOINT SYNOPTIC MAGNETIC MAPS WITH SO/PHI AND SDO/HMI

Philipp Löschl [1], Gherardo Valori [1], Johann Hirzberger [1], Hanna Strecker [2], Artem Ulyanov [1], Francisca Santos [1], David Orozco Suárez [2], Sami K. Solanki [1]

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The global photospheric magnetic field is the essential boundary condition for coronal and heliospheric space weather models, yet a truly simultaneous global measurement remains out of reach. Standard synoptic maps are assembled over a full 27-day solar rotation from a single Earth-side viewpoint, meaning farside observations are up to two weeks old and any flux emerging in the interim goes entirely unseen. Recent multi-model studies have shown these limitations translate into significant solar wind forecast uncertainties, and early SO/PHI farside observations have demonstrated that including farside magnetic field data can meaningfully alter coronal topology.

As the only magnetograph currently capable of direct farside observations, SO/PHI offers a unique path to systematic global coverage. When combined with SDO/HMI, the two instruments can provide global magnetic field coverage in as little as two weeks under favourable orbital geometries, capturing newly emerged farside flux well before it rotates into Earth's view. We present this combined synoptic map data product, using SO/PHI and SDO/HMI magnetograms from a range of SO orbital configurations during the synoptic campaigns of 2024 and 2025.

Utilizing near-side overlap phases, we demonstrate that SO/PHI and SDO/HMI observations are mutually compatible through careful data processing, providing the foundation for combined maps at large SO-Earth separations when SO/PHI covers the farside. For these farside configurations, we compare PFSS extrapolations from traditional SDO/HMI-only and combined maps to quantify how farside coverage alters the coronal hole boundaries, open flux, and field topology that drive the coronal and heliospheric models used in space weather forecasting.

We outline the path toward public release of this data product, including planned data formats and access pathways, and invite the space weather community to adopt these maps as improved boundary conditions for coronal and heliospheric models.

Date: Tuesday, November 03, 2026

Session Info: SOL2: SOLAR ORBITER CROSS-SCALE OBSERVATIONS OF THE ORIGINS OF SPACE WEATHER

A SUPER ACTIVE REGION AND ITS SPACE WEATHER IMPACT

Ioannis Kontogiannis [1], Yingjie Zhu [1,2], Krzysztof Barczynski [2], Adriana De-Sassi [1], Marina Kirchheim Moreno [1], Svetlana Berdyugina [3], Louise Harra [1,2]

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Super active regions are long-lived, magnetically complex regions driving the most extreme forms of solar activity and space weather. During Solar Cycle 25, several such regions produced major impacts throughout the heliosphere and geospace environment. We present recent results on the evolution and activity of the exceptionally eruptive active region NOAA 13664, which produced the strongest geomagnetic storm since 2003, and its subsequent derivatives, NOAA 13697 and 13723. Using Solar Dynamics Observatory observations we investigated the processes that led to the region's extreme magnetic complexity and fueled its strongest eruptions. Combined with Solar Orbiter observations, the region was then tracked continuously over more than three months, from emergence through peak complexity and eventual decay, overcoming the observational limitations imposed by solar rotation. NOAA 13664 exhibited unprecedented complexity, with interacting subregions and persistent current-carrying magnetic structures closely linked to repeated major flaring episodes. Using the combined datasets, we achieved the first long-term parametrization of its nonpotentiality, producing long-duration time series of relevant parameters. High levels of nonpotentiality and eruptive activity were maintained throughout most of the region's lifetime, with magnetic parameters strongly correlated with sustained flare and CME activity. We further investigated how the flare/CME productivity evolved throughout the region's lifetime. Additionally, coronal spectroscopy from Hinode facilitated the identification of outflow regions that are potential sources of the slow solar wind. Our results highlight the multi-faceted influence of super active regions across the solar atmosphere and heliosphere and demonstrate the importance of coordinated multi-vantage-point and multi-wavelength observations for understanding and forecasting extreme space weather.

Date: Tuesday, November 03, 2026

Session Info: SOL2: SOLAR ORBITER CROSS-SCALE OBSERVATIONS OF THE ORIGINS OF SPACE WEATHER

THE ROLL OF EUV OBSERVATIONS IN SPACE WEATHER CAPABILITIES: INSIGHTS FROM A STATISTICAL STUDY OF PROMINENCE ERUPTIONS OBSERVED WITH SOLO/EUI/FSI

Brenda Dorsch [1,2], Daria Shukhobodskaia [1], Dana Telpeanu [1], Marilena Mierla [1,3], Elke D'Huys [1], Luciano Rodriguez [1], Matthew West [4]

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This presentation shows the results of the first statistical study of prominence eruptions observed with the FSI (Full Sun Imager) 304 Angstrom instrument of EUI (Extreme Ultraviolet Imager) onboard SolO (Solar Orbiter). The large field of view of FSI allows observation of solar eruptions from the solar disk up to heights never observed before in EUV passbands. We identified 229 prominence eruptions in the years 2021 and 2022 from the detailed catalogue available at https://www.sidc.be/EUI/solar-eruptions. The analysis of the 229 prominence eruptions offers a wide perspective on the variability within these phenomena of different properties such as speed, deflection, maximum height, and morphological features.
These results demonstrate the unique capability of EUI/FSI to bridge the gap between the low and high corona. The observed diversity in morphology and kinematics provides new constraints for models of solar eruptions and their role in driving space weather disturbances.

Date: Tuesday, November 03, 2026

Session Info: SOL2: SOLAR ORBITER CROSS-SCALE OBSERVATIONS OF THE ORIGINS OF SPACE WEATHER

CROSS-SCALE OBSERVATIONS OF SOLAR FLARES BY EUI AND STIX ON SOLAR ORBITER

David Berghmans [1], Lakshmi Pradeep Chitta [2], Hannah Collier [3], Marie Dominique [1], Laura Hayes [4], Jana Kasporova [5], Emil Kraaikamp [1], Juraj Lorincik [6], Luciano Rodriguez [1], Cis Verbeeck [1]

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Major solar flares are at the origin of many space weather phenomena. Besides the flash across the entire spectrum, flares are associated with shock waves, particle acceleration, radio bursts, prominence eruptions and CMEs. Since 2024, Solar Orbiter has embarked on a series of campaigns to observe Major Solar Flares. In this presentation we discuss the results so far of a series of unique data sets collected mainly by the STIX instrument and the HRIEUV telescope of the EUI instrument.

As an X-ray imaging spectrometer, STIX has continuously observed on the order of 10^5 flares from solar minimum in 2020 till now. For the high resolution HRIEUV imager it is much harder to catch a flare, because it can operate only occasionally and with subfield as small as 1/30th of the solar disk at perihelion. Thanks to the so-called short exposures at 2s cadence, HRIEUV can however for the first time observe flare dynamics at small length & time-scales that have remained veiled for earlier EUV imagers due to pixel saturation & blooming.

These Solar Orbiter Major Flare observations indicate that flares are not always the monolithic, catastrophic collapse of an entire magnetic structure but rather a build-up or an avalanche of magnetic threads reconnecting. The footpoint kernels in the flare ribbons have time and length-scales that are barely resolved with the 2s cadence /100 km pixel size characteristics of HRIEUV datasets. Also the width of some post-flare loops are at the 2-pixel scale suggesting the actual width is smaller than 200km. These small scales pose new questions on the required energy and plasma densities.

Whereas the impact of solar flares can be felt at heliospheric scales, the data from Solar Orbiter are thus telling us that the physics driving major flares, operates at remarkably small spatial and temporal scales. Using this insight for timely flare reporting suggests that modest resolution requirements for monitoring instruments might be suboptimal.

Date: Tuesday, November 03, 2026

Session Info: MIT1: SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

SOLAR WIND - MAGNETOSPHERE COUPLING REDUCTION DUE TO THE PRESENCE OF PLASMASPHERIC PLUMES DURING SOUTHWARD IMF: NINE YEARS OF MMS OBSERVATIONS.

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It is well known that during southward Interplanetary Magnetic Field (IMF) conditions, the extent and rate of magnetic reconnection at the Earth's magnetopause are favoured, resulting in effective coupling of the two systems, with solar wind plasma and energy being injected into the magnetosphere. The major driver of this coupling is the solar wind forcing, including for instance IMF orientation or solar wind dynamic pressure. Previous studies have suggested that internal forcing from the magnetosphere may also play a role, e.g., when the inflow conditions in the magnetosphere side change considerably. During disturbed times, more ions (H+, He+, O+) are detached from the plasmasphere and the ionosphere, via plasmaspheric plumes, detached plasmaspheric material, ion outflows, etc. These detached ions enter the magnetosphere region which is dominated by convection of the magnetic field, and eventually reach the dayside magnetopause, resulting in additional mass-loading of the boundary. In this work ,we use nine years of MMS observations of the plasmaspheric plume occurrence. We show that the amount of solar wind - magnetosphere coupling, inferred from the Dst index, is statistically smaller when a plasmaspheric plume is observed in the outer magnetosphere, for the same solar wind convection electric field conditions (-vBz). This situation persists for approximately -3 to +3 days, this time extent being consistent with the typical residence time of plumes in the magnetosphere and the orbital bias of MMS.

Date: Tuesday, November 03, 2026

Session Info: MIT1: SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

TURBULENT DISSIPATION AND STATISTICAL PROPERTIES OF IONOSPHERIC FIELD-ALIGNED CURRENTS UNDER DIFFERENT GEOMAGNETIC CONDITIONS: A MULTISCALE ANALYSIS OF ELECTRIC FIELD FLUCTUATIONS MEASURED BY EFD-02.

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The ionospheric dynamics at auroral and polar latitudes is strongly influenced by Field-Aligned Currents (FACs), which mediate energy transfer between the solar wind, magnetosphere, and ionosphere. In this work, we investigate the turbulent dissipation and statistical properties of FAC-driven electric field fluctuations using high-resolution measurements from the Electric Field Detector (EFD-02) onboard the CSES-02 satellite. EFD-02 provides continuous full-vector electric field observations with a sampling frequency of 5 kHz, enabling for the first time the exploration of physical processes down to meter-scale ionospheric fluctuations at high latitudes. We analyze the multiscale turbulent statistical properties of electric field fluctuations in terms of power spectral densities, structure functions, and intermittent energy transfer and dissipation, and their dependence on geomagnetic activity. Preliminary results suggest that disturbed conditions are associated with enhanced small-scale variability and increased dissipation, highlighting the role of turbulence in ionospheric heating and energy redistribution. This study highlights the capability of CSES-02/EFD-02 to probe turbulent processes and contributes to a better understanding of magnetosphere-ionosphere coupling at high latitudes.

Date: Tuesday, November 03, 2026

Session Info: MIT1: SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

ASYMMETRIES IN AURORAL ELECTRON PRECIPITATION AND MAGNETOSPHERIC DYNAMICS

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Recent studies have shown that geomagnetic activity and particle precipitation are enhanced in both hemispheres when the interplanetary magnetic field (IMF) By component and the Earth's dipole tilt angle (ψ) have opposite signs. This so-called explicit IMF By-effect is not taken into account in the widely used coupling functions that assume symmetric solar wind-magnetosphere coupling between the two IMF By signs.

We use satellite and ground-based measurements to study the IMF By-effect in auroral electron precipitation, geomagnetic activity, and field-aligned currents during times of high dipole tilt angle ψ, that is, near the winter and summer solstices. Statistical analysis shows that for fixed solar wind driving, the dawnside auroral precipitation depends significantly on the sign of the IMF By. We also investigate the IMF By-effect in the dawnside auroral electron precipitation and geomagnetic activity in a first-ever case study, where we study two subsequent high-speed stream events with similar solar wind driving but opposite IMF By polarities and show that the IMF By-effect is evident during high-speed stream events during which the polarity of IMF By component is persistent.

We show first-ever results on the temporal dynamics of the IMF By-effect. A superposed epoch analysis shows that field-aligned currents, dawnside auroral electron precipitation, and horizontal ionospheric currents display the maximum IMF By-effect 2-3 hours after asymmetry starts to build in the magnetosphere. Furthermore, we show evidence that the IMF By-effect could originate from the modulation of the dayside reconnection rate. However, the physical mechanism of the IMF By-effect is still unknown.

Date: Tuesday, November 03, 2026

Session Info: MIT1: SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

EXPLORING THE EARTH'S MAGNETOSPHERIC RESPONSE DURING INTENSE SPACE WEATHER EVENTS

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Extreme Space Weather (SWE) events have a crucial role in shaping the dynamics of Earth's magnetospheric boundary layer. Under such conditions, several plasma processes can be triggered, including the Kelvin-Helmholtz instability (KHI), that arises from the velocity shear at the boundary between the magnetosphere (MSP) and the magnetosheath (MSH).
KHI can grow into waves, which may subsequently roll-up into large-scale vortices (KHVs). In the context of planetary magnetospheric dynamics, such instability is fundamental because it drive (i) substantial mass, energy, and momentum transport into the MSP; and (ii) field-aligned currents (FACs), that couple the magnetosphere to the ionosphere, contributing to the auroral activity.
In this work, we analyze two prominent SWE events that occurred in January (Case1) and November (Case2) 2025, following the arrival of Earth-directed coronal mass ejections (CMEs).
In Case1, we combine in-situ magnetospheric observations from MMS with ionospheric measurements from Swarm in order to assess the generation of FACs due to the twisting and shearing of magnetic flux tubes by KHVs. To confirm the KHV development and the corresponding currents we use a magneto-hydrodynamic (MHD) model, MIM (Biasiotti et al. 2024, Ivanovski et al. 2011) and, then, we examine ionospheric irregularities through total electron content (TEC) and scintillation measurements, as well as ground magnetometer observations of the horizontal equivalent ionospheric currents (EIC) and the vertical spherical elementary current (SEC).
For Case2, we investigate the KHI development combining in-situ observations from THEMIS with MHD simulations, in order to assess whether the periodic variations of the IMF Bz expose the magnetospheric system to successive intervals of magnetic flux (during Southward IMF via dayside reconnection) and mass (during Northward IMF via KHI) loading, which can enhance the ring current through plasma energization driven by tail reconnection.

Date: Tuesday, November 03, 2026

Session Info: MIT1: SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

INVESTIGATION OF INTER-HEMISPHERIC ASYMMETRY USING SWARM-DERIVED INDICES

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Swarm-derived geomagnetic activity indices can monitor magnetospheric substorms through the Swarm-based AE-like index at least as efficient as the standard ground-based activity index AE. Importantly, Swarm-based AE is of a more global character in comparison to AE, because the satellite index covers both hemispheres, while the ground index is derived with data from the northern hemisphere only, since magnetic observatories at auroral latitudes are very rare at the southern hemisphere. Additionally, Swarm observations offer us the possibility to derive separate indices for the northern hemisphere (Swarm-based AE-North) and southern hemisphere (Swarm-based AE-South), thus enabling us to perform investigations of the North-South asymmetry.
The Swarm-based Sheet Field-Aligned Current (SFAC) index quantifies the large-scale FAC system through the maximum absolute value of the magnetic perturbation for each Swarm crossing of the auroral oval and can be easily provided as a near real-time index at a cadence defined by the Swarm orbital period. The SFAC relevance in the space weather context has been proved by correlation studies with other integral quantities that characterize the ionospheric electrojet current, such as the AE index, based on ground data, and (even better) the Polar Electrojet index, based on Swarm data. Similarly, the SFAC appears to correlate well also with the horizontal magnetic field perturbation at conjugate ground-based observatories, near the Swarm magnetic footpoint.
Swarm-based AE, AE-North, AE-South and SFAC indices are used to investigate the cause and effect of the inter-hemispheric asymmetry in high-latitude electrodynamics. This is a research topic of great importance because inter-hemispheric asymmetry is related to Magnetosphere-Ionosphere Coupling (MIC) and can be associated with high-latitude forcing that intensifies during storm time. However, we currently lack a comprehensive understanding of the mechanisms that generate this asymmetry.

Date: Tuesday, November 03, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

LARGE SCALE TRAVELING IONOSPHERIC DISTURBANCES LAUNCHED BY HIGH-LATITUDE GEOMAGNETIC STORMS

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Large Scale Traveling Ionospheric Disturbances (LSTIDs) are wave like disturbances in the ionospheric plasma density that can affect radio communication and satellite navigation. The propagate from high to mid and low latitudes and are believed to be triggered by sudden energy input into the high-latitude ionosphere in the form of Joule heating or auroral precipitation during geomagnetically active periods.

In this talk, we show two case studies of LSTIDs, which are triggered during two moderate storms caused by solar wind high-speed streams (HSSs). The LSTIDs are analysed from GNSS total electron content (TEC) data in the Madrigal data base using detrending technique. In the first event in 2016, we have additionally mid-latitude Millstone Hill radar measurements, which show the effect of LSTIDs on plasma parameters as the waves propagate through the radar field-of-view. The most significant effect is the F-peak fluctuation up and down and associated increase in electron density. We also show that the arrival of the LSTIDs at mid latitudes is the main contributor to the positive ionospheric storm phase at mid latitudes, increasing the TEC by 11 TECU. The new method to estimate hemispheric Joule heating distribution indicates that the source of these LSTIDs is Joule heating in the auroral oval. The second event in 2025 in the European sector is measured by the EISCAT Tromso radar and additional ground-based measurements in the Scandinavian sector. The source of these LSTIDs is in the vicinity of and poleward of Tromso. The effect seen by the EISCAT radar is mainly a depletion in the F-region electron density due to local Joule heating. The LSTIDs propagate southward and cross the ionospheric trough. Additionally, advanced 4D (3D + time) tomographic reconstruction of the LSTIDs is carried out, which shows how the LSTID wave fronts are tilted on the altitude-latitude plane as they propagate in the equatorward direction.

Date: Wednesday, November 04, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

THE SHIELD MISSION, A POTENTIAL SUB-L1 GAME CHANGER FOR SOLAR WIND AND CME UNDERSTANDING, MODELLING AND FORECASTING.

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The SHIELD mission is currently under study by ESA's Space Weather Office within the Space Safety Programme (S2P). Its primary objective is to improve space weather resilience through enhanced end-to-end monitoring of the solar wind and CME propagation from the Sun to Earth. SHIELD's central ambition is to enable in-situ monitoring of the solar wind and CMEs from over 10 times farther upstream than SEL1, at approximately 20 million km from Earth towards the Sun. This would provide warning times exceeding 120 minutes even for the fastest observed CMEs.
Beyond operational services, SHIELD will enable more comprehensive monitoring of the near-Earth solar wind environment, supporting advances in heliospheric science and the development of more accurate models for space weather forecasting.
The mission concept is based on a Sun-Earth distant retrograde orbit (DRO), enabling upstream solar wind observations. However, DRO trajectories do not allow spacecraft to remain continuously on the Sun-Earth line, the optimal geometry for CME detection. From Earth, the satellites appear to orbit around the planet while remaining synchronized with Earth's annual motion around the Sun. Consequently, SHIELD requires a constellation of 4 to 9 spacecraft to ensure that at least one remains sufficiently close to the Sun-Earth line to provide the required in-situ measurements.
A Phase A study is currently being conducted by ESA together with industrial and institutional partners, building on the soon-to-be-launched Henon in-orbit demonstration mission.
This presentation introduces the mission concept, its objectives, and development timeline, with particular emphasis on upcoming data utilization studies and how Henon mission data could support SHIELD development.

Date: Wednesday, November 04, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

MULTI-SPACECRAFT MEASUREMENTS OF CORONAL MASS EJECTIONS NEAR 1 AU NEAR THE MAXIMUM OF SOLAR CYCLE 25: CONSEQUENCES FOR FUTURE SPACE WEATHER MISSIONS

Noé Lugaz [1], Bin Zhuang [1], Nada Al-Haddad [1], Sahanaj Banu [1]

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Over the maximum phase of solar cycle 25 in 2022-2026, STEREO-A was in relatively close proximity to the Sun-Earth line and Solar Orbiter made frequent passes in proximity to STEREO-A or L1. Combined with the typical level of activity of this cycle, this results in several dozens coronal mass ejections, shocks and energetic particle events being measured jointly by two (or more) spacecraft between 0.8 and 1 au. Here, we discuss how these data can be used to deduce the average longitudinal extent of magnetic ejecta (MEs) based on in-situ measurements. MEs are found to typically have total angular widths of about 35 degrees, significant smaller that what is determined from remote-sensing and what is used to initiate CMEs for space weather forecasting within WSA-Enlil. The cause for this difference is discussed in terms of the coherence of the CMEs. The consequences of these statistics for the orbits and design constraints of future space weather advanced monitors are also discussed.
We then turn our attention to the question of how data from future sub-L1 monitors can be used to forecast the incoming corotating and radially propagating components of the solar wind at Earth using case studies from Solar Orbiter, STEREO-A and L1.

Date: Wednesday, November 04, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

MODELING CORONAL AND SOLAR WIND STRUCTURE FOR THE AUGUST 12, 2026 TOTAL SOLAR ECLIPSE

Jon Linker [1], Cooper Downs [1], Ronald Caplan [1], Michal Ben-Nun [1], Ryder Davidson [1], Roberto Lionello [1], Emily Mason [1], Erika Erika Palmerio [1], Andres Reyes [1], Pete Riley [1], Viacheslav Titov [1], Tibor Torok [1], James Turtle [1], Solar Orbiter PHI Team [2]

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The solar corona is the birthplace of the solar wind. Total solar eclipses offer a rare opportunity to observe the low and middle corona, where the wind originates. As is our tradition, the solar physics team at Predictive Science predicted the structure of the corona for the August 12, 2026 total solar eclipse, using a magnetohydrodynamic (MHD) model.

As we first did for the April 8, 2024 total solar eclipse, we employ a data-assimilative, time-evolving model (described by Downs et al. Science, 2025) to produce a continuously updated prediction. The MHD model incorporates non-ideal thermodynamic transport terms and employs a wave-turbulence-driven (WTD) description of coronal heating and solar wind acceleration. To capture the evolution of the photospheric magnetic field, the model employs the Open-source Flux Transport (OFT) model. OFT primarily assimilates Solar Dynamics Observatory HMI measurements at an hourly cadence. For this eclipse we supplemented HMI observation with Solar Orbiter PHI observations from the far side of the Sun (as viewed from Earth).

We discuss the time evolution of the corona and solar wind as predicted by the model in the days leading up to the eclipse and compare with observations, including available images from the eclipse.

Research supported by NASA and NSF. Computational resources provided by the NSF ACCESS program and the NASA Advanced Supercomputing division at Ames.

Date: Wednesday, November 04, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

IMPROVEMENTS TO SOLAR WIND MODELS FOR REAL-TIME FORECASTING: DATA-DRIVING AND VALIDATION METHODOLOGIES

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Understanding the conditions that regulate the formation of the solar wind, its acceleration across the corona, and its transition to the heliospheric propagation regime is key to addressing many open questions in heliophysics and space weather.
We will address some of the main challenges related to the implementation and validation of solar wind models and to the pernicious issues that stem from the scarcity of observations made at intermediate heliocentric distances, between the two boundaries of the Sun-Earth system.
Results from data-driven global solar wind simulations that cover several solar activity cycles will be presented, as well as the use of recent observational datasets for their calibration and validation.
These efforts are part of ongoing and forthcoming developments for building an integrated model capable of propagating solar storms from the Sun to Earth, together with high-energy particle emissions from the solar corona by coupling different models. The resulting global model will be based on several world-renowned solar wind, CME and SEP models, some of which are already available to users 24/7 via the STORMS weather forecasting service (storms-service.irap.omp.eu) accredited by the CNRS and maintained by Infor'Marty and IRAP/University of Toulouse.

We acknowledge funding by ANR/AID (grant ANR-25-ASTR-0025, PARASOL) and by ESA/SWESNET.

Date: Wednesday, November 04, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

IMPROVING SOLAR WIND MODELS FOR SPACE WEATHER: TIME-DEPENDENCY AND FAST SOLAR WIND FOR CORONAL MODELS

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In the peak of activity, the Sun makes space weather predictions increasingly challenging as small-scale structures on its surface evolve rapidly. We aim to better understand the solar corona to better predict the solar wind, and this within an operational timing.
We have two main focuses using our MHD code Wind Predict (WP): improve the simulation itself or its post-processing. On one hand, we aim to incorporate time-dependency within the boundary conditions at the solar surface. The solar wind predictions then update in sync with magnetograms every two hours, or even more frequently with interpolation between them. We need a test case where the time evolution is known. Then, we will test the configuration with discontinuous maps. On the other hand, we focus on a more operational aspect: coupling heliospheric models with Wind Predict, which together form a complete forecasting model. We will automatically correct our Wind Predict solution using empirical formulae to improve especially the description of the fast solar wind.
With our test case, we now have the time evolution of the physical parameters for a Sun with differential rotation. Furthermore, our model is now able to update the solar wind solution along with magnetograms. Eventually, we found the best method of interpolation of the surface magnetic field and we only need its implementation for time-dependency in Wind Predict. For the second approach, we first tried already existing methods. One using empirical formulae developed by Wang, Sheeley and Arge and one based on Reville et al., 2023 results. We could indeed reproduce both fast and slow wind, and we extended the routine to correct other physical parameters. After a comparison to a more physical version of Wind Predict, including heating by Alfven waves, we are currently testing to find our own WP-adapted empirical correction.

Date: Wednesday, November 04, 2026

Session Info: SOL3: BRIDGING THE INNER SOLAR ATMOSPHERE TO THE HELIOSPHERE: INTEGRATING LOW-ATMOSPHERIC PHYSICS INTO NEXT-GENERATION SPACE WEATHER FORECASTING

LINKING NESTED ACTIVE REGION EVOLUTION TO HELIOSPHERIC STRUCTURE: THE IMPACT OF CME-HCS INTERACTIONS IN OCTOBER 2024 ON SPACE WEATHER FORECASTING

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Accurate Space Weather forecasting requires a holistic understanding of how magnetic structures rooted in the low solar atmosphere evolve and interact with the global heliospheric configuration. This study investigates a sequence of eruptive events from October 1-5, 2024, originating from a long-lived 'nested' active region (AR 3842) that persisted over several solar rotations. This activity period culminated in an X9.0 flare on October 3, 2024, to date the largest directly observed flare of Solar Cycle 25.

By combining remote-sensing observations with in-situ measurements at 1 AU and drag-based modeling, we trace the propagation of multiple Coronal Mass Ejections (CMEs) and their interaction with the Heliospheric Current Sheet (HCS). We demonstrate that the global magnetic topology, shaped by the long-term flux emergence in the inner atmosphere, played a decisive role in the heliospheric response. Specifically, we identify a complex interaction where the HCS was locally replaced by CME signatures, resulting in a long-duration magnetic sector reversal exceeding 48 hours.

Crucially, our analysis provides a physical explanation for the observed disconnect between flare intensity and geoeffectiveness during this period. We show how the orientation of the HCS and the 'same-side/opposite-side' effect can mitigate the impact of even the most energetic eruptions. These findings highlight the necessity of integrating low-atmospheric magnetic evolution and HCS topology into next-generation forecasting models. More details on that study can be found in Temmer et al. (2026).

Date: Wednesday, November 04, 2026

Session Info: SOL3: BRIDGING THE INNER SOLAR ATMOSPHERE TO THE HELIOSPHERE: INTEGRATING LOW-ATMOSPHERIC PHYSICS INTO NEXT-GENERATION SPACE WEATHER FORECASTING

A GLOBAL SOLAR ATMOSPHERE MODEL

Stefaan Poedts [1]

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In my ERC-AdG project 'Open SESAME' (project No 101141362), we aim to develop a time-evolving model for the entire solar atmosphere, including the chromosphere and transition region, based on a multifluid description. Currently, models are primarily steady, rely on a single-fluid description and include only the corona due to computational challenges. We plan to use time-evolving ion-neutral and ion-neutral-electron models. The multifluid approach will enable us to describe the intricate physics in the partially ionised chromosphere and quantify the transfer of momentum and energy between the atmospheric layers. The questions of where the solar wind originates and how solar flares and coronal mass ejections are driven have fundamental scientific importance and substantial socio-economic impact.

This goal is now achievable by combining our implicit numerical solver with a high-order flux reconstruction (FR) method. The implicit solver enables larger time steps, avoiding the numerical instabilities that lead to strict time-step limitations in explicit schemes. The high-order FR method enables high-fidelity simulations on very coarse grids, even in zones of high gradients. We introduce three critical innovations. First, we combine high-order FR with physics-based r-adaptive (moving) unstructured grids, redistributing grid points toward regions with high gradients while preserving the HPC cluster's load-balancing. Second, we implement CPU-GPU algorithms for the new heterogeneous supercomputers advanced by HPC-Europa. Third, we implement AI-augmented magnetograms to enable the model to respond to the time-varying photospheric magnetic field, which is crucial for understanding key properties of the solar plasma and processes.

Thus, we develop a first-of-its-kind high-order GPU-enabled 3D time-accurate solver for multifluid plasmas. We will use it to implement the most advanced AI-augmented, data-driven solar atmosphere model in an operational environment.

Date: Wednesday, November 04, 2026

Session Info: SOL3: BRIDGING THE INNER SOLAR ATMOSPHERE TO THE HELIOSPHERE: INTEGRATING LOW-ATMOSPHERIC PHYSICS INTO NEXT-GENERATION SPACE WEATHER FORECASTING

HOW CAN THE LOWER ATMOSPHERE INFLUENCE SPACE WEATHER PREVISIONS?

Barbara Perri [1], Allan Sacha Brun [1], Antoine Strugarek [1], Stefaan Poedts [2,3], Brigitte Schmieder [4], Étienne Pariat [5]

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Space weather previsions are done through numerical modeling by coupling successive models from the solar surface up until the Earth space environment. The first model is the coronal one, usually starting at the inner corona after the transition region, once the solar wind is well established. Models which focuses on the lower atmospheric layers are usually more local, and are not suited for near-real time operational runs. However, they demonstrate an important interconnection between the chromosphere and the corona, as well as between small-scales and global scales. In this review talk, we will examine the scientific questions which could be unlocked by incorporating the low atmosphere in space weather previsions, both from the numerical and observational point of view, and from the physics of the continuous interplanetary medium (solar wind and interplanetary magnetic field) and of transients. We will in particular put this in context with the next-generation observations of the lower atmospheric layers such as EST.

Date: Wednesday, November 04, 2026

Session Info: SOL3: BRIDGING THE INNER SOLAR ATMOSPHERE TO THE HELIOSPHERE: INTEGRATING LOW-ATMOSPHERIC PHYSICS INTO NEXT-GENERATION SPACE WEATHER FORECASTING

FIRST IMAGING OBSERVATIONS OF THE EVOLUTION OF ERUPTIVE PROMINENCES AND CORONAL MASS EJECTIONS AT RADIO K-BAND (18-26 GHZ), A NEW OBSERVING TOOL LINKING THE SOLAR ATMOSPHERE WITH THE HELIOSPHERE

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The radio emergence of coronal mass ejections (CMEs) and eruptive prominences (EPs) has been the subject of several studies, given their relevant role in exploring the solar atmosphere and modelling its magnetic structure process, which can lead us to understand the energy release mechanisms of active regions (ARs), which are among the main drivers of space weather.
In this work we present and analyse the first detection of an EP/CME event at 18.8 and 24.7 GHz performed by the Sardinia Radio Telescope (SRT) on August 19 and 20, 2025, under the SunDish project (https://sites.google.com/inaf.it/sundish).
We discuss the complex structure of the erupting event including an unprecedented radio feature extending over 15 arcmin from the solar disk and emerging from a region characterised by reconnection threads involving helical kink instabilities, ARs and filaments. Through spectral and polarimetric information we can constrain EP/CME physical parameters including an extrapolation of the magnetic field associated with gyro-magnetic and synchrotron emission components.
This work paves the way for the systematic search of CME events in high-frequency radio images and their correlation with standard coronographic images and space-based measurements, in the frame of space weather applications.

Date: Wednesday, November 04, 2026

Session Info: SOL3: BRIDGING THE INNER SOLAR ATMOSPHERE TO THE HELIOSPHERE: INTEGRATING LOW-ATMOSPHERIC PHYSICS INTO NEXT-GENERATION SPACE WEATHER FORECASTING

COMBINING MULTI-SPACECRAFT OBSERVATIONS OF A CME WITH NUMERICAL SIMULATIONS (I): DATA-DRIVEN MODELLING WITH RIMAP

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We investigate the fast coronal mass ejection (CME) of 5 September 2022, one of the most energetic events of the current solar cycle, by combining remote-sensing observations, in situ measurements, and data-driven magnetohydrodynamic (MHD) simulations. The eruption was observed in the corona by the Solar and Heliospheric Observatory and STEREO spacecraft, and sampled in situ by Parker Solar Probe at 0.07 AU and Solar Orbiter at 0.71 AU.

Using multi-viewpoint coronagraphic data, we reconstruct the three-dimensional geometry and kinematics of the CME-driven shock, deriving its propagation direction, expansion, and speed. These parameters are used to constrain a data-driven MHD simulation based on the RIMAP framework, including realistic solar wind conditions reconstructed from PSP and WIND measurements.

The simulation reproduces the main shock and CME properties observed by PSP, showing good agreement with in situ plasma and magnetic-field measurements. At Solar Orbiter, the model captures the overall shock evolution, although discrepancies remain in the detailed temporal structure and in the downstream plasma evolution. Our analysis highlights the key role of the ambient solar wind and CME geometry in shaping shock propagation through the inner heliosphere. In particular, we find that a simple cone model cannot reproduce the observed duration of the event, requiring the inclusion of an extended velocity 'tail' in the CME profile.

These results demonstrate the potential of combining multi-spacecraft observations with physics-based MHD simulations to investigate CME evolution and shock propagation across the inner heliosphere, providing important constraints for understanding extreme solar events, shock-driven particle acceleration, and improving space weather forecasting capabilities.

Date: Wednesday, November 04, 2026

Session Info: HEL2: COSMIC RAYS IN THE HELIOSPHERE

MODELING OF THE INTERACTION OF SOLAR ENERGETIC NEUTRAL ATOMS WITH EARTH'S IONOSPHERE

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Solar Energetic Neutral Atoms (ENAs) provide a new observational tool to assess particle acceleration processes at intermediate energies in the solar atmosphere without the blurring effect of interplanetary charged particle transport. ENAs are produced from energetic protons (and other singly charged ions) by charge exchange processes in the solar corona and can provide information on spatially integrated energetic particle populations in the corona. So far, only two solar ENA events have been identified from the measurements of STEREO / Low Energy Telescope (Mewaldt et al. 2009, ApJL, doi:10.1088/0004-637X/693/1/L11; Cohen et al. 2024, ApJL, doi:10.3847/2041-8213/ad4038). However, more than a dozen events interpreted as being due to solar ENAs have been indirectly detected by SAMPEX / Low energy Ion Composition Analyzer by measuring the fluxes of protons freshly ionized from the ENA population in Earth's ionosphere (Mason et al. 2021, ApJ, doi:10.3847/1538-4357/ac2fa2).

We present modelling results of solar energetic neutral hydrogen atoms ionized in Earth's ionosphere and subsequently transported as (quasi-)trapped protons in Earth's inner magnetosphere. We compare the model results with the observations for the 5 December 2006 solar ENA event, where observations of both neutral hydrogen (by STEREO) and freshly ionized protons (by SAMPEX) exist, allowing us to validate the modelling. While the applied atmospheric density model and the ionization cross-sections affect the results appreciably, we show that the modelling is in qualitative agreement with interpretation of Mason et al. (2021) of the solar origin of the low-altitude near-equatorial proton populations observed in connection with large SEP events.

Date: Wednesday, November 04, 2026

Session Info: HEL2: COSMIC RAYS IN THE HELIOSPHERE

PARTICLE ACCELERATION AT INTERPLANETARY SHOCKS: FROM DIFFUSIVE TO SUPERDIFFUSIVE SCENARIOS

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Interplanetary shocks are widely regarded as one of the main particle accelerators in the heliosphere. In-situ measurements typically show that energetic particle fluxes peak at the shock, indicating a local acceleration process. On the other hand, the time profile of energetic particle fluxes is highly influenced by particle transport properties upstream and downstream of the shock.
We present a simple test-particle model that simulates the transport of energetic particles around an infinite planar shock. Such particles can also be accelerated via energy gains at each shock crossing, in a first-order Fermi-type mechanism. We inject a seed population of 70 keV protons and we integrate their trajectories via a Langevin-type equation upstream and downstream of an infinite planar shock. Particles can diffuse in the simulation box via random 'kicks', which belong either to a Gaussian distribution (normal diffusion) or to a Levy distribution (superdiffusion). We perform several simulations by varying the parameters of the model. The particle energy spectra in both diffusive and superdiffusive simulations are in remarkable agreement with the theoretical predictions and the energetic particle densities reproduce the ones observed by spacecraft when superdiffusive transport is considered. Space weather implications will also be discussed.

Date: Wednesday, November 04, 2026

Session Info: HEL2: COSMIC RAYS IN THE HELIOSPHERE

MODULATION OF 1~GV PROTONS - COMPARISON OF SOHO/EPHIN TO AMS-02 FLUXES

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The Electron Proton Helium INstrument (EPHIN) aboard SOHO is designed to measure high-energy particles and is operating since 1995. It provides energy spectra of protons in the energy range from 4 to about 800 MeV. Above 50 MeV the energy loss vs. energy loss and Bowtie-method is used to determine the energy dependent flux. To validate the measurements, we used published proton fluxes from 2011 to 2019 obtained by the Alpha Magnetic Spectrometer (AMS-02) which is a state-of-the-art particle physics detector designed to study cosmic rays and provides proton fluxes from ~400 MeV to 100 GeV. Here we present the methods and their results that lead to an agreement with AMS-02 within 20% for protons with energies between 400 and 700 MeV.
This work received funding from the BMWI (50OC2302,50OC2404) and the EU (101135044 - SPEARHEAD).

Date: Wednesday, November 04, 2026

Session Info: HEL2: COSMIC RAYS IN THE HELIOSPHERE

CALCULATING ANISOTROPIC RADIATION DOSE RATES USING THE ANIMAIRE TOOLKIT, UPDATES, AND INTEGRATION WITH OTSO

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AniMAIRE is a Python toolkit for calculating radiation dose rates due to anisotropic ground level enhancements/solar particle events where the anisotropic spectrum is known. AniMAIRE has been openly available online since 2024, and most recently we've updated it to utilize OTSO for Magnetospheric calculations. In this presentation, we showcase AniMAIRE's abilities as a tool for those who aren't aware of it, and discuss recent updates to it. We also discuss future work we plan on doing with AniMAIRE, as well as future features to add.

Date: Wednesday, November 04, 2026

Session Info: MIT2: CROSS-SCALE GNSS-BASED MONITORING OF IONOSPHERIC IRREGULARITIES: FROM PHYSICS TO OPERATIONAL SPACE WEATHER SERVICES

PHYSICS-INFORMED DEEP LEARNING FOR RAY-PATH-AWARE GNSS IONOSPHERIC DELAY ESTIMATION AT HIGH LATITUDES

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Disturbed ionospheric conditions at high latitudes can challenge the thin-shell representation used in SBAS ionospheric corrections, including EGNOS, increasing positioning errors or rendering the system unavailable due to integrity requirements. This work aims to quantify this degradation and deliver a user-friendly index nowcasting GNSS positioning degradation due to space weather.
We propose a hybrid deep learning model with a physically-grounded architecture predicting slant ionospheric delay with calibrated uncertainty for individual GNSS links. The input set consists of ionospheric maps processed by a CNN to extract information about the three-dimensional structure of the ionosphere, complemented by space weather indices, time-position metadata and ray-path geometry features, all encoded by MLPs. The resulting representations are fused via cross-attention driven toward each signal's ionospheric pierce point (IPP) by an additive bias. The maps consist of both observations (VTEC, gradTEC, ROTI) and topside electron-density shape parameters (NmF2, hmF2, H0, dH/ds) predicted by the neural networks of Smirnov et al. (2023), trained on radio-occultation data. Training targets are dual-frequency ionospheric delays from EPN stations above 55 degrees latitude.
Ablation and explainability analyses reveal that direct station-position information needed to be removed of the inputs for the model to capture space-weather-related variability rather than station-specific climatology. Attention patterns and UMAP projections further corroborate the capacity of the model to learn space-weather-related features, showing structured differences between quiet and disturbed periods.
We confirmed spatial generalisation by evaluating on held-out stations, which yield comparable performance across European polar regions. These outputs are combined into an index of ionospheric range error in meters with calibrated uncertainty, evaluated against EGNOS availability and integrity bounds.

Date: Wednesday, November 04, 2026

Session Info: MIT2: CROSS-SCALE GNSS-BASED MONITORING OF IONOSPHERIC IRREGULARITIES: FROM PHYSICS TO OPERATIONAL SPACE WEATHER SERVICES

INTEGRATING MULTI-NETWORK GNSS OBSERVATIONS ACROSS THE ARCTIC: THE PAGINA PROJECT

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The PAGINA (Pan-Arctic GNSS Infrastructure for Atmospheric Science) project addresses the current observational gap across the Arctic by developing a unified IT infrastructure for the integration, management, and dissemination of high-rate GNSS observations acquired from distributed ground-based monitoring networks. PAGINA combines data from at least 20 GNSS Ionospheric Scintillation Monitoring Receivers (ISMRs) deployed in Svalbard, Finland, Greenland, and Canada through the collaboration between Istituto Nazionale di Geofisica e Vulcanologia (INGV), University of New Brunswick (UNB), Finnish Meteorological Institute (FMI).

Currently, the infrastructure is designed to support investigations of small-scale ionospheric irregularities through the access and visualization of historical and near-real time scintillation indices. Potentially, the infrastructure can manage and distribute GNSS data and products from other observing systems in the Arctic area. By adopting such a multi-regional observation approach, PAGINA enables improved characterization of the morphology and dynamics of auroral and polar ionospheric disturbances and the study of irregularities across a wide range of spatial and temporal scales.

PAGINA is conceived as a scalable platform supporting operational space weather services and the development of ionospheric irregularities nowcasting and forecasting products tailored for the Arctic area. The system architecture is designed to facilitate interoperability, standardised data access through web-API and the integration of complementary observations from other observing infrastructures.

This contribution presents the current status of the project, the architecture of the web-based platform, and the available tools for GNSS data access and visualisation. We also discuss the benefits of shared infrastructures in advancing GNSS-based monitoring of ionospheric irregularities and in strengthening operational capabilities for high-latitude space weather services.

Date: Wednesday, November 04, 2026

Session Info: MIT2: CROSS-SCALE GNSS-BASED MONITORING OF IONOSPHERIC IRREGULARITIES: FROM PHYSICS TO OPERATIONAL SPACE WEATHER SERVICES

PROBABILISTIC RADIO OCCULTATION INVERSION AND UNCERTAINTY-AWARE IONOSPHERIC SCINTILLATION GEOLOCATION

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GNSS radio occultation (RO) provides globally distributed limb observations of ionospheric scintillation, including over oceans and polar regions where ground receivers are sparse. However, scintillation measured along an RO ray path is not naturally localized: a phase or amplitude disturbance in a one-dimensional occultation time series may be consistent with several irregularity locations along the propagation geometry. Existing back-propagation and focusing methods show that RO scintillation contains localization information, but their output is often interpreted as a best-fit point or curve rather than as an uncertainty-qualified region.

We present a probabilistic RO inversion framework for uncertainty-aware scintillation geolocation. Candidate disturbance locations are evaluated using propagation sensitivity, Fresnel-scale resolution, phase and amplitude consistency, and focusing or S4-reduction behavior. Instead of returning one deterministic location, the method assigns likelihood to candidate locations and produces a posterior disturbance volume conditioned on observations and geometry.

This representation treats multi-valued solutions, altitude ambiguity, finite Fresnel-zone sensitivity, and the non-unique mapping between scintillation signatures and possible irregularity locations. It also provides quality indicators, including posterior peak strength, entropy, credible-volume size, and separation between competing regions. These quantities help distinguish well-constrained events from cases where geometry or signal response does not support unique geolocation.

The framework can support future fusion of RO scintillation observations with ground GNSS, ionosondes, radars, SuperDARN, or empirical priors. By converting RO scintillation geolocation from deterministic focusing into an uncertainty-aware disturbance-volume estimate, the approach supports robust cross-scale monitoring of ionospheric irregularities, especially in high-latitude and data-sparse regions.

Date: Wednesday, November 04, 2026

Session Info: MIT2: CROSS-SCALE GNSS-BASED MONITORING OF IONOSPHERIC IRREGULARITIES: FROM PHYSICS TO OPERATIONAL SPACE WEATHER SERVICES

GROUND- AND SPACE-BASED GRADIENT INDICES FOR CHARACTERIZING AND MONITORING THE IONOSPHERIC PERTURBATION DEGREE

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Ionospheric irregularities remain a major source of uncertainty for GNSS-based positioning, navigation, and timing, especially during disturbed space-weather conditions. Their impact is often associated with enhanced spatial gradients and rapid TEC variations, requiring diagnostics sensitive to different scales and domains.

We present recent DLR developments for characterizing ionospheric perturbations using complementary ground- and space-based indices. The ground-based component focuses on the Gradient Ionosphere indeX methodologies GIXM and GIXV, complemented by the Sudden Ionospheric Disturbance indeX (SIDX). GIXM and GIXV are derived from TEC differences between pairs of ionospheric pierce points. GIXM represents the averaged TEC-gradient magnitude along selected dipoles and can serve as a perturbation-degree measure comparable to positioning-oriented indicators. GIXV estimates the mean gradient vector over broader regions, allowing intensity and dominant direction of structuring to be assessed.

The space-based component is provided by Swarm operational indices NeGIX and TEGIX. NeGIX uses in-situ electron density from the Swarm Langmuir Probe, while TEGIX is derived from Swarm TEC observations. Using the near-parallel Swarm A/C configuration, both characterize horizontal gradients at satellite altitude and provide an independent view of medium-scale structuring.

Together, SIDX, GIXM, GIXV, NeGIX, and TEGIX can describe the morphology, intensity, direction, and evolution of ionospheric perturbations. They may also support short-term forecasting and early warning: signatures observed within SWEPOS, the Swedish GNSS reference network, may help identify perturbations over northern Europe. Then, SAPOS, the German GNSS reference network and positioning service, can help assess their equatorward development and positioning impact at mid-latitudes. Designed for low-latency implementation, these indices are intended to support near-real-time products within DLR's IMPC.

Date: Wednesday, November 04, 2026

Session Info: OTH4: EDUCATION AND OUTREACH IN SPACE WEATHER: ENGAGING COMMUNITIES AND SHAPING THE NEXT GENERATION

A STUDY OF POLAR CAP IONOSPHERIC IRREGULARITIES OVER ANTARCTICA DURING THE 2024 MOTHER'S DAY STORM

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The propagation of trans-ionospheric radio signals is significantly affected by ionospheric irregularities, which manifest as local variations in plasma density. These variations induce refraction and diffraction on the signals passing through them, known as ionospheric scintillations. Such effects present a considerable challenge to the accuracy and robustness of Global Navigation Satellite Systems (GNSS) services. Ensuring the resilience of GNSS systems requires a deeper understanding of the physical processes that govern these plasma structures.

This research focuses on the formation and dynamics of high-latitude ionospheric irregularities, leveraging high-rate data acquired from a network of dedicated GNSS Ionospheric Scintillation Monitoring Receivers (ISMRs) during the Mother's Day storm in May 2024. The considered ISMRs are those operating at Concordia station (Dome-C, Antarctica). Our primary methodology is the spectral analysis of raw GNSS measurements. Specifically, we analyse the Power Spectral Density (PSD) of the signal's amplitude to extract characteristic Fresnel frequencies to estimate the irregularity drift speeds.

Additionally, we applied a complementary cross-correlation technique based again on the raw amplitude measurements, utilising data concurrently collected by nearby GNSS stations oriented in the north-south (N-S) and east-west (E-W) directions. This dual-approach validation minimizes potential instrumental biases and increases confidence in the estimated plasma movement. More importantly it allows for the determination of the N-S and E-W drift velocity components, adding important information on the ionospheric dynamics prior and during the storm.

This study was carried out in part within the Space It Up project funded by the Italian Space Agency, ASI, and the Ministry of University and Research, MUR, under contract n. 2024-5-E.0 - CUP n. I53D24000060005.

Date: Wednesday, November 04, 2026

Session Info: SCL1: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS

ANNUAL SOLAR IRRADIANCE RECONSTRUCTION OVER THREE MILLENNIA

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Space-based measurements of solar irradiance revealed variability on timescales from minutes to decades. However, assessing the long-term trends necessary to understand the Sun's impact on Earth's climate remains challenging due to the short period covered by the satellite era, which spans only about 50 years. Irradiance variations are driven by the evolution of the solar surface magnetic field through the competing effects of dark sunspots and bright faculae.
Because direct magnetic-field measurements are limited to recent decades, proxies must be used to extend reconstructions back in time. While telescopic sunspot records provide a direct proxy extending back 400 years, extending records further into the past requires indirect proxies. Millennial reconstructions have traditionally relied on decadal records of cosmogenic isotopes, such as 14C and 10Be, stored in terrestrial archives. Recent advancements in measurements, however, have provided 14C concentrations at annual resolution, yielding annual sunspot number estimates spanning the last three millennia. We present the first annually resolved physics-based reconstruction of solar irradiance extending back over this entire period. We achieve this by driving the recently-revised, physics-based SATIRE irradiance model with these newly available annual sunspot data. To capture the important contribution of bright faculae, the model incorporates observations showing that the emergence rate of all magnetic features follows a power law that scales with solar activity. This reconstruction offers a critical input for long-term climate models.

Date: Wednesday, November 04, 2026

Session Info: SCL1: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS

LONG-TERM SOLAR VARIABILITY LEARNED FROM DOME FUJI ICE CORES IN ANTARCTICA: PRESENT STATUS AND ONGOING PROJECT

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Ice cores yield information about past astronomical phenomena in addition to that about climate change. We will present time-series analyses of annually resolved nitrate concentration variations in an ice core drilled at the Dome Fuji station in East Antarctica, covering the period from CE 1610 to 1904, when ice-core nitrate data and observed sunspot numbers by telescopes overlapped. Our analyses revealed clear evidence of ~11-, ~22-, and ~90-year periodicities, comparable to the respective periodicities of the Schwabe, Hale, and Gleissberg solar cycles. Also, a ~210-year De Vries (Suess) cycle appears to be seen in the data. Furthermore, we detected 11-year and 22-year periodicities in nitrate concentrations even during the Maunder Minimum (1645-1715), supporting the cyclic behavior of the solar dynamo during the grand Minimum. These results show, for the first time, that Dome Fuji ice-core nitrate concentrations can serve as a reliable proxy for past solar activity on decadal to multidecadal time scales. Then we mention our - Astro-Glaciology Ice-core Data Factory-Project, to investigate solar activity over the past 1 million years using our newly-developed LMS (Laser Melting Sampler), applying it to Dome Fuji deep ice cores.

Date: Wednesday, November 04, 2026

Session Info: SCL1+SCL2: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS - EXTREME SOLAR EVENTS: FROM SOLAR ORIGIN TO COSMOGENIC ISOTOPE SIGNATURES

VARIATION OF THE SOLAR ACTIVITY OVER THE LAST 1400 YEARS BASED ON TWO NEW 10BE HIGH-RESOLUTION RECORDS FROM DOME C AND TALOS DOME (ANTARCTICA)

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Documenting solar activity before the instrumental period is important to improve our knowledge of the solar-dynamo process, which generates the cyclically varying large-scale solar magnetic field. Cosmogenic nuclides, such as beryllium-10 (10Be) and carbon-14 (14C), measured in ice cores and tree rings, respectively, provide information on variations of past solar activity. We present two new 10Be records, covering the last 1400 years, from the Dome C and Talos Dome ice cores (Antarctica). Sub-annual resolution was achieved at the Dome C site through the 1800 10Be measurements that were made on the first 60 m of the ice core, while the 465 samples measured on the first 1430 m of the Talos Dome ice core allowed an average resolution of 2.5 - 3 years.

The five minima of solar activity (Oort, Wolf, Sporer, Maunder and Dalton) are detected and characterized by a 10Be concentration increase of about 20% above average. We propose a reconstruction of the 10Be production signal based on our two new 10Be records which is in a very good agreement with the 14C production obtained from tree rings records covering the two millennia (Brehm et al.,2021, Wang et al., 2026). This shows, firstly, that the chronologies of Dome C and Talos Dome are well established, and secondly, that the production signal obtained, independently, from these two cosmogenic nuclides records, is robust.

At Dome C, the high resolution allows the detection of the 11-year solar cycle. We will show the importance of applying a correction to 10Be ice core records in order to remove the volcanic disturbance on the 10Be deposition (Baroni et al., 2019). This correction is based on the relationship between the 10Be and the sulphate concentrations obtained from the exact same samples.

Different geomagnetic reconstructions are also used in order to better isolate the solar component for improved irradiance reconstructions.

Date: Wednesday, November 04, 2026

Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

NOWCASTING THE AURORA USING AN IRREGULAR NETWORK OF GEOMAGNETIC OBSERVATORIES

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Since the loss of the IMAGE spacecraft in 2005, no global ultraviolet imager has monitored the auroral oval, leaving a two-decade gap in our ability to track its global position and study hazardous space weather. We show that ground-based magnetometers can fill this gap when combined with a graph transformer designed for irregular networks. Treating each magnetometer station as a node, the model classifies whether it lies under the auroral oval using both local and distributed magnetic field properties, achieving strong discrimination (AUC = 0.98) with stronger reliability during geomagnetically active periods. Attention and feature importance diagnostics reveal the model adaptively re-weights input features with changing global context. From the individual station predictions, we show that post-processing can recover the auroral oval boundaries to a high degree of accuracy (MAE = 2 degrees). Applied out-of-sample to the large May 2024 storm, the model tracks the oval's expansion and recovery in agreement with independent satellite imagery (DMSP).

Date: Wednesday, November 04, 2026

Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

A NEW MACHINE LEARNING IONOSPHERIC MODEL FOR GLOBAL AND LOCAL PREDICTION OF F2-LAYER PEAK PARAMETERS FOR OPERATIONAL AND SCIENTIFIC APPLICATIONS

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This study presents a new standalone physics-informed machine learning ionospheric model for global and location-specific nowcasting and forecasting of the F2-layer peak parameters, foF2 and hmF2, for high-frequency (HF) communication applications. The model combines ionospheric observations from COSMIC radio occultation satellite measurements with ground-based ionosonde observations from all available stations within the GIRO network to construct a unified dataset capable of representing both large-scale ionospheric structure and regional day-to-day variability under quiet and disturbed space weather conditions. The framework incorporates physically meaningful drivers describing solar radiation, geomagnetic activity, and thermosphere-ionosphere coupling, including F10.7 solar flux, Kp, ap, Dst, interplanetary magnetic field Bz, solar wind speed, density, dynamic pressure, solar zenith angle, local time, seasonal variability, geomagnetic geometry, and spatial ionospheric descriptors. A climatological background component derived from monthly and hourly foF2 maps is integrated to provide a physically consistent baseline ionosphere, while the machine learning framework captures storm-time disturbances, equatorial ionization anomaly variability, auroral dynamics, and day-night transition effects. The model employs an attention-enhanced U-Net deep learning architecture with squeeze-excitation attention blocks, latitude-weighted loss functions, masked learning strategies, and spatial smoothness constraints to improve reconstruction of physically complex ionospheric regions. Validation against independent ionosonde stations demonstrates that the proposed model achieves significantly improved R2 values compared to the IRI-2020 model in reproducing both foF2 and hmF2 variability, particularly in capturing local day-to-day ionospheric fluctuations during varying space weather conditions.

Date: Wednesday, November 04, 2026

Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

A MACHINE LEARNING ALGORITHM FOR THE CLASSIFICATION OF RADIATION DATA

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RAMIS (size: 140x140x35mm3, mass: 608 gram, power consumption 1.8 Watt) is a radiation detector developed for the DLR Eu:CROPIS satellite mission. RAMIS uses an arrangement of two silicon detectors in telescope geometry and maps the radiation environment in the course of the mission. For this RAMIS stores count- and dose rate data with a 1-minute and energy deposition spectra with a 5-minute cadence. Eu:CROPIS was launched on December 03rd 2018 into a polar orbit circling around Earth at an average altitude of ~600 km in 2018 and ~510 km in 2026. RAMIS is located on the outside of the satellite and was activated on December 05th 2018 and has continuously provided data during the course of the mission. Due to the polar orbit of the satellite RAMIS measures a) the variation of galactic cosmic radiation (GCR) in dependence on the orbit, b) the contributions of protons in the inner Earth radiation belt (Van Allen belt), c) variations of the trapped electron intensity during crossings of the outer radiation belt and (d) the changes in the radiation environment due to the changes in the solar cycle. Due to the large amount of data and the complexity of the radiation environment a separation of GCR, inner and outer radiation belt and SEPs is a challenge. We solved this problem by using for the first time a machine learning approach classifying data points based on a random forest algorithm. For this a training data set was defined and used as input for the radiation environment classification. This enabled the correct attribution/mapping of the various particle populations. First results applying this machine learning tool will be presented focusing on SEPs as measured with RAMIS in the course of the mission with a focus on the year 2024.

Date: Wednesday, November 04, 2026

Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

ONBOARD MACHINE LEARNING FOR SPACE WEATHER: COMPACT MODELS AND SPACE-GRADE ACCELERATION FOR SOLAR, SEP AND PLASMA-REGION INFERENCE

George Miloshevich [1], Ekaterina Dineva [1], Panagiotis Gonidakis [1], Jonah Ekelund [2], Stefano Markidis [2], Artur Podobas [2], Pedro Antunes [2], Maria Federica Marcucci [3], Monica Lorenza [3], Rossana de Marco [3], Alessandro Retinò [3], Gian Luca Giuffrida [5], Francesco Valentini [4], Stefaan Poedts [1]

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The exponential growth of observational and simulation datasets in geospace and space-weather research is increasingly outpacing both conventional analysis methods and the downlink capacity of the missions that generate the data. To ease the work of the mission scientists-in-the-loop, the HORIZON project ASAP addresses this bottleneck by developing machine-learning models that can be run on the ground or directly onboard spacecraft, together with the reconfigurable hardware and software needed to deploy them under realistic flight constraints. We present results across several space plasma-relevant applications: a beta VAE that compresses HMI/SHARP active-region maps into a physically meaningful latent space for activity characterisation and compressed downlink; convolutional networks predicting GOES soft X-ray flux from full-disk SDO imagery for solar-flare detection; the ESPERTA model for solar-energetic-particle prediction; and a 3D convolutional classifier that autonomously identifies near-Earth plasma regions to trigger burst-mode acquisition and selective downlink. For solar coronal structures, we replace a heavy U-Net segmentation model with a lightweight YOLO-based detector for active regions and coronal holes, reducing the number of trainable parameters from 7M to 3.2M while predicting bounding boxes suitable for onboard triggering. A central theme is the trade-off between model size and predictive performance: we show classifier compression above 95% and demonstrate that all target models map to space-grade FPGAs, achieving speedups up to 220x for the autoencoder with Vitis AI, and full-model inference at 4.8 Watts on a Kintex UltraScale soft-GPU. We discuss implications for AI-ready, FAIR-compliant on-ground and on-board data products and for the research-to-operations pathway in next-generation space-weather monitoring.

Date: Wednesday, November 04, 2026

Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

UNLOCKING GLOBAL AIRGLOW ARCHIVE: DEEP LEARNING FOR AUTOMATED IONOSPHERIC IRREGULARITY TRACKING

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The network of all-sky imagers operated by Boston University has established the most extensive archive of airglow images globally, covering from low to subauroral latitudes. To unlock the full potential of this vast dataset, we developed a suite of deep learning models designed to automatically identify and isolate target airglow structures, such as Equatorial Plasma Bubbles (EPBs) and Medium-Scale Traveling Ionospheric Disturbances (MSTIDs). Utilizing advanced image segmentation techniques, our pipeline extracts the key morphological characteristics of these irregularities. This automated approach uncovers critical seasonal occurrence patterns and generates a unique dataset optimized for statistical studies on how space weather drivers manifest and dissipate within the thermosphere-ionosphere system. Crucially, the precise geometric and spatial characteristics extracted from the EPBs provide vital ground-truth interpretation for ESA Swarm in-situ measurements and directly contribute to the scientific foundation of future ESA space safety missions like Swing and Sawa.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

MULTI-SOURCE DATA FUSION FOR GLOBAL TEC MAP CONSTRUCTION WITH VISTA ALGORITHM

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The global Total Electron Content (TEC) map based on the VISTA (Video Imputation with SoftImpute, Temporal smoothing and Auxiliary data) algorithm provides high-quality TEC estimation for both space weather and radio science and has been applied to the Madrigal ground-based TEC database in the past. This original VISTA dataset has been used for training a well-performing U-Net model for TEC prediction. While VISTA effectively leverages spatial smoothness and temporal consistency, its performance over the ocean is still limited due to the sparse and uneven distribution of GNSS ground stations. To address this, we integrated complementary observations from optical remote sensing (GOLD), LEO satellites (COSMIC2; PlanetIQ), altimeters (Jason-3 / Sentinel-6) and Doppler orbitography and radio positioning (DORIS) GNSS measurements into VISTA. Bias between different dataset and the Madrigal TEC has been removed based on each source's unique observing and archiving characteristics. The effectiveness of the heterogenous data is tested by comparing the new results with the original VISTA results based on ground-based TEC only. The complete TEC maps show obvious improvement above ocean regions and preserve more observed meso-scale structures. The multi-source VISTA can also provide optimized training and validation datasets for Machine Learning (ML) models (e.g., U-Net model) for TEC prediction. It provides an advanced tool for space weather research and ionospheric correction in radio science.

Date: Wednesday, November 04, 2026

Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

PHYSICALLY MEANINGFUL MODELING OF DST EVOLUTION FROM SYMBOLIC REGRESSION

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Accurate and physically interpretable models of the Dst index are central to understanding geomagnetic storm processes and improving space weather prediction. In this study, we use symbolic regression with the PySR framework to derive governing equations for Dst evolution directly from observational data.

To ensure that candidate models are dynamically stable and capable of reproducing the full temporal morphology of geomagnetic storms, we employ a strict evaluation scheme based on free-running, iterative integration using the forward Euler method. This iterative approach evaluates the model's ability to autonomously propagate the magnetospheric state over time, representing a more rigorous test of dynamical stability than standard one-step-ahead predictions.

We benchmark the performance of the symbolic regression derived equations against established empirical models in the literature, specifically the classic formulations by Burton and O'Brien and McPherron, as well as recent interpretable data-driven methods. Our results demonstrate that the equations discovered via symbolic regression outperform all baseline models across multiple statistical metrics.

Additionally, the resulting best-performing model provides significant physical insights through a structured injection-decay formulation. The injection term retains the classical VBs dependence associated with the dawn-dusk electric field while introducing a square-root dependence on solar wind dynamic pressure, representing variations in the effective reconnection region. Simultaneously, the decay term naturally unifies previously separate exponential and hyperbolic recovery formulations into a single mathematical expression, linking storm recovery behavior directly to the magnetospheric state.

These results demonstrate that symbolic regression can infer physically meaningful descriptions of magnetospheric dynamics without imposing a priori functional assumptions.

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Session Info: OTH3: MACHINE LEARNING AND DATA SCIENCE FOR GEOSPACE AND SPACE WEATHER

MACHINE LEARNING FOR MULTI-HORIZON FORECASTING OF GEOMAGNETIC DISTURBANCES WITH HORIZON-DEPENDENT FEATURE IMPORTANCE

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Space weather, driven by solar phenomena such as coronal mass ejections and high-speed solar wind streams, can lead to geomagnetic storms that pose significant risks to technological infrastructure. These disturbances are typically monitored using geomagnetic indices, such as SYM-H, which reflect variations in the Earth's magnetospheric current systems. Recently, machine-learning approaches have emerged as promise tools for forecasting such events using solar wind data from the L1 Lagrangian point.

In this work, we employ Long Short-Term Memory neural networks to forecast severe geomagnetic disturbances, defined by SYM-H decreases below -50 nT, up to 8 hours in advance. The task is formulated as a supervised binary classification problem within a multi-horizon framework, where a dedicated model is trained for each forecast lead time. Unlike previous studies, the analysis focuses exclusively on the rising and maximum periods of the solar cycle. Models are trained and validated on data from solar cycles 23 and 24 and subsequently tested on solar cycle 25, allowing the assessment of model generalization under highly active solar conditions. Alongside standard solar wind parameters, the feature set also includes derived physical quantities, such as magnetic helicity and solar-wind-transported energy.

To investigate the temporal evolution of input variables relevance, we perform a feature importance analysis across different forecast horizons. The results provide insights into the most predictive solar wind features during active solar phases, highlighting their varying relevance and demonstrating that derived physical parameters contribute significantly to sustaining geomagnetic activity. These findings demonstrate that horizon-specific feature selection improves model performance, while also enhancing the robustness and operational applicability of space-weather forecasting models.

Date: Wednesday, November 04, 2026

Session Info: MIT3: RADIATION BELTS AND PLASMA IN THE MAGNETOSPHERE

A REAL-TIME NOWCASTING MODEL FOR THE ELECTRON RADIATION BELT BASED ON MEASUREMENTS FROM EUROPEAN MISSIONS

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We present a Machine Learning model for the nowcasting of the near-Earth electron radiation environment developed in the framework of NEXUS (NORM Exploitation and Utilisation System), supporting Norwegian Radiation Monitor (NORM) data analysis and exploitation. The model uses electron flux measurements from Next Generation Radiation Monitor (NGRM) units on board European missions at LEO and GEO accompanied by solar wind parameters and geomagnetic indices. All inputs are available in real-time ensuring the ability for live operation. The model provides unidirectional electron fluxes from 180keV to 4MeV capturing the most critical populations for electron radiation effects in the outer belt. Also, unidirectional electron fluxes are provided for all energies at any equatorial pitch-angle [0-90 degrees], and the model is effectively able to estimate the pitch-angle distribution (PAD). Therefore, it is also used to estimate the commonly used omnidirectional flux at any latitude making it relevant for low and high inclination missions. Finally, the model uses real-time flux measurements from the NORM unit on board the ASBM-2 satellite in a data-assimilation approach for on-the-fly adjustment of the outputs, further improving its accuracy. We show the model is able to derive accurate estimations for the electron fluxes in the whole outer radiation belt (L*~3-7), while providing instantaneous spectra for the whole 180keV - 4MeV energy range ensuring the spectral coherency of the outputs. We validate the model with out-of-sample data as well as electron fluxes from several missions such as ARASE/XEP, GALILEO/EMU, and INTEGRAL/SREM, showing the nowcasted fluxes to be of high quality and demonstrating the model's usefulness in real-time Space Weather operations.

This work has been implemented under NORM Exploitation and Utilization System (NEXUS) project supported by the the European Commission, Directorate-General for Defence Industry and Space under contract EC-DEFIS/2024/OP/0012

Date: Wednesday, November 04, 2026

Session Info: IOM4: RADIATION INSTRUMENTATION FOR IN-SITU SPACE WEATHER MONITORING ACROSS THE SOLAR SYSTEM

REPE - RELATIVISTIC ELECTRON AND PROTON EXPERIMENT: ADVANCED RADIATION INSTRUMENT FOR SPACE WEATHER APPLICATIONS

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The Relativistic Electron and Proton Experiment (REPE) is a compact energetic particle instrument designed for a variety of space weather missions. Building on an original concept developed at the University of Turku (UTU) for radiation belt studies with the Foresail-2 nanosatellite mission, ASRO and UTU have continued the development of REPE instrument towards ESA's HEliospheric pioNeer for sOlar and interplanetary threats defeNce (HENON) mission. For the HENON variant of REPE, UTU provides the detector head while ASRO is responsible for the other elements of the instrument.

HENON is a deep space 12U CubeSat mission with the purpose of providing early alerts of space weather events and understanding of physical mechanisms of space weather phenomena. It will fly for the first time in the Sun-Earth Distant Retrograde Orbit, at a distance of ~0.1 AU from Earth, enabling on average a 6-hour advance warning of geomagnetic storms in the sunward side. REPE electron data will be exploited to predict in real time solar energetic particle events with a 1-hour average warning time. In addition to providing constant monitoring of radiation environment and producing valuable scientific data for heliophysics, HENON will demonstrate the performance of CubeSat instruments, such as REPE, in deep space missions.

REPE is a ~1U instrument (95 x 90 x 97 mm3) with a mass of 1.0 kg. It measures electrons in the energy range of 0.2 - 10 MeV and protons from 2 - 200+ MeV using a stack of three silicon detectors and a scintillator with a photodiode readout. The design of the stack and collimator allows adaptability for the energy range and geometric factor, making REPE suitable for scientific as well as commercial missions from Low Earth Orbit to interplanetary space. We will present the qualification and on-ground calibration activities and the obtained results together with the latest performance simulations. The mission is planned to be launched in January 2027.

Date: Wednesday, November 04, 2026

Session Info: IOM4: RADIATION INSTRUMENTATION FOR IN-SITU SPACE WEATHER MONITORING ACROSS THE SOLAR SYSTEM

MERIT AND AGILE: TWO IN-SITU SOLID STATE DETECTOR BASED ENERGETIC PARTICLE INSTRUMENTS

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Measurement os charged energetic particle in space have relied upon particle telescopes based on solid state detectors from Voyager to Van Allen Probes. I describe two instruments: the Miniaturized Electron pRoton ion Telescope, MERIT, a classic particle telescope, for The Heliophysics Environmental and Radiation Measurement Experiment Suite, HERMES slated to fly on SR-1 mission to Mars, and, the Advanced enerGetic Ion eLectron tElescope, AGILE, the science payload on GenSat-1 CubeSat, manifested to fly in a high inclination LEO December, 2026. Both the instruments have been built, tested, calibrated and delivered. While SR-1 is expected to be launched towards Mars, details of the trajectory or orbit are yet to be determined. MERIT is based on a classic dE/E approach, AGILE utilizes for the first time in space, full pulse shape discrimination, PSD, to identify and characterize solar energetic particles (SEP). PSD measures the pulse shape within a single SSD using a state-of-art sampling ASIC with pico second time resolution, developed for high energy physics applications

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Session Info: IOM4: RADIATION INSTRUMENTATION FOR IN-SITU SPACE WEATHER MONITORING ACROSS THE SOLAR SYSTEM

RESULTS FROM RADIATION SPECTROMETER HARDPIX ONBOARD ISS AND ION SATELLITE

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HardPix is a miniature Timepix3-based radiation spectrometer developed by the Institute of Experimental and Applied Physics, Czech Technical University in Prague. HardPix builds on the success of our SATRAM detector, which is monitoring radiation environment in space onboard Proba-V since 2013, but adds a multi-layer design and onboard processing capability. Particle identification is performed using a combination of track morphology and stopping-power information, enabling effective separation of electrons, protons, and heavier ions, measuring their deposited energy and in some cases even determining the incident energy. HardPix detectors were launched to LEO in 2023 and 2025 onboard D-Orbit ION satellites as part of the UK Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) project. Two more HardPix units were successfully operating on the outer shell of the ISS in 2025 and 2026 as part of the New Zealand mission Heki. Details of the HardPix instrument will be presented together with processed space weather data it measured in orbit. Additionally, Neutron HardPix will be introduced - a modification to HardPix using conversion layers for capability to measure fluxes of thermal, epithermal and fast neutrons. This semiconductor neutron spectrometer is planned for lunar rover mission MAGPIE and NASA mission to study the the biological risks of the lunar neutron environment.

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Session Info: IOM4: RADIATION INSTRUMENTATION FOR IN-SITU SPACE WEATHER MONITORING ACROSS THE SOLAR SYSTEM

DEVELOPMENT OF AN IMPROVED GOES - SOHO/EPHIN COMBINED PROTON DATASET

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Proton data from the Geostationary Operational Environmental Satellites (GOES) are widely used in real-time space weather monitoring and as input for forecasting models. However, there are some problems within these data sets, especially in the earlier GOES generations. For example, proton measurements are performed with passive shielding instrumentation. High-energy protons can penetrate the shielding from all sides and contribute to or even dominate the flux in lower differential energy channels (particular in the < 100 MeV range). This often leads to the problem that the Solar Energetic Particles (SEP) event onset energy dispersion is not visible in GOES observations. This also affects the calculation of the > 10 MeV integral channels. Unaddressed, these problems might impact the determination of dose rates from historical events. Use of currently available GOES proton data for training purposes can lead to biased forecasting systems that cannot be used as is in the future when more accurate observations are available. Moreover, it might lead to inaccurate determination of Probability of Detection and False Alarm Rate.
We can address these problems by replacing the lower energy bins from GOES with custom SOHO/EPHIN proton data. The EPHIN instrument uses an active anti-coincidence and has in general a lower background level. By using Pulse Height Analysis (PHA) data we created energy bins that match the ones from GOES below 51 MeV. By combining these two data sets, we provide an improved version covering both historical data from 1996 onward and real-time updates.

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THE 3D ENERGETIC ELECTRON SPECTROMETER (3DEES) ONBOARD PROBA-3: FIRST RESULTS ON ELECTRON FLUXES AND THEIR PITCH ANGLE DISTRIBUTIONS

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On 5 December 2024, a demonstrator model of the 3D Energetic Electron Spectrometer (3DEES), was launched on-board PROBA-3 into a highly elliptical orbit (apogee: 60,530 km, perigee: 600 km, inclination: 59 degrees, period: 19.7 hours). Equipped with six apertures, each offering a 15 degrees field of view and spread across a 180 degrees arc, the 3DEES enables directional measurements of particle fluxes in the radiation belts on a three-axis stabilized spacecraft. It specifically targets electrons in the energy range 0.14 - 10 MeV, providing critical data for understanding the dynamics of energetic particles in near-Earth space. In addition, it enables quantification of proton fluxes in the 2.5 - 50 MeV energy range. Since 29 July 2025, 3DEES is operated on a regular basis, performing measurements in the radiation belts every orbit when the satellite is at an altitude < 40000 km.
Validation studies confirmed the consistency of 3DEES measurements, both against its ground-based calibration, GEANT4 simulations and across its six apertures. Furthermore, the extracted flux data showed good agreement with observations from other radiation detectors.
The presentation will provide a brief overview of the 3DEES instrument onboard PROBA-3, and present preliminary results on electron flux extraction and their pitch-angle distributions. It will focus on the inter-calibration of the six apertures within the 3DEES instrument and on comparison with other radiation detector measurements at magnetic conjunction points. The instrument capabilities to capture radiation belt dynamics, such as sudden drop-outs, subsequent flux enhancements and steady decays, will also be shown. So, it will illustrate that the 3DEES dataset constitutes a valuable new data source for the development and validation of space radiation environment models.

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Session Info: IOM4: RADIATION INSTRUMENTATION FOR IN-SITU SPACE WEATHER MONITORING ACROSS THE SOLAR SYSTEM

MINI.PAN: A COMPACT HIGH PRECISION MAGNETIC SPECTROMETER FOR REAL TIME PARTICLE FLUX MONITORING IN SPACE

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The Penetrating Particle Analyzer (PAN) instrument has been conceived to precisely measure the flux, composition and arrival direction of charged particle in space with energy ranging from 100 MeV/n to 20 GeV/n. Precise measurements energy spectra and composition are of great interest to study the radiation environment around planets and to improve Space Weather predictions for Deep Space travels. The instrument is designed based on a modular magnetic spectrometer of small size, reduced power consumption and weight which make it suitable for deep space and interplanetary missions. Each sector is made with an high-field permanent magnet, instrumented with high resolution silicon micro-strip detectors and Time-Of-Flight scintillator counters readout by SiPMs. An active Pixel detector is added, to maintain the detection capabilities in high rate conditions occurring during solar energetic particle events (SEPs) or when traversing radiation belts around planets. In this contribution the description of the instrument will be given, as well as the details of the built instruments. The development and tests of the mini.PAN demonstrator will be presented, with the performance obtained with different particle's beam.

PAN Collaboration
X. Wu, G. Ambrosi, P. Azzarello, B. Bergmann, B. Bertucci, F. Cadoux, M. Duranti, M. Ionica,
M. Kole, M. Paniccia, G. Silvestre, N. Tomassetti, A. Tykhonov

Date: Wednesday, November 04, 2026

Session Info: HEL3 RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

RADIO OBSERVATIONS FOR SPACE WEATHER SCIENCE, INTRODUCING IDOLS (INCREMENTAL DEVELOPMENT OF LOFAR SPACE-WEATHER) AND PLANS FOR LOFAR 2.0

Pietro Zucca [1], Soham Dey [1], Maaijke Mevius [1], Mattia Mancini [2], Kamen Kozarev [3], Peter Gallagher [4], Monica Laurenza [5]

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Low-frequency radio observations have become a powerful tool for advancing our understanding of space weather, providing key insights into solar imaging spectroscopy, inner heliospheric conditions, solar wind dynamics, and ionospheric behavior. In addition to regular LOFAR observing campaigns that support space missions such as Parker Solar Probe and Solar Orbiter, our work is extended through the dedicated IDOLS station (Incremental Development of LOFAR Space Weather).

The IDOLS station enables continuous 24-hour monitoring of ionospheric scintillation, using Cassiopeia A as a reference source, and performs calibrated solar dynamic spectroscopy during daylight hours. This contribution presents the current status of the IDOLS project and highlights its potential for monitoring space weather phenomena and testing new radio-based forecasting tools.

We introduce key developments within the project, including automated detection of solar radio bursts, calibration methods for accurate flux and fluence measurements, real-time ionospheric scintillation monitoring, and the implementation of a predictive tool for solar energetic particles (SEPs). The station operates autonomously, with observations scheduled according to local sunrise and sunset, ensuring year-round coverage of both solar activity and ionospheric response.

Finally, we outline the current status and future plans for LOFAR solar and space weather observing campaigns and associated data processing pipelines.

Date: Wednesday, November 04, 2026

Session Info: RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

RADIO AND MILLIMETER OBSERVATIONS OF THE SUN - PROBING THE SOLAR ORIGINS OF SPACE WEATHER

Sven Wedemeyer [1], Mats Kirkaune [1], Timothy S Bastian [2], Roman Brajsa [3], Stanislav Gunar [4], Adam Kobelski [5], Atul Mohan [6], Galina Motorina [7,8], Alexander Nindos [9], Pellizzoni Alberto Paolo [10], Marco Potenza [11], Maryam Saberi [1], Rohit Sharma [12], Paulo Simões [13,14], Stephen White [15]

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Observations at radio and millimeter wavelengths provide a unique window into the thermal and magnetic structure of the solar chromosphere and corona, where the drivers of space weather originate. Recent technological advances are opening powerful new diagnostic capabilities. The Atacama Large Millimeter/submillimeter Array (ALMA) has transformed solar observations by delivering unprecedented spatial and temporal resolution, enabling detailed studies of dynamic small-scale processes that are fundamental to solar flares, coronal mass ejections, and the acceleration of solar energetic particles.

Looking ahead, the proposed Atacama Large Aperture Submillimeter Telescope (AtLAST), a 50-m single-dish facility, would provide rapid multi-wavelength full-disk scans with cadences of one minute or less, an essential capability for capturing fast-evolving solar phenomena. At lower radio frequencies, the Square Kilometre Array (SKA), currently under construction, will probe the solar corona with unprecedented sensitivity.

Beyond advancing our physical understanding of the Sun, millimeter observations hold strong potential for space weather forecasting. They provide sensitive diagnostics of chromospheric and coronal heating and dynamics, offering real-time constraints for data-driven and operational prediction models. The Solaris project, designed to enable continuous year-round observations from Antarctica and the Arctic, will serve as an important demonstrator of this capability.

We present recent advances in solar radio and millimeter observations, highlight synergies with forward modelling and data-driven simulations, and discuss opportunities offered by upcoming facilities such as AtLAST, Solaris, and SKA. Together, these developments demonstrate the growing importance of millimeter observations for understanding the solar origins of space weather and for providing critical observational input to future forecasting frameworks.

Date: Wednesday, November 04, 2026

Session Info: HEL3: RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

SPADE: A FULLY DIGITAL SOLAR RADIO ARRAY FOR SPACE WEATHER

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We present SPADE (Small Phased Array DEmonstrator), a novel fully digital low-frequency solar radio instrument developed by the Radio Workgroup of the Solar Influences Data Analysis Center at the Royal Observatory of Belgium for operational Space Weather applications. Installed at the Humain Radio-Astronomy Station, SPADE continuously monitors solar radio activity between 25 and 75 MHz during daytime observations.
SPADE is a compact autonomous phased-array demonstrator in which all core functions, including Sun tracking, beamforming, and dynamic spectrum generation, are implemented digitally using commercial software-defined radio receivers and open-source software. This fully digital architecture provides flexibility, scalability, and cost efficiency while enabling continuous autonomous operation in an operational environment.
The instrument targets low-frequency solar radio bursts associated with eruptive phenomena such as solar flares and coronal mass ejections, which are directly relevant for Space Weather monitoring and forecasting. First observations demonstrate the capability of SPADE to detect and characterize solar radio activity with high temporal and spectral resolution, allowing detailed monitoring of burst morphology and propagation effects in the solar corona.
We present the system architecture, digital processing chain, operational implementation, and first observational results. Particular emphasis is placed on the role of SPADE as a technological and operational pathfinder for future fully digital solar radio monitoring systems supporting Space Weather services and scalable distributed monitoring infrastructures.

Date: Wednesday, November 04, 2026

Session Info: HEL3 RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

USING TYPE III RADIO BURSTS AS EVIDENCE OF PARTICLE ESCAPE FROM THE SUN FOR ENHANCING SOLAR PROTON FORECASTING CAPABILITIES

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Reliable forecasts with sufficient advance warning of Solar Energetic Particle (SEP) events can contribute to swift mitigation of space weather effects by reducing radiation hazards to astronauts, especially in low-shielding situations on future Lunar and Mars missions. The HESPERIA Relativistic Electron Alert System for Exploration (REleASE) forecasting tools currently provide real-time predictions of the proton flux (30-50 MeV) at L1. These predictions are based on relativistic and near-relativistic electron measurements from the SOHO/EPHIN and ACE/EPAM instruments. Likewise, a recently developed forecasting scheme, STEREO REleASE, provides real-time predictions of proton flux (21-40 MeV) for the first time at the location of STEREO-A, relying on electron measurements by the Solar Electron Proton Telescope (SEPT) and the High Energy Telescope (HET) and respective forecasting matrices derived from the analysis of 15-years of historical SEPT/HET electron and HET proton data. Additionally, two novel implementations are also reported, namely, HESPERIA REleASE+ and STEREO REleASE+, that combine for the first time real-time Type III solar radio burst observations by the STEREO S/WAVES instrument, as clear evidence of particle escape from the Sun, within the HESPERIA and STEREO REleASE systems respectively, with the goal of improving their accuracy by reducing known sources of false alarms. From an exploration perspective, these new real-time products inform current and future strategies for SEP forecasting and monitoring at L1 and beyond, where longitudinal separation and magnetic connectivity can strongly influence SEP forecasting and advanced warning performance. Our forecasting schemes have attracted attention and are used to inform various space organizations (e.g., ESA Space Weather Service Network (SWESNET), CCMC, NASA/SRAG) They are accessible through the Space Weather Operational Unit of the National Observatory of Athens i.e. https://hesperia.astro.noa.gr

Date: Wednesday, November 04, 2026

Session Info: HEL3 RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

THE SMOS 1.4 GHZ SOLAR RADIO BURST DATABASE: PROPERTIES AND OPPORTUNITIES

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The Soil Moisture and Ocean Salinity (SMOS) mission can be exploited to provide full-polarization solar flux at 1.4 GHz, acquired with an integration time of 1.2 s. This signal is fit for solar radio burst detection, thanks to its high time resolution and the possibility to characterize events based on both solar flux intensity, and the associated Degree of Circular Polarization (DoCP).
This added layer of information brings potential value to the SMOS dataset, as the DoCP is related to both emission mechanisms behind the solar radio bursts, as well as serving as a potential diagnostic tool to understand coupling effects on Global Navigation Satellite Systems (GNSS) signal quality. As solar radio telescope ground-based measurements availability is limited by day-night cycles and availability of polarimetric receivers at 1.4 GHz, and the DoCP intensity and sign may change drastically even in a small frequency range, SMOS measurements may thus provide a unique source of information.
In this work, the SMOS solar radio burst detection algorithm is explained and its performance is described compared against the National Oceanic and Atmospheric Administration (NOAA) 1.4 GHz solar radio burst bulletin. The recall metric outperforms the results granted by the NOAA while granting the same precision.
Solar radio burst events captured by SMOS are statistically compared against the Nobeyama Radio Polarimeters (NoRP) 1 and 2 GHz channels, to characterize the 1.4 GHz solar radio burst population, including a focus on possible sign reverse of DoCP levels presence around 1.4 GHz across the frequency range, and correlation between DoCP and peak solar flux intensity.
Relevant polarized solar radio burst events are showcased to further consolidate the potential of SMOS data.

Date: Wednesday, November 04, 2026

Session Info: MIT1: SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

HIGH-FREQUENCY MAGNETIC LOOPS FOR MONITORING SOLAR RADIO BURSTS

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Radio emissions in the HF range (typically 30 kHz to 30 MHz) provide an important diagnostic of solar activity; of particular interest are type II solar radio bursts that are produced by interplanetary shocks and are associated with geoeffective coronal mass ejections. These electromagnetic emissions have been classically detected using electric field antennas. However, their magnetic component can also be measured by means of magnetic loop antennas. These magnetic sensors consist of a small circular loop with an air core, typically with a diameter of 30 cm. Some of the major advantages of such magnetic sensors are their compact size and simple design, and their higher sensitivity for detecting radio emissions relative to the galactic noise level.

Such loop antennas have already flown on the POLAR spacecraft and the CHARM sounding rocket, measuring one component only of the HF magnetic field. In this study, we explore the potential of tailoring a three-component magnetic loop sensor to microsatellite missions and highlight their application to space weather surveillance systems.

Date: Wednesday, November 04, 2026

Session Info: MIT1: SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

EXAMINATION OF COMPLEX SOLAR STORMS WITHIN THE FORECASTING SERVICE SODA

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Space weather disturbances affect low Earth orbiting (LEO) satellites throughout their mission lifetime. An increase in atmospheric neutral density, caused by solar phenomena such as coronal mass ejections (CMEs), enhances the drag force acting on a LEO satellite and can subsequently lead to an additional storm-induced orbit decay. Since satellites equipped with reasonable accelerometers are extremely rare, it is meanwhile a common practice to derive thermospheric densities along a satellite trajectory using Global Navigation Satellite System (GNSS) based kinematic orbit information. Previous studies have shown that the derivation of orbit decay for isolated events cannot be directly applied to complex (multiple) solar storm events, since in this case the thermospheric density behaves differently due to the interaction of multiple factors. Within the framework of the FWF project Earth and Space Weather: Interdisciplinary research (ESPIRE), we utilize GNSS-based kinematic orbits and satellite accelerometer data to investigate the differing behaviour of atmospheric neutral density in different orbit heights between 300 km to 800 km, during isolated and multiple events. Our objective is to adapt the derivation of orbit decay for multiple events accordingly. The findings of this study will be incorporated into the Satellite Orbit Decay (SODA) (forecasting service, which currently predicts storm-induced orbit decay of CME events for LEO satellites at an altitude of 490 km.

Date: Wednesday, November 04, 2026

Session Info: MIT1 SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

MULTIFRACTAL MIT COUPLING: FROM 24TH SOLAR CYCLE EXTREMES TO RECENT GEOMAGNETIC STORMS

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The ionosphere is a highly nonlinear, multiscale system where energy and momentum flow are driven by the complex coupling between solar wind (SW) forcing and the Magnetosphere-Ionosphere-Thermosphere (MIT) system. This study provides a new data-driven perspective on the MIT system by applying combined persistence and multifractal analysis to characterize intermittent energy transfer and non-classical turbulence across solar cycle extremes. By comparing high-resolution vertical Total Electron Content (vTEC) data with solar EUV/X-ray fluxes and geomagnetic indices from the solar maximum (2014) and minimum (2019), we characterize how external forcing alters the system's correlation structure and scale-dependent dynamics.
Our findings reveal that solar minimum is characterized by strong long-range correlations and persistent dynamics, while solar maximum exhibits reduced memory and increased intermittency, indicative of nonlinear coupling and externally driven instabilities. Specifically, Multifractal Detrended Fluctuation Analysis (MF-DFA) demonstrates significantly broader singularity spectra during active periods, linked to flare-induced perturbations and storm-time variability.
Building on this framework, the same techniques are applied to investigate the signatures of the different phases of recent major geomagnetic storms. This analysis aims to capture the rapidly evolving dynamics and intermittent energy transfer across the coupled MIT system, ranging from global circulation to mesoscale structures.
By characterizing these turbulent processes, this work emphasizes the importance of multifractal frameworks in advancing space weather monitoring and forecasting capabilities.

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Session Info: MIT1 SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

WHAT DO SATELLITE ORBITS REVEAL ABOUT THE SPATIO-TEMPORAL THERMOSPHERIC RESPONSE TO SPACE WEATHER? A MULTI-SATELLITE STUDY ACROSS ~470-810 KM ALTITUDE DURING 2023 AND 2024

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The vulnerability of the space sector to space weather is increasing with the growing number of spacecraft in Earth orbit. Geomagnetic storms resulting from enhanced solar activity can strongly perturb the upper atmosphere and increase drag on low Earth orbit satellites, complicating orbit prediction and maneuver planning for collision avoidance and re-entry mitigation. We investigate the spatial and temporal orbital response of ten spacecraft at altitudes between ~470-810 km during 2023 and 2024 using high-precision orbit data derived from GNSS-based orbit determination. We address the following questions: (1) How do background solar variability and transient events in the solar wind influence orbital decay rates?; (2) How do response amplitudes vary across geomagnetic storm classes?; and (3) Do orbital responses to solar activity exhibit spatial patterns over time? We find a strong association between solar radio flux at 10.7 cm and orbital decay rates at weekly timescales, alongside a clear solar-rotation periodicity in the orbital response. In addition, we quantify the fraction of orbital decay events associated with interplanetary shocks, coronal mass ejections, and streaming interaction regions. Consistent with previous studies, we observe faster orbital decay rates during stronger storms. While spacecraft position relative to the subsolar point and polar regions have a known influence on decay rates, we observe distinct spatial patterns during quiet and storm conditions. This study uses satellite orbit data to characterize the thermospheric response to space weather over a broad altitude range and provides a quantitative basis for future modeling of satellite drag from space weather observables.

Date: Wednesday, November 04, 2026

Session Info: MIT1: SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

QUANTIFYING THE IONOSPHERE-THERMOSPHERE RESPONSE THROUGH A STATISTICAL STUDY OF 100+ SOLAR FLARE EVENTS

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Solar flares refer to impulsive rises in solar forcing that directly perturb the photochemical and dynamical state of Earth's upper atmosphere. Yet, the altitude-resolved pathways through which flare-driven X-ray and EUV enhancements translate into ionosphere-thermosphere (I-T) variability remain poorly understood-a key gap in the magnetosphere-ionosphere-thermosphere (MIT) chain. We address this through a statistical investigation of over 100 solar flares (C to X class), combining high-cadence soft X-ray fluxes from GOES with altitude-resolved dayglow measurements from the MIGHTI instrument aboard the ICON mission.
We quantify the I-T response using the twin-peak structure of the 557.7 nm green line in the E region (~105 km) and the F region (~135 km), and the 630.0 nm red line, which samples even higher altitudes (~220 km). Results reveal a strongly altitude- and flare-geometry-dependent response: green-line enhancements exceeding 100% during X-class flares, while red-line enhancements remain within 20%. Importantly, the F-region response does not scale solely with flare magnitude but also shows pronounced sensitivity to the flare's location on the solar disk and its rise and decay times. Flares near the disk center or with a sharp rise affect the atmosphere differently than limb flares or those with gradual rises. This demonstrates that the efficiency of impulsive energy coupling into neutral and plasma populations is modulated by the geometry and temporal profile of the forcing, showing how driver characteristics control cross-scale energy transfer in the I-T system.
We synthesize these findings into a set of empirical relationships that map observed flare parameters directly onto dayglow enhancement factors. These relationships use routinely measured flare parameters to estimate upper-atmospheric emissions during flare events, offering immediate operational value and supporting improved physics-based modeling of solar impacts on the near-Earth environment.

Date: Wednesday, November 04, 2026

Session Info: MIT1 SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

STATISTICAL ANALYSIS OF IONOSPHERIC MORPHOLOGY AND DYNAMICS USING LOFAR

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While extreme space weather events provide examples of system coupling, characterising the underlying physical mechanisms requires robust, data-driven baseline models. This study utilises over 2,400 hours of continuous, high-resolution intensity data from the Low Frequency Array (LOFAR) radio telescope collected between 2014 and 2016 to construct a comprehensive climatology of kilometre-scale plasma irregularities above the high-to-mid latitude European sector. By applying a velocity reconstruction algorithm across LOFAR's core network, in the Netherlands, we track the micro-scale drift of diffractive plasma structures. Our statistical findings provide empirical evidence that these kilometre-scale irregularities are fundamentally characterised by a dominant magnetic field-alignment.

This structural alignment is shown to be a persistent feature of the nighttime ionosphere and correlates positively with the S4 scintillation index, demonstrating that increasing plasma turbulence corresponds to highly organised, field-aligned structures.

Furthermore, the analysis of the correlation reveals a persistent structural anisotropy, with plasma structures elongated perpendicular to the reconstructed velocity vector.

Crucially, we evaluate the interaction of these structures with lower ionospheric layers by cross-validating LOFAR-derived metrics against a coordinated ground-based network of ionosondes.

This multi-instrument approach demonstrates that Sporadic-E layers can act as a driver of diagnostic noise, violating standard F-region thin-screen models and disrupting tracking coherence.

By characterising the morphology, alignment, and stability of these kilometer-scale structures under a wide spectrum of geomagnetic conditions, this work advances data-driven approaches to space weather monitoring and directly supports telescope calibration and smart observation scheduling during windows of optimal ionospheric clarity.

Date: Wednesday, November 04, 2026

Session Info: MIT1 SOLAR WIND FORCING AND COUPLED MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE DYNAMICS

NEUTRAL MASS DENSITY SCALE HEIGHT IN THE UPPER THERMOSPHERE ESTIMATED FROM LEO SATELLITE MEASUREMENTS

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Scale height in the upper thermosphere is a key parameter for describing the altitude profile of a neutral gas. Experimental estimation of the scale height is difficult. However, this can be done when two low-Earth-orbit (LEO) satellites are coplanar (similar local solar times at their ascending/descending nodes) with neutral mass density measurement. During 2014-2024, we found six coplanar periods between two satellites of the Swarm, GRACE, and GRACE-FO missions, spanning more than 600 days in total and occurring during both high- and low-solar-activity years. Using the neutral mass density measured by those satellites, we can estimate the neutral mass density scale height in the upper thermosphere. The results are used to perform a statistical analysis showing how the neutral mass density scale height depends on solar EUV radiation (F10.7 index as a proxy), local solar time (LST), latitude, seasons, solar EUV radiation (F10.7 index as a proxy), and geomagnetic activity. Our main findings include: (1) the neutral mass density scale height is highly correlated with F10.7P index between 09 and 18 LST at low and mid latitudes, indicating a dominant effect of solar EUV radiation, which increases hemispheric neutral temperature and thus increases the scale height; (2) In the winter hemisphere, the scale height increases at mid- and high latitudes, particularly when F10.7P index is low, indicating winter Helium bulge at the satellites' altitudes; and (3) the scale height increases during geomagnetic storms due to an increase of neutral temperature associated with high-latitude Joule heating.

Date: Wednesday, November 04, 2026

Session Info: IOM2 SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

STUDY OF ENERGETIC PARTICLE PRECIPITATION AND ATMOSPHERIC IMPACTS (SEEP): AN ESA NEW EARTH OBSERVATION MISSION IDEA (NEOMI)

Dedong Wang [1], Huiting Feng [1], Yuri Y. Shprits [1], Miroslav Hanzelka [2], Hilde Nesse [3], Jia Jia [4], Miriam Sinnhuber [5], Günther March [6], Patrick Espy [7], Ondrej Santolik [2], Benjamin Grison [2], Xingzhi Lyu [1], Kaori Nakashima [1], Alwin Roy [1], Martin Mlynczak [8], Yoshizumi Miyoshi [9], Bernd Funke [10]

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Energetic particle precipitation (EPP) is a key driver of magnetosphere-atmosphere coupling and a fundamental component of space weather. However, current in-situ observations provide limited and discontinuous coverage in energy, pitch angle and space, restricting our ability to quantify the total particle energy input into the atmosphere and to fully characterise precipitation processes.

The NEOMI SEEP (Study of Energetic Particle Precipitation and Atmospheric Impacts) is an European Space Agency New Earth Observation Mission Idea project that addresses these limitations through a dedicated observational concept combining comprehensive in-situ particle measurements with co-located atmospheric observations. SEEP is designed to deliver continuous, gap-free measurements of precipitating particles across a broad energy range, together with pitch-angle-resolved fluxes and supporting magnetic field and wave measurements.
The mission directly targets key open questions in space weather, including the role of wave-particle interactions in driving precipitation, the variability of EPP under different geomagnetic conditions, and the contribution of different energy ranges to atmospheric forcing. By resolving the full energy spectrum of precipitating particles, SEEP will significantly improve the quantification of energy deposition into the atmosphere.

A unique aspect of SEEP is the combination of in-situ particle measurements with simultaneous observations of atmospheric response, including NOx production, ozone variability, and temperature changes. This will enable a direct observational link between particle precipitation and its atmospheric impacts, providing critical constraints for physics-based and data-driven models. NEOMI SEEP will deliver high-value datasets for the space weather community, supporting improved modelling of energetic particle precipitation and their atmospheric effects, and better representation of particle forcing in coupled Sun-Earth system models.

Date: Wednesday, November 04, 2026

Session Info: IOM2: SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

OBSERVING THE CORONA, MONITORING THE SOLAR WIND: THE FIRST YEAR OF THE SOLAR-1 MISSION

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Launched in September 2025, the SOLAR-1 mission (Space weather Observations at L1 to Advance Readiness 1; formerly SWFO-L1) is NOAA's latest solar and heliospheric mission at Lagrange 1 (L1). Its coronagraph, CCOR-2, designed to observe the middle and outer corona has been operating continuously for more than a year in parallel to the nearly identical CCOR-1 on board GOES-19 which has been operational since April 2025. Their images have captured a large number of coronal events, and derived CME parameters have been used as input into heliospheric MHD models such as Enlil, EUHFORIA, and SUSANOO.

Further, SOLAR-1's three in situ instruments, SWiPS, STIS, and MAG, supply measurements of the solar wind plasma, suprathermal ions and electrons, and interplanetary magnetic field. They thus extend the historical datasets of ACE and DSCOVR and are essential in understanding the solar wind properties at 1 AU. SOLAR-1 measurements have been used to identify transient structures such as CMEs, CIRs, shocks, etc. at high temporal and energy resolution, while driving geospace models and informing forecasts. The presentation gives an overview of the coronal and solar wind measurements in the first year of the mission with an emphasis on those which have been linked to significant magnetospheric and/or ionospheric disturbances.

Date: Wednesday, November 04, 2026

Session Info: IOM2 SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

FUTURE STRATEGIES FOR SPACE WEATHER OBSERVATIONS AND DATA TO ADDRESS SOCIETAL NEEDS

James Spann [1], Irfan Azeem [1], Yaireska Collado-Vega [1], Erin Lynch [1], Dimitrios ùVassiliadis [1], Nai -Yu Wang [1], Nicholas Zaremba [1], Laurel Rachmeler [1], Clinton Wallace [1], Howard Singer [1], Tzu -Wei Fang [1], Jamie Favors [2], Kelly Korreck [2], Esayas Shume [2], Michele Cash [2]

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Space weather is increasingly recognized as a critical factor shaping national policies, commercial investments, research priorities, and societal infrastructure. While international cooperation is actively facilitated through numerous global organizations (e.g., WMO ET-SWx, CGMS SWCG, COSPAR ISWAT, UNOOSA ISWI, ISES, ICAO), assessing potential impacts and the cost-benefit ratios of mitigation infrastructure must remain central to these discussions. Equally important is addressing the complex challenge of transitioning research to operations and back to research (R2O2R). Evaluating future capability requirements is essential to drive realistic funding strategies and pragmatic implementation plans at regional, national, and global levels. This presentation highlights the critical need to support future operational capabilities and explores actionable strategies to mitigate space weather impacts. Key focus areas include space exploration, technological advancement, societal dependence on space assets, ground system resilience, and the vital role of compelling narratives and clear explanations in guiding decision-makers.

Date: Wednesday, November 04, 2026

Session Info: IOM2: SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

SOFT X-RAY SPECTROSCOPIC DIAGNOSTICS OF M-CLASS SOLAR FLARES WITH ADITYA-L1/SOLEXS

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We present a statistical analysis of 47 M-class (M5-M9.9) solar flares observed by the Solar Low Energy X-ray Spectrometer (SoLEXS) onboard Aditya-L1. We performed spectral fitting using the CHIANTI-based isothermal model to derive flare plasma parameters (temperature and emission measure). Peak plasma temperature (T_peak) ranges from ~16 to 25 MK (mean 20.0 +/- 2.1 MK) while peak emission measure (EM_peak) spans ~(1150-2800) x 10^46 cm^-3 (mean 1694 +/- 415 x 10^46 cm^-3). The EM_peak correlates strongly (Spearman rho = 0.80) with GOES peak flux, following EM_peak = 10^(53.34) x F_G^(0.98 +/- 0.12), while T_peak shows no significant correlation with GOES class or emission measure within this narrow M-class sample. In 46 of 47 flares, we observe a consistent temporal sequence: t(T_peak) < t(SXR_peak) < t(EM_peak), with median lags of t(SXR_peak) - t(T_peak) = 4.0 min and t(EM_peak) - t(SXR_peak) = 1.3 min, consistent with the chromospheric evaporation scenario. Using a 1:1 lag criterion, we classify 39 flares (~83%) as EM-controlled and 7 (~15%) as T-controlled, indicating that SXR emission is predominantly governed by emission measure rather than temperature. The t(EM_peak) - t(T_peak) lag correlates positively with flare duration (Spearman rho = 0.82) and negatively with peak temperature (Spearman rho = -0.45). These results demonstrate the capability of SoLEXS to reliably constrain flare plasma diagnostics.

Date: Wednesday, November 04, 2026

Session Info: IOM2: SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

WHERE SHOULD THE PERFECT SUB-L1 MONITOR BE? INSIGHTS FROM GLOBAL MHD SIMULATIONS

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Space weather predictions of the solar wind and transient events impacting Earth, such as coronal mass ejections (CMEs), are typically based initially on remote-sensing observations of the solar atmosphere and corona, and later refined using in-situ measurements acquired at the Sun-Earth L1 Lagrange point. However, this operational framework provides, on average, only a few tens of minutes of lead time, which decreases further for faster-and often more geoeffective-CMEs and other solar wind structures. To address this limitation, the space weather community has recently begun exploring the concept of sub-L1 solar wind monitoring, involving spacecraft positioned closer to the Sun than 0.99 au. ESA will conduct a first demonstration of this approach with the CubeSat HENON, scheduled for launch in January 2027.

By design, a sub-L1 monitor should achieve an optimal balance between proximity to the Sun, to maximise warning time for incoming structures, and proximity to Earth, to minimise the evolution of those structures before they reach 1 au. To date, however, only a limited number of observational studies have been able to address this problem using direct in-situ data, mainly through fortuitous spacecraft conjunctions. Consequently, the optimal heliocentric distance-and, in the case of a constellation, the optimal spacecraft separation-for sub-L1 monitoring remains poorly explored. Here, we address this observational gap using MHD simulations of Earth-impacting CMEs performed with the CORHEL model. By deploying a swarm of synthetic spacecraft at different heliocentric distances between the Sun and Earth-including realistic trajectories based on existing mission concepts-we aim to determine the most effective configuration for sub-L1 monitors to make predictions of the solar wind at L1 as timely and as accurately as possible.

Date: Wednesday, November 04, 2026

Session Info: IOM2 SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

STATISTICAL OBSERVATION SYSTEM ANALYSIS (SOSA)

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We introduce the Statistical Observation System Analysis (SOSA), a method of estimating the impact of an observation system on estimating the state of a geophysical field, such as thermospheric density, ionospheric density, or radiation belt phase-space density, in the context of an operational data assimilation model. SOSA is meant to be a preliminary step to explore a large trade space of observation systems, before selecting the most effective systems for more detailed analysis with an Observation System Simulation Experiment (OSSE). The SOSA is meant to be simpler to perform and less computationally intensive than an OSSE, allowing it to explore a larger trade space. However, simplifying assumptions required to evaluate the SOSA equations necessarily do not provide as much fidelity as a full OSSE would. The SOSA is built on the statistics of environment variation extracted from a 'truth' model as well as the observation system details, such as sensor platform location and motion, sensor orientation, and sensor response. Together, these inputs can be used to estimate a skill score of a given observation system relative to a baseline model, such as a parametric climatology. Such skill scores can then be used to select the most promising observation systems for inclusion in an OSSE.

Date: Wednesday, November 04, 2026

Session Info: IOM2: SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

OBSERVING THE INNER HELIOSPHERE FROM THE SUN-VENUS LAGRANGE POINTS: DEFINING A NEW SPACE MISSION CONCEPT FOR SPACE WEATHER FORECASTING

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Predicting the occurrence of solar flares and coronal mass ejections (CMEs) impacting Earth is crucial for mitigating the harmful effects of solar energetic particles on human health and technological infrastructures. A constellation of observatories located at different positions in space, capable of monitoring both solar activity and the physical conditions of the heliosphere, is essential for accurate Space Weather forecasting.

We propose a new space mission concept based on spacecraft carrying remote-sensing telescopes and in-situ instruments positioned at the Sun-Venus Lagrange points. We show that observations of the solar corona performed with EUV telescopes and coronagraphs aboard these hypothetical spacecraft would offer several advantages, including continuous 360 degrees coverage of the Sun, higher spatial resolution compared to observations from 1 AU, and periodic quadrature configurations between the Sun-Venus Lagrange points and Earth.

In addition, measuring the properties of the interplanetary medium at distances closer to the Sun would enable earlier detection of solar wind conditions potentially affecting Earth. The proposed Sun-Venus Lagrange mission could therefore significantly contribute to a deeper understanding of Space Weather processes in the inner heliosphere.

Date: Wednesday, November 04, 2026

Session Info: IOM2: SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

PHASE A OF SWORD: ADVANCING THE ESA RADIATION BELT MONITORING MISSION FROM CONCEPT TO FUTURE SPACE WEATHER SERVICE

Andrea Ferrara [1], Francesco Ferrari [1], Erik Garofalo [1], Maria Consiglia Salvemini [1], Sebastian Benoit [2], Vytenis Orlauskis [2], Ingmar Sandberg [3], Theodoros Sarris [4], Melanie Heil [5]

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The Space Weather Orbital Radiation Detector (SWORD) is an ESA Gamma-class mission developed within the Space Safety Programme (S2P) contributing to the Distributed Space Weather Sensor System (D3S). SWORD aims to provide in-situ monitoring of the Earth's Van Allen radiation belts. Two slowly rotating small satellites on a low-inclination quasi-geostationary transfer orbit (GTO) enable revisiting each belt at least once every 5 hours and provide near-real time data on the radiation and plasma environment. Building on the successful completion of earlier mission concept definition and industrial pre-Phase A studies, the currently ongoing Phase A of SWORD focuses on payload consolidation, system performance assessment, and refinement of the mission architecture toward an operational European space weather capability. The SWORD mission baseline enables the provision of low-latency data on thermal plasma populations, spacecraft charging conditions, medium and high-energy electrons, energetic protons spanning from tens of keV to several hundreds of MeV, and magnetic field variations. These observations address key gaps in existing monitoring capabilities and support both scientific investigation and the development of space weather nowcasting and forecasting services. This work will provide an overview of the baseline mission configuration, payload capabilities, and Phase A progress, highlighting SWORD's role in enabling, from 2032 onward, a European operational system for radiation belts and plasma environment monitoring.

Date: Wednesday, November 04, 2026

Session Info: HEL1: ADVANCING CROSS-SCALE SPACE WEATHER AT THE MOON, MARS, AND BEYOND IN SUPPORT OF SCIENCE, OPERATIONS, AND EXPLORATION

SEE: A CUBESAT TO STUDY SOLAR ACTIVITY AND SPACE WEATHER

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The Sun cubE onE (SEE) is a 12U CubeSat mission in LEO that will investigate Gamma and X-ray fluxes and UV solar emission to support studies in Sun-Earth interaction and Space Weather. The mission is developed in the frame of the ALCOR program of the Italian Space Agency by a team composed of Tor Vergata University of Rome, Argotec, INFN, School of Aerospace Engineering, OPTEC, and NEXT.
SEE's main objective is to monitor the emission of solar flares, from soft-X to Gamma rays, and the solar activity through images of the Sun in the Mg II doublet (280 nm). The Gamma and X-ray fluxes will be studied with unprecedented temporal resolution and with a multi-wavelength approach thanks to the combined use of silicon photodiode and SiPM-based detectors. The flare spectrum will be explored from the keV to the MeV range of energies by the same payload, and with a cadence greater than 10 kHz, to unveil the sources of the solar flares. The UV telescope will allow us to observe the evolution of UV emission on the solar disk both during part of the solar cycle and during flares.

Date: Thursday, November 05, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

19 JANUARY 2026: ASSESSING THE GEOEFFECTIVE POTENTIAL OF THE CME EVENT WITH THE STRONGEST TOTAL MAGNETIC FIELD MEASURED IN SITU AT L1

Eva Weiler [1], Christian Möstl [1], Emma E. Davies [1], Satabdwa Majumdar [1], Tanja Amerstorfer [1], Maike Bauer [1,2], Noé Lugaz [3], Veronika Haberle [4], Astrid Veronig [2,5], Tim Horbury [6]

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From 19-21 January 2026, an intense geomagnetic storm disturbed Earth's magnetic field and produced auroral displays at mid-latitudes. The storm was driven by the CME with the highest peak magnetic field strength of 87 nT since continuous observations began at L1 in 1995. We present an analysis of this event from its solar source to its geomagnetic response at Earth. Despite its strong magnetic field, the CME magnetic structure remained predominantly northward-oriented, limiting its geoeffectiveness and resulting in the third strongest geomagnetic storm of Solar Cycle 25. Analysis of the source region strongly suggests that the event consists of two filament eruptions, further highlighting the importance of CME-CME interactions in driving extreme space weather.

In addition to observations at L1, the CMEs were measured by Solar Orbiter at 0.74 au and 8 degrees west of the Sun-Earth line. We investigate whether a spacecraft at this location could have provided operationally useful forecasts of the storm's geomagnetic response up to seven hours before their arrival at L1.
We also explore a hypothetical scenario in which the predominantly northward magnetic field of the January 2026 event had instead been southward-oriented. Using the recently developed solar wind-to-Dst model of Pennati et al., validated against several geomagnetic superstorms, we place this scenario in the context of other major Solar Cycle 25 events to assess its potential geoeffectiveness and to better understand how extreme solar wind conditions translate into geomagnetic impact. Finally, we discuss the implications of this event for future upstream monitoring missions, emphasizing the operational value of sub-L1 spacecraft concepts such as SHIELD and HENON.

Date: Thursday, November 05, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

MULTI-VIEW VECTOR SYNOPTIC MAPS FROM SO/PHI AND SDO/HMI AS BOUNDARY CONDITIONS FOR CORONAL MODELING

Francisca Santos [1], Thomas Wiegelmann [1], Xiaohong Li [1], Victor Réville [2], Philipp Löschl [1], Gherardo Valori [1], Johann Hirzberger [1], Jan Staub [1], Sami Solanki [1], Laurent Gizon [1]

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Synoptic maps of the solar photospheric magnetic field are widely used as boundary conditions for data-driven coronal and heliospheric models in space weather applications. Current maps, commonly generated from a single Earth-based viewpoint, require approximately 27 days to complete, introducing temporal inconsistencies that can affect the accuracy of coronal models and their forecasts. With deep-space missions operating from different orbital perspectives, such as Solar Orbiter and Vigil, complementary viewpoints become available, allowing for faster and more temporally consistent maps.

In this work we present recent developments in synoptic maps combining observations from Solar Orbiter Polarimetric and Helioseismic Imager Full Disk Telescope (SO/PHI-FDT) and Solar Dynamics Observatory Helioseismic and Magnetic Imager (SDO/HMI), with particular focus on vector synoptic maps. While line-of-sight magnetic field synoptic maps are predominantly used, vector synoptic maps provide access to the full magnetic field vector and improve the derivation of the radial field where line-of-sight assumptions break down. We first discuss the implications of combining different observations for synoptic maps, namely the cross-calibration, noise levels and differences in data coverage. We further assess the impact of multi-view vector synoptic maps on coronal modeling by comparing models using different types of input maps: SO/PHI-SDO/HMI combined maps and SDO/HMI-only maps, evaluating both line-of-sight derived and full vector cases. Finally, we illustrate the relevance of our work for the development of space-weather data-products from the upcoming Photospheric Magnetic field Imager (PMI) aboard ESA's Vigil mission.

Date: Thursday, November 05, 2026

Session Info: HEL4 ALL ABOUT THE SOLAR WIND AND CMES

CHARACTERIZING THE 'MARTIN LUTHER KING' STORM: SEVERE SOLAR RADIATION AND GEOMAGNETIC IMPACTS OF THE 19 JANUARY 2026 EVENT

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We present a comprehensive Sun-to-Earth analysis of the MLK storm, which produced a G4-level geomagnetic disturbance and S4-level solar radiation storm on 19 January 2026. Using multi-instrument remote-sensing and in situ observations together with physics-based simulations performed with the CORHEL-CME framework, we investigate how background heliospheric structure influenced CME propagation, magnetic evolution, and geoeffectiveness. The study emphasizes establishing robust links between near-Sun observations and near-Earth signatures, including CME kinematics, shock formation, and magnetic structure.

To bridge the observational gap between the corona and 1 au, we employ data-constrained simulations to reconstruct the three-dimensional evolution of the CME and its interaction with the structured solar wind.

Our results demonstrate the importance of CME-solar wind coupling in determining the timing and severity of geomagnetic disturbances and highlight the role of heliospheric preconditioning in shaping extreme space weather events. This work was conducted through close collaboration between forecasters at the Moon to Mars Space Weather Analysis Office (M2M-SWAO) and the LArge-Scale Structures Originating from the Sun (LASSOS) research team at NASA GSFC, providing both operational context and scientific validation. The study illustrates the value of integrating observations and physics-based modeling to improve understanding of CME evolution and advance predictive space weather forecasting capabilities.

Date: Thursday, November 05, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

SIGNATURES OF PARTICLE ENERGIZATION DURING MAY 2024 SOLAR STORM AND CURRENT SHEET BASED ON ASPEX MEASUREMENTS ONBOARD ADITYA-L1

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Interplanetary coronal mass ejections (ICMEs) and their interaction regions are key drivers of plasma heating, particle energization, and large-scale heliospheric disturbances. Using observations from the Solar Wind Ion Spectrometer (SWIS) subsystem of ASPEX onboard Aditya-L1, we investigate the complex ICME-ICME interaction event of May 2024 near the L1 point. Measurements from the two mutually orthogonal top-hat analyzers, THA-1 and THA-2, provide an unprecedented two-plane perspective of the interaction region for the first time from L1. The analysis reveals the formation of an extended downstream region generated by the propagation of a forward shock within a preceding ICME. Observations further show signatures of proton and alpha-particle energization and redistribution within the interaction region, highlighting the role of ICME interactions in modifying solar wind plasma dynamics and energetic particle transport.
In the next study, we further investigated the evolution of embedded current sheets using coordinated multi-spacecraft observations. A current-sheet structure identified within an ICME at Aditya-L1 is also observed earlier by Parker Solar Probe at 0.55 AU, providing a rare opportunity to study its radial evolution through the inner heliosphere. The study focuses on the identification, morphology, and large-scale evolution of current sheets and discontinuities embedded within ICMEs, offering new insights into ICME substructure and magnetic field evolution during heliospheric propagation.

Date: Thursday, November 05, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

ANALYSIS OF PLASMA COMPOSITION IN ICME SHEATHS AND MAGNETIC OBSTACLES AT 1 AU

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Plasma composition serves as a powerful diagnostic tool for understanding the origin and evolution of Interplanetary Coronal Mass Ejections (ICMEs). While the composition of Magnetic Obstacles (MO) has been extensively documented as a signature of coronal material, the properties of the preceding sheath regions remain less understood. This study investigates the relationship between the average iron charge state (QFe) and the oxygen ratio (O76) across different ICME samples. By applying increasingly restrictive filtering criteria-accounting for iron charge state thresholds and the presence of upstream structures such as Corotating Interaction Regions (CIRs) and ICME In Sheath (IIS)- we characterize the correlation between these two compositional variables across the ambient solar wind, sheath, and magnetic obstacle (MO). Our results indicate that while the QFe versus O76 correlation remains remarkably stable in the MO across all samples, it significantly weakens in the sheath region as external interactions are filtered out. This divergence suggests that the sheath's compositional signature is heavily influenced by swept-up ambient material rather than purely ejecta material. Additionally, we explore the kinematic coupling between sheath and MO speeds. The outcomes of this analysis offer new insights into the extent of mixing and interaction between ICMEs and the heliospheric environment at 1 AU.

Date: Thursday, November 05, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

CORONAL DIMMINGS AS EARLY DIAGNOSTICS OF CME STRUCTURE AND EVOLUTION

Larisza Krista [1]

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Coronal mass ejections (CMEs) are the primary drivers of severe geomagnetic storms, yet their early evolution in the low corona remains difficult to constrain observationally. Coronal dimmings - regions of rapid EUV intensity depletion observed at the eruption site - offer a unique window into this early phase. As the low-corona footpoints of the expanding CME flux rope, dimmings trace regions dominated by transient open magnetic field and evolve in direct response to the ejection's development and propagation into interplanetary space.

In this study, we present an integrated analysis of dimming evolution alongside CME morphology and physical properties, tracked from the solar corona to Earth. Photospheric magnetic footpoint distributions within dimming regions are characterized using the CoDiT algorithm (Krista 2013, 2017), active region loop structures are modeled using the PFSS model, CME morphology is derived from STEREO-A/COR2 coronagraph observations, and CME orientation is constrained through the GCS flux rope model. By combining these complementary diagnostics, we demonstrate how dimming observations can provide early insight into CME structure - including flux rope geometry and geoeffectiveness - ahead of coronagraph detection.

These results contribute to the growing evidence that dimmings are not passive byproducts of eruptions but active tracers of CME evolution, with direct implications for improving real-time space weather forecasting.

Date: Thursday, November 05, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

WHAT WE KNOW AND DO NOT KNOW ABOUT CORONAL MASS EJECTIONS

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Coronal Mass Ejections (CMEs) are gigantic magnetized plasma clouds expelled from the Sun. They propagate throughout the heliosphere and drive the most intense space weather disturbances in planetary magnetospheres, ionospheres, and atmospheres. Although significant progress has been made in understanding CMEs since their discovery by the first space-borne observations in the 1970s, many fundamental aspects remain poorly understood. This review talk first provides a brief overview of the basic properties of CMEs in both the solar corona and interplanetary space. It then discusses several major open questions in current CME research. Topics include determining CME magnetic fields, understanding why some coronal flux ropes erupt while others remain stable, identifying the drivers and limits of extreme eruptions, and explaining the complex structures frequently observed in interplanetary CMEs. Recent multi-spacecraft observations in particular suggest that most CMEs may not behave as coherent flux ropes, but instead exhibit substantial mesoscale variability. It remains unclear to what extent this complexity is intrinsic to the eruption process, and to what extent it results from interplanetary evolution and interactions during propagation.

Date: Thursday, November 05, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

MODERN TOOLS FOR WHITE LIGHT GEOMETRIC RECONSTRUCTIONS WITH MASS ESTIMATES

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Remote imaging of the Sun, corona, and interplanetary space allow us to observe structures as they develop and how they propagate out through the heliosphere. Remote imaging instruments observe sunlight scattered off the electrons within these dynamic structures. This approach inherently loses information about the 3D structure because the line of sight (LoS) is compressed into 2D images of total brightness per pixel. Some of this information can be recovered using reconstruction techniques. Often, a graphical user interface (GUI) is used to manually align a wireframe shape with simultaneous images from different satellite viewpoints.

We present a new fully Python-based GUI, the Wireframe Object Mapped onto Background Alignment Tool (WOMBAT), which functions similarly to existing community tools, but offers more wireframes, additional wireframe shapes, and support for a wider range of observations, including SoloHI and PSP WISPR. Additionally, WOMBAT can calculate the masses enclosed by wireframe objects using basic electron-scattering theory. The Density Inferred from Nice Grid Object (DINGO) routine when used with WOMBAT, derives densities within the wireframe region using 3D wireframe shapes and LoS-integrated masses. These densities can also be extrapolated to expected in situ observations using a basic propagation model. We present WOMBAT and DINGO, including their new user-friendly features, their application to modern missions, and their ability to track mesoscale features to greater distances. WOMBAT and DINGO can facilitate routine mass measurements, thereby improving both space weather forecasting and scientific research.

Date: Thursday, November 05, 2026

Session Info: HEL4: ALL ABOUT THE SOLAR WIND AND CMES

ANALYSIS OF INTERPLANETARY CORONAL MASS EJECTIONS OBSERVED BY SOLAR ORBITER (2020-2024) AND THEIR SOLAR SOURCES

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We identify, categorize, and analyze 77 interplanetary coronal mass ejections (ICMEs) observed in situ by Solar Orbiter between April 2020 and April 2024. For 28 of these events, we reliably associate their solar sources observed in remote white-light coronagraphs by applying a drag-based back-propagation model. In most of these associated cases, we further identify corresponding low-coronal signatures using observations from SDO/AIA, STEREO-A/EUVI, and/or Solar Orbiter/EUI. We perform a 3D reconstruction of the CME based on white light images and fit in situ data with an expansion modified force-free model to derive the local properties of the magnetic structure. In addition, we analyse the ambient solar wind and interplanetary magnetic field conditions in which CME has progagated and evolved using the Magnetic Connectivity Tool. We perform a statistical analysis of the ICME properties and compare our results with previous studies conducted at 1 au and at smaller heliocentric distances. Our findings largely confirm previously reported ICME characteristics, while also providing new insights into the evolution of ICME sheaths. The compiled event list offers a valuable reference for future CME-ICME studies utilizing Solar Orbiter observations.

Date: Thursday, November 05, 2026

Session Info: MIT2: CROSS-SCALE GNSS-BASED MONITORING OF IONOSPHERIC IRREGULARITIES: FROM PHYSICS TO OPERATIONAL SPACE WEATHER SERVICES

PREDICTING CORONAL MASS EJECTIONS AT L1 USING IPS-DRIVEN TIME-DEPENDENT TOMOGRAPHY

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Coronal Mass Ejections (CMEs) are the drivers of significant geomagnetic disturbances at Earth and constraining their physical properties via remote sensing techniques is key to addressing their geomagnetic impact. A leading approach is to use Interplanetary Scintillation (IPS) measurements from ground-based radio observatories as a means to constrain heliospheric plasma parameters via analysis of radio signals from distant sources as they pass through the solar wind. Novel analysis techniques applied to these observations, combined with cutting-edge modelling, are being performed as part of the Radio Investigations for Space Environment Research (RISER) project. This is with the goal of improving the precision, accuracy and lead-times of forecasts of space weather conditions and impacts at Earth.

We use IPS observations from the European Low Frequency Array (LOFAR) and the Institute for Space-Earth Environment Research (ISEE) in Japan to calculate solar wind speed and density in the inner heliosphere, which are then used to drive the UCSD time-dependent tomography model and make forecasts of solar wind conditions at L1, including CMEs. We present an overview of this analysis applied to eleven case studies during the period September 2025-March 2026, where moderate-to-severe geomagnetic activity was observed, with a Kp value of 6 or higher. We assess our capability to provide upstream warnings by applying the analysis to each event using different lead times, ranging from zero to three days, and comparing these to real observations at L1. Furthermore, the analysis is run using ISEE and LOFAR separately, and with both combined, as a means to investigate the improvements afforded by increasing the ground-based coverage of IPS observations.

Date: Thursday, November 05, 2026

Session Info: OTH4: EDUCATION AND OUTREACH IN SPACE WEATHER: ENGAGING COMMUNITIES AND SHAPING THE NEXT GENERATION

A TOUCH OF SPACE WEATHER: COMMUNICATING SCIENCE TO BLIND AND VISUALLY IMPAIRED STUDENTS THROUGH MULTILINGUAL AUDIOBOOKLETS

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Science communication in space weather relies heavily on visual content - diagrams, satellite images, and colour-coded plots - creating persistent barriers for blind and visually impaired (B&VI) people. A Touch of Space Weather (ATOS) is an inclusive outreach initiative developed at the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) that transforms space weather concepts into multisensory experiences accessible through touch and sound, with a primary focus on students aged 10-18.

A central initiative is the development of professionally recorded multilingual audiobooklets, developed in Dutch, French, and English, covering topics such as the Sun, solar storms, auroras, Earth's atmosphere and many more. Each audiobooklet uses vivid analogies, structured narrative, and carefully crafted descriptions to make abstract heliophysical concepts accessible without reliance on visual imagery. The scripts are co-developed with B&VI educators and students, and the recordings are tested directly in specialised schools to ensure clarity, engagement, and scientific accuracy. The audiobooklets are designed to complement tactile images and sonified space weather data used during hands-on workshops, forming a coherent multisensory learning ecosystem.

In this contribution, we present the design principles behind the audiobooklets, share feedback collected from B&VI students and educators, and discuss lessons learned in producing accessible science narratives - including the importance of analogy-driven language, co-development with the B&VI community, and iterative testing in classroom settings. We also reflect on how the audiobooklet format extends the reach of space weather outreach beyond the workshop setting, supporting independent learning and continued engagement. Looking ahead, we will outline plans for completing the full multilingual series and expanding distribution to schools and organisations across Belgium and beyond.

Date: Thursday, November 05, 2026

Session Info: OTH4: EDUCATION AND OUTREACH IN SPACE WEATHER: ENGAGING COMMUNITIES AND SHAPING THE NEXT GENERATION

USER-FOCUSED TRAINING AND COMMUNITY ENGAGEMENT OPPORTUNITIES AT THE COMMUNITY COORDINATED MODELING CENTER (CCMC)

Elana Resnick [1], Maria Kuznetsova [1], Leila Mays [1], Yihua Zheng [1], Claudio Corti [1,3,4], Anders Lundkvist [1,5], Jia Yue [1,5]

[1] NASA GSFC CCMC, Greenbelt, MD, USA, [2] ASRC Federal, Greenbelt, MD, USA, [3] The University of Hawaii, Honolulu, HI, USA, [4] Universities Space Research Association, Washington DC, USA, [5] The Catholic University of America, Washington DC, USA

The Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center (GSFC) supports heliophysics educational endeavors such as space weather summer schools, contests, research visits and exchanges. The CCMC has collaborated with users and developed training materials to meet the needs of the community to understand how CCMC's space weather models and tools can aid them in decision making and situational awareness. The CCMC also collaborated with the European Space Weather and Space Climate Association (E-SWAN) on their space weather training course prior to European Space Weather Week in 2025 and 2026. This is aligned with the International Space Weather Action Teams (ISWAT) action team O4-01, 'User-focused Space Weather Training Network'. Additionally, the CCMC has partnered with the OpenSpace project to create planetarium shows using real-time and historical data and models. OpenSpace project is open-source interactive data visualization software designed to visualize the entire known universe and portray our ongoing efforts to investigate the cosmos. We include space weather models and data in the planetarium shows, including the Artemis II mission as well as Mars data and visualizations of missions.

Date: Thursday, November 05, 2026

Session Info: OTH4: EDUCATION AND OUTREACH IN SPACE WEATHER: ENGAGING COMMUNITIES AND SHAPING THE NEXT GENERATION

THE DARK SIDE OF THE SUN: MAKING SPACE WEATHER PERSONAL AND RELATABLE THROUGH AUDIENCE ENGAGEMENT

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Space weather is often communicated through extreme, low-probability scenarios, while its more frequent, ordinary impacts on technology and everyday life remain underappreciated. Communicating these effects without sensationalism is essential to fostering realistic risk perception, improving public awareness, and strengthening societal preparedness.

Within the INAF communication project Sorvegliati Spaziali, we have developed “Il Lato Oscuro del Sole” (The Dark Side of the Sun), a monthly live broadcast series on YouTube, Facebook, and Instagram designed to make space weather accessible, engaging, and personally relevant to a broad audience. Each episode connects solar and geomagnetic activity to real-world systems—such as satellite operations, aviation, power grids, and GNSS—starting from lived experiences shared by the audience. Sometimes we dive into research with modellers and planetologists.

Audience participation is central to the format. Prior to each episode, we collect responses to targeted questions about personal experiences or awareness of space weather. These contributions are integrated into the live discussion, fostering identification with the topic and highlighting its tangible societal impact. This approach has proven effective in increasing engagement and shaping a more inclusive dialogue around space weather.

Over the past year, the project has shown steady growth in audience reach, live interactions, and feedback, indicating increasing interest and awareness and contributing to a stronger connection between researchers and the public.
The series has recently evolved into a more structured and dynamic format, with narrative-driven introductions aimed at catching audience interest with engaging stories and an expanded roster of guest experts from different disciplines.
We present updated audience metrics, engagement strategies, and lessons learned, with a focus on the project’s impact on community building and outreach practices in Italy.

Date: Thursday, November 05, 2026

Session Info: OTH4: EDUCATION AND OUTREACH IN SPACE WEATHER: ENGAGING COMMUNITIES AND SHAPING THE NEXT GENERATION

RECRUITING AURORA CHASERS FOR CINEMA-MOVIE: WORKFLOWS AND COMMUNICATION FOR PARTICIPATORY-SCIENCE CONTRIBUTIONS

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CINEMA (Cross-Scale INvestigation of Earth's Magnetotail and Aurora) is a NASA Small Explorer mission that will use a constellation of satellites carrying particle, magnetic-field, and auroral-imaging instruments to study connections between Earth's magnetotail and the aurora. MOVIE (Multi-platform Observations from Volunteers: Ionospheric Experiments) is CINEMA's citizen-science component, linking spacecraft measurements to coordinated ground-based observations from volunteer and enthusiast communities, including aurora chasers and amateur radio operators.

This presentation focuses on the techniques and workflows being developed to recruit the aurora chasing community and integrate their observations into CINEMA science. Aurora chasers can supply ground-based context in regions and conditions that fixed all-sky imager networks do not fully cover, including mid-latitude aurora during enhanced geomagnetic activity, subauroral emissions such as STEVE and SAR arcs, gaps between camera fields of view, and multi-viewpoint observations of the same auroral structure.

We describe the framework being established before mission operations: a selected advisory group of aurora chasers drawn from major northern and southern hemisphere observing communities; a layered communication model built around a public project website, a moderated announcement email list, and a rapid coordination channel; candidate photo and data submission workflows; and a plan for volunteer recognition and reciprocity. We summarize expected participation, draw lessons from past parcitipatory-science engagement with the aurora community, and outline open questions relevant to the broader space weather community for planning volunteer campaigns.

Date: Thursday, November 05, 2026

Session Info: SOL1: MAGNETIC FIELDS IN THE LOWER SOLAR ATMOSPHERE - THE ENGINE BEHIND SOLAR WIND AND ERUPTIVE EVENTS

MODERN HELIOPHYSICS: ADVANCED CONCEPTS IN PLASMA SCIENCE FOR TEACHERS

Francesco Berrilli [1], Umberto Villante [2], Francesco Salamida [2], Giuseppe Consolini [3], Stefania Lepidi [4]

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Despite its dominance in the observable universe, plasma physics remains a peripheral topic in secondary school curricula. This presentation details a specialized teacher-training initiative held at the University of L'Aquila (May 2026) during the International School on Heliospheric Space Plasma Physics. The program addresses the pedagogical disconnect between standard three-state matter education and the complex, magnetized environments of the solar system.
Drawing on the established Progetto Lauree Scientifiche (PLS) methodology, in a collaboration between the Universities of Rome Tor Vergata and L'Aquila, we present strategies for translating abstract magnetohydrodynamics and plasma kinetics into accessible classroom models. By centering the curriculum on the Active Sun and Sun-Earth interactions, we provide educators with a rigorous yet intuitive framework to introduce the fourth state of matter, ultimately fostering a new pipeline for future researchers in astrophysics and space weather.

Date: Thursday, November 05, 2026

Session Info: OPS: OPEN SESSION

SOLAR FLARE IMPACT ON CONTINUOUS HF COMMUNICATION

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Current models use digisondes to measure radio signal attenuation along a vertical path. However, in HF communication beyond line of sight, the signal path through the ionosphere is no longer vertical, causing these models to deviate from practical conditions. As the distance between the transmitter and receiver increases, the signal path through the ionosphere becomes longer, resulting in greater attenuation. To measure actual signal attenuation across different frequencies and distances, multiple HF posts have been established in different countries to monitor continuous HF transmissions from the Royal Dutch Navy. The setup was initially tested with two HF posts in the Netherlands from Nov 2025 to Feb 2026. During this period, several X-class and M5+ solar flares occurred, which were observed to measure the impact on signal strength reception. The X4.0 flare on Nov 14 caused a complete radio blackout on the 12 MHz signal during its duration, with the signal dropping from -91 dBm to the background noise level of -101 dBm. The 4 MHz signal dropped from -73 dBm to BGN level of -105 dBm, resulting in an attenuation of 30 dB, while models predicted an attenuation of 3.5 dB. This resulted in a 59% to 335% higher attenuation rate than predicted. To extend the experiment and monitor signals over greater distances, additional HF posts have been deployed in DNK, SWE, LTU, HUN, and NOR.
In this talk, we will present results from the initial NLD setup, including attenuation measurements for each frequency (2 MHz, 4 MHz, 6 MHz, 8 MHz, and 12 MHz) during solar flares, as well as preliminary results from the European network. With the current geopolitical climate, the use of HF radio communication in the armed forces has increased
and became essential once again. The empirical attenuation data collected across multiple frequencies and distances in this experiment can therefore contribute to improved ionospheric models, benefiting military operations during periods of heightened solar activity.

Date: Thursday, November 05, 2026

Session Info: OPS: OPEN SESSION

ADAPTIVE DETECTION OF HOT ONSET PRECURSOR EVENTS IN GOES SOFT X-RAY OBSERVATIONS

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The Flare Anticipation Index, introduced by Hudson in 2025, is a method designed to identify an early stage of solar flare development known as the Hot Onset Precursor Event. This stage appears in GOES soft X-ray observations shortly before the main impulsive peak of a flare. The method is not intended to predict flares far in advance, but to provide an early alert that a flare is already developing, usually a few minutes before its main peak.

In this work, we test an adaptive version of the Flare Anticipation Index using GOES soft X-ray data. Instead of following both emission measure and temperature, our approach focuses only on the temperature derived from GOES observations. It studies how the temperature changes over short and longer timescales and automatically adjusts depending on whether the flare develops rapidly or gradually. The trigger is designed to run continuously on the GOES X-ray data stream.

As a first test, we apply the method to solar flare activity observed during May 2024. We compare the detected triggers with two flare catalogs: the operational NOAA flare list and the archival ASR catalog of Berretti and collaborators from 2025. Compared with the NOAA catalog, the method detects most listed flares within five minutes before the reported flare start time, although many triggers do not match any NOAA-listed event. When compared with the ASR catalog, most of these unmatched triggers are associated with flare-like events.

These results show that the apparent performance of real-time flare anticipation methods depends strongly on the reference catalog used. Differences in catalog completeness, flare start-time definitions, and reporting thresholds can strongly affect the measured detection and false-positive rates. The full study will extend the validation to a longer ASR archive, examine anticipation times for different flare classes, and study NOAA-unassociated triggers in more detail.

Date: Thursday, November 05, 2026

Session Info: OPS: OPEN SESSION

SPACE WEATHER IMPACTS ON DEFENCE AND SECURITY

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During severe space weather events, technologies such as radio communications, Global Navigation Satellite Systems (GNSS), satellites, and power grids can be seriously disrupted, while radiation levels may increase at aviation altitudes and even on the ground. As governmental, commercial, and military operations become increasingly dependent on space-based infrastructure, space weather is emerging as a significant security and defense concern. In this work we reviews the space weather cause-effect chain during solar cycle 25, from solar phenomena such as solar flares, coronal mass ejections, and energetic particle events to their effects on satellites, the Earth's magnetosphere and ionosphere, and ultimately on critical technologies and infrastructures. Particular attention is given to the vulnerabilities of communication, navigation, surveillance, and satellite systems that are essential for defense and security operations. Radiation hazards to humans, aviation sector and satellites are also discussed. The multidisciplinary nature of space weather is emphasized, combining expertise from space physics, operational forecasting, and risk management. This work highlights the importance of international coordination initiatives led by organizations such as the World Meteorological Organization and the European Space Agency to strengthen monitoring, data sharing, and preparedness. By examining historical events and current challenges, this contribution underlines the necessity of integrating space weather resilience into broader security and defense strategies.

Date: Thursday, November 05, 2026

Session Info: OPS: OPEN SESSION

GATES: A GROUND-BASED NETWORK FOR SPACE WEATHER OBSERVATION

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Global Automatic Telescopes Exploring the Sun (GATES) is a multi-site ground-based network of telescopes for synoptic space weather observation. The GATES Network currently consists of two nodes: the Tor Vergata Synoptic Solar Telescope (TSST) and the Mojave Solar Observatory (MSO). Both instruments are designed as cost-effective, robotic facilities that use Magneto-Optical Filter (MOF)-based instruments to acquire full-disk, simultaneous line-of-sight velocity and magnetic field maps (Dopplergrams and magnetograms, respectively). The TSST employs two channels: a potassium K I D1 769.9 nm centered MOF for photospheric Doppler- and magnetogram observations and a narrowband H-alpha Daystar telescope for chromospheric intensity images. MSO consists of a dual-MOF-based telescope with channels centered on K I D1 769.9 nm and sodium Na I D2 589.0 nm for photospheric and low-chromospheric Doppler- and magnetogram observations, respectively. Additionally, the GATES team has developed and tested a helium He I 1083 nm MOF for probing the velocity and magnetic field dynamics of the upper chromosphere. The final mounting locations of the two active GATES nodes - La Palma, Spain (TSST) and Apple Valley, CA, USA (MSO) - are separated by ~ 150 degrees of longitude, providing an average of 20 hours of solar observation per day, enabling near-synoptic observations for space weather monitoring.

To demonstrate a proof-of-concept for this multi-nodal MOF-based network, GATES conducted a successful three-phase observing campaign during the summer of 2025 - Phase 1: dual-site observing with the TSST and MSO; Phase 2: extended dual-height observing with MSO; and Phase 3: He MOF observing. We present results from this observing campaign, including cross-site comparisons, multi-height phase/ power spectrum analysis, and full-disk He magnetogram observations. Additionally, we present the optomechanical designs and operational schemes of the individual GATES nodes and the network as a whole.

Date: Thursday, November 05, 2026

Session Info: IOM1: PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

THE UPDATED COSPAR PSW-ISWAT 2025+ SPACE-WEATHER ROADMAP - SUMMARY AND A LOOK TO THE FUTURE

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In February 2020, the COSPAR Panel on Space Weather (PSW) in conjunction with the COSPAR International Space Weather Action Teams (ISWAT) Initiative embarked upon a multi-faceted update to the 2015 COSPAR International Living With a Star (ILWS) space-weather roadmap (Schrijver et al., 2015). This is a true global effort which has also grown the COSPAR ISWAT Initiative to over 700 active researchers from around the world.

We took the novel approach in developing a true community-driven space-weather roadmap to include papers across two distinct, but complimentary, Special Issues of the COSPAR Advances in Space Research (ASR) journal. Due to COVID and other delays, the first Special Issue was only released in December 2023 with the second in 2026. The first special issue focussed primarily on the research as a driving force for advancing space weather through the COSPAR ISWAT Initiative. This second Special issue focussed on: overarching sub-domains of space weather (aligned to the COSPAR ISWAT Initiative); key impact pathways; learning from terrestrial forecasting; international collaboration, communication, cooperation, and coordination; knowledge transfer; new/advanced instrumentation/modelling techniques; an overview of the COSPAR ISWAT Initiative; and an overarching high-level summary (Bisi et al., 2026) of all the key recommendations across the 60 papers collectively making up the COSPAR PSW-ILWS 2025+ Space Weather Roadmap, among other things.

With the completion of final papers of long endeavour, we present the journey of the space-weather roadmap update from start to finish, and we also provide a high-level summary of the many outcomes and recommendations with a look to the future. Critically, international coordination is needed. This work is on behalf of all the updated COSPAR space-weather roadmap contributors as well as the wider members of the COSPAR ISWAT Initiative and COSPAR PSW members.

Date: Thursday, November 05, 2026

Session Info: IOM1: PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

THE SO/PHI MAGNETOGRAPH ON SOLAR ORBITER AS A MODEL SYSTEM TO TEST THE SCIENCE PLANNED FOR VIGIL/PMI

Sami Solanki [1], Johann Hirzberger [1], Jan Staub [1], Calchetti Daniele [1], Alex Feller [1], Francisca Ferreira [1], Achim Gandorfer [1], Laurent Gizon [1], David Ivens [1], Xiang Li [1], Philipp Loeschl [1], David Orozco [2], Jude Simmons [1], Jonas Sinjan [1], Hanna Strecker [2], Artem Ulyanov [1], Gherardo Valori [1], Joachim Woch [1]

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Significant improvements in the prediction of space weather are expected from ESA's Vigil mission thanks to its intended location at the Lagrange L5 point. Among the three key instruments in its payload, Vigil will carry a vector magnetograph, PMI, which will see features on the Sun from a vantage point that differs by 60 degrees in longitude than the view from Earth. From this location, PMI will have the advantage of seeing and being able to follow solar active regions already 4-5 days before they become visible from Earth, allowing longer-term monitoring of regions that could become sources of space weather.

Before PMI finally flies on Vigil, we can use the Full Disc Telescope (FDT) of the Polarimetric and Helioseismic Imager on Solar Orbiter (SO/PHI) as a model system to test and predict some of the things that PMI will see and the results it will obtain. The SO/PHI-FDT is a reasonable model of PMI, as both instruments cover the Sun at almost the same spatial resolution (at perihelion of Solar Orbiter), observe in the same spectral line, with almost the same spectral filters, the same polarization modulators, etc. In fact PMI builds on the technology developed for and the design of SO/PHI.

Such a study is best carried out with data obtained by SO/PHI at times when the Solar Orbiter - Sun - Earth angle is close to 60 degrees, i.e. similar to what it will be for Vigil at L5. Some of the questions leading to and results of studies made at roughly this angle will be presented that may be relevant for the science of PMI.

Date: Thursday, November 05, 2026

Session Info: IOM1: PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

IMPROVING CME ARRIVAL FORECASTS WITH L5 OBSERVATIONS

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The Lagrange point 5 (L5) of the Sun-Earth system represents a critical vantage point for next-generation operational space weather forecasting. In this presentation, we evaluate the performance of an L5 monitor by analyzing historical STEREO-B observations of an Earth-directed coronal mass ejection (CME) captured while the spacecraft was positioned near L5. By integrating these data into propagation models, we demonstrate that CME arrival-time predictions at Earth can be drastically improved compared to traditional L1 forecasting.
This operational advantage is further illustrated using recent observations from the Extreme Ultraviolet Imager (EUI) onboard Solar Orbiter, which has crossed the L5 longitudinal angle on several occasions, acting as a real-world proxy for future missions like ESA's Vigil.
Utilizing these distinct case studies, we discuss the advantages of an L5 monitor for constraining the interplanetary propagation of CMEs.

Date: Thursday, November 05, 2026

Session Info: IOM1: PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

THE PLASMA ANALYSER INSTRUMENT FOR VIGIL

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Vigil is ESA's operational space weather mission, planned to be launched in 2031. The spacecraft will be at the Sun-Earth Lagrange point 5 (L5), from which it will provide crucial remote sensing and in-situ observations, allowing for early warnings of potentially hazardous space weather events. The Plasma Analyser instrument (PLA) is the ion analyser on board Vigil, which is designed to measure and resolve the bulk parameters of solar wind protons, such as density, speed, and temperature. PLA is currently in development. In this presentation, we will first describe the status of the instrument development, and we will outline the future manufacturing steps. We will then describe the numerical modelling of the instrument's response, which we have developed during the designing phase. We will explain how this model allows us to simulate the expected measurements and quantify the accuracy of the solar wind parameters to be determined. Moreover, with the use of the instrument model we will design the methodology pipeline for the on-ground data analysis. We will focus on preparation studies we have done in the past few years addressing the effects of the instrument finite resolution to the observations and exploring the appropriate analysis methods.

Date: Thursday, November 05, 2026

Session Info: IOM1: PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

THE SCIENCE OF JEDI FOR THE VIGIL MISSION AT L5

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JEDI is a next-generation high cadence, multi-thermal EUV Imager selected by NASA to fly on the European Space Weather Mission Vigil in a halo orbit around the Lagrange Point L5. JEDI will improve our understanding of space weather and enhance space weather operations capability by providing vital observations of earth-directed space weather events from the solar disk out 6 solar radii. JEDI will also answer fundamental questions about the Ground State of Space Weather...the Solar Wind.

With 10x greater throughput than EUI/FSI in occulted mode >1.4 solar radii, JEDI makes high cadence observations of the Middle Corona (West et al. 2023) out to 6 solar radii standard and routine. This important, yet little-observed, middle corona, is the critical region of CME acceleration, flare reconnection and solar wind formation. With its large FOV, JEDI directly complements other Vigil instruments, providing overlapping FOVs that connect the observations from the Photospheric Magnetic Field Imager (PMI) with those from CCOR (Compact Coronagraph).

The JEDI instrument is comprised of two simple, reliable, low-risk/high-heritage telescopes, the Space Weather Operational Coronal Imager (SWOC) and the Enhanced Wide-angle Observations of the Corona (EWOC). SWOC takes 4 min cadence images of the full solar disk and extended corona out to 3.2 solar radii on the Earthward limb in three narrow passbands corresponding to temperatures ranging from the chromosphere to the flaring corona. EWOC takes images of the full solar disk and extended corona in two passbands sensitive to chromospheric and coronal plasma out to 6 solar radii. EWOC's game-changing FOV is enabled by a moveable occulter, proven by Solar Orbiter Extreme Ultraviolet Imager (EUI/FSI), allowing interleaved, low-scattered light images of the extended corona and on-disk coronal structures.

Date: Thursday, November 05, 2026

Session Info: IOM1: PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

ASSESSING THE USE OF AUTOMATIC CME TRACKING IN HI WITHIN A DRAG-BASED FORECASTING PIPELINE

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Accurately forecasting the arrival time and speed of CMEs is an important step towards mitigating the impacts of severe space weather events. The Vigil mission will provide continuous, high-quality coverage of the Sun-Earth line from the L5 point, promising to enhance early-warning capabilities for space weather forecasting. To be able to make the best possible use of these new data products, it is important that we thoroughly assess our current capabilities. To this end, we evaluate the performance of a fully automated CME prediction pipeline based on HI data. We use the STRUDL algorithm to automatically detect and track CMEs in data from the STEREO-HI instrument over a one-year period. The STRUDL-generated tracks are then used together with CME initial parameters from the DONKI CME database to serve as input for the drag-based ELEvoHI prediction model. We compare the automatically produced time-distance profiles to manually generated tracks, and evaluate the difference in ELEvoHI's performance for predicting CME arrival times at Earth when using either type of track. As a baseline, we also compare to the ELEvo prediction model, which shares the assumptions underpinning the ELEvoHI model but does not rely on HI data.

Date: Thursday, November 05, 2026

Session Info: MIT3: RADIATION BELTS AND PLASMA IN THE MAGNETOSPHERE

ULF WAVE - COLD PLASMA COUPLING AND THE IMPACTS ON RADIATION BELT DYNAMICS

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ULF wave driven radial diffusion plays a key role in the energisation, loss, and transport of radiation belt electrons. But what regulates when and where ULF waves exist in the inner magnetosphere? The cold plasma population coexists with radiation belts in the inner magnetosphere, and the cold plasma mass density controls how ULF waves propagate through the region, their polarisaion, and where they deposit their energy. During geomagnetic storms, the structure and mass density of the cold plasma is intensely distorted, and drastically modifies the ULF wave - cold plasma coupling.

Using remote observations of global cold plasma imaging combined with ground magnetometer array measurements of ULF waves, we identify how cold plasma structures can alter the polarisation of the waves. As well as being associated with storm-time plasmaspheric plumes in the afternoon sector, dawn side features such as plasmaspheric shoulders also prove to be important. The discussion is placed in the context of radiation belt dynamics, where we will explore implications for electron energisation. Overall, we demonstrate that cold plasma dynamics are an important source of uncertainty in ULF wave processes and radiation belt dynamics, and understanding cold plasma-ULF wave coupling is a critical area of future investigations.

Date: Thursday, November 05, 2026

Session Info: MIT3: RADIATION BELTS AND PLASMA IN THE MAGNETOSPHERE

REDUCED-ORDER EMULATION OF THE EARTH ELECTRON RADIATION BELTS

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Radiation belts consist of populations of energetic particles, such as electrons and protons, trapped in the near-Earth space vicinity by the geomagnetic field. Given that they cover the vast majority of existing orbits and that the particles' dynamics, which are highly coupled with solar activity, can strongly affect spacecraft components and missions, the accurate modeling of these regions is of utmost importance for monitoring near-Earth space dynamics.

Traditionally, radiation belts are modeled by solving a three dimensional diffusion equation using numerical solvers. While a single 3D simulation can easily be run in real time, as is done routinely in many space weather forecasting pipelines, the computational burden can become significant when the model is utilized in ensemble based data assimilation. This approach potentially requires hundreds of runs over very long periods, such as those needed for space climate studies.

In this context, machine learning based Reduced Order models (ROMs) offer an interesting solution to approximate the solutions of traditional high-fidelity physics-based models with reasonable accuracy and at a reduced computational cost. This is achieved by projecting highly non-linear features onto a disentangled, interpretable latent space of reduced dimension, the dynamics of which could be driven by external variables.

In this work, we present the different steps of the design of an Emulator for the Earth electron radiation belts, from the reduction of high-dimensional electron fluxes on a refined grid to meaningful, information intensive, latent variables to the driving of their dynamics with external geomagnetic parameters.

This work was supported by both the Event-Based Electron Belt Radiation Storm Environments Modelling Activity led by the Space Applications & Research Consultancy (SPARC) under ESA Contract 4000141351/23/UK/EG and ONERA internal fundings, through the federated research project PRF-FIRSTS.

Date: Thursday, November 05, 2026

Session Info: MIT3: RADIATION BELTS AND PLASMA IN THE MAGNETOSPHERE

SIMULATING EXTREME EVENTS IN THE RADIATION BELTS: PART 2

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As society increasingly relies on satellites orbiting through the Earth's radiation belts, understanding the effect that extreme space weather can have on the radiation environment in the belts becomes more important. This work aims to understand the effect that a severe interplanetary shock would have on the radiation belts. In Part 1 of the study, the immediate effect of an interplanetary shock of similar magnitude to the 1859 Carrington Storm and the 2012 event that missed the Earth was investigated. This showed that the outer radiation belt would be removed and that the slot region would be filled by electrons with energies above 5 MeV. This part of the study focusses on the evolution of the radiation belts in the days following the initial shock.

The evolution of the belts is modelled by the British Antarctic Survey Radiation Belt Model (BAS-RBM). Typically, the BAS-RBM uses geomagnetic indices as drivers and electron flux from observations to provide boundary conditions. As no such data is available for an extreme event, we will describe how these were modelled. Our results show that radial diffusion transports the multi-MeV electrons left in the slot region by the shock into the inner belt. The enhanced inner belt will then persist for months, posing a risk to satellites orbiting in this region. During the days after the initial storm, the outer radiation belt rebuilds and we show that the acceleration of low energy electrons by chorus waves, rather than inward radial diffusion, is the main mechanism for this is.

Date: Thursday, November 05, 2026

Session Info: MIT3: RADIATION BELTS AND PLASMA IN THE MAGNETOSPHERE

ESTIMATING THE OCCURRENCE CONDITIONS OF EMIC WAVES USING DUAL-RBSP OBSERVATIONS

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Electromagnetic ion cyclotron (EMIC) waves play an important role in energetic particle scattering and loss in the inner magnetosphere, thereby influencing radiation belt dynamics and space weather processes. In this study, we use magnetic field observations from the Van Allen Probes (RBSP-A and RBSP-B) to investigate the occurrence of EMIC waves in the inner magnetosphere. By exploiting simultaneous observations from two spacecraft at varying separations in L-MLT space, we use the co-occurrence of EMIC wave detections to infer the spatial scales of EMIC wave activity. Based on this approach, we construct an independent climatological distribution of EMIC wave occurrence in the inner magnetosphere and estimate their overall occurrence rate within the geostationary orbit region. We also examine the dependence of EMIC wave occurrence on upstream solar wind parameters and geomagnetic activity indices. The results indicate that solar wind dynamic pressure and the SME index exert the strongest influence on EMIC wave occurrence, highlighting the combined roles of external solar wind driving and substorm-related energy input. These results provide a useful observational basis for improving empirical modeling of EMIC wave occurrence and for understanding their coupling with solar wind-magnetosphere-ionosphere dynamics.

Date: Thursday, November 05, 2026

Session Info: MIT3: RADIATION BELTS AND PLASMA IN THE MAGNETOSPHERE

NEW APPROACHES CALCULATING RADIAL, PITCH ANGLE DIFFUSION COEFFICIENTS IDENTIFY DOMINANT MECHANISMS RESPONSIBLE ELECTRON FLUX ENHANCEMENT PATTERNS INOUTERRADIATIONBELTUNDERCOMPLEX SOLAR WIND STRUCTURES

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The solar photosphere produces various solar structures, such as Coronal Mass Ejections - CMEs and High-Speed Solar Wind Streams - HSSs, which can propagate toward Earth and interact in the interplanetary medium, forming complex solar wind structures. In this study, we focus on events composed of two identical solar wind structures, specifically those formed by two CMEs or two HSSs. While the coupling between a single ICME or HSS and the Earth's magnetosphere, as well as its impact on electron flux variability in the outer radiation belt, is relatively well understood, the effects of complex solar wind structures remain insufficiently explored, particularly regarding outer radiation belt dynamics. This work uses the solar wind parameters measured at L1 Lagrangian point to identify the main characteristics of each complex solar wind structure, especially in terms of velocity components and the energy transport, which exhibit markedly different behaviors. In the inner magnetosphere, in situ measurements of high-energy electron flux and magnetospheric waves, such as ultra-low frequency (ULF) and whistler-mode chorus waves, together with calculations of radial and pitch angle diffusion coefficients, indicate that these processes respond differently during electron flux enhancements driven by each type of complex structure. We explicitly compare how the different solar wind drivers modulate energy transfer, wave activity, and diffusion processes, thereby governing the dynamic response of the outer radiation belt. These results demonstrate that the coupling between complex solar wind structures and outer radiation belt dynamics depends on the specific type of solar structures composing the event, as their intrinsic properties differ substantially. Furthermore, our findings suggest that empirical models used to calculate radial and pitch angle diffusion coefficients may require refinement to account for the distinct characteristics of different complex solar wind drivers.

Date: Thursday, November 05, 2026

Session Info: IOM2: SPACE WEATHER MISSIONS - FROM SCIENCE TO OPERATIONS

PROTON BELT DYNAMICS FOLLOWING THE MAY 2024 GEOSPACE MAGNETIC SUPERSTORM

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In May 2024, a massive sunspot region produced a series of intense solar flares and coronal mass ejections. This resulted in an extreme G5 geomagnetic storm, the largest to hit Earth in two decades, which coincided with a significant solar radiation storm (solar proton event). As a result, the May 2024 superstorm led to a pronounced enhancement of proton fluxes in Earth's inner radiation belt. In this study, we utilize the Sentinel-6 Michael Freilich Level 1 Version 1 Proton Differential Flux Dataset in the 5-73 MeV energy range to investigate the proton radiation belt response following the storm. We quantify storm-time flux enhancements and characterize the evolution of the radiation belt through estimates of decay rates as a function of energy and L-shell. Radial transport processes are examined through the first adiabatic invariant (μ), providing insight into the governing particle dynamics. The results indicate that storm-time injections populated the outer regions of the inner magnetosphere, followed by inward radial diffusion and adiabatic acceleration. We investigate phase space density (PSD) profiles in combination with radial diffusion simulations, to verify the aforementioned results. These findings improve our understanding of the dynamics of the outer edge of the inner radiation belt in response to extreme geomagnetic activity and proton injections from SEPs.

Date: Thursday, November 05, 2026

Session Info: SWI: SW EFFECTS ON INFRASTRUCTURE - ADVANCES IN THE ASSESSMENT OF GEOMAGNETICALLY INDUCED CURRENTS AND GROUND GEOELECTRIC FIELDS

SPACE WEATHER IMPACT ON GROUND INFRASTRUCTURES PROJECT

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The Space Weather Impact on Ground Infrastructures project is the result of a collaboration between the Grenoble University Space Center (CSUG), the UGA Foundation, AXA XL insurance, the AXA Research Fund, and the G2ELAB (Grenoble Electrical Engineering) laboratory. This project is funded by AXA Research Fund and AXA XL, in the context of the Joint Research Initiatives set up by AXA Research Fund.
This two-year project (2024-2026) aims to better understand the impact of space weather on ground infrastructure, and more specifically on power grids, pipelines, rail networks, and submarine cables affected by geomagnetically induced currents (GICs). The aim of this project is to raise awareness of these risks among AXA's various customers and society as a whole, highlighting technical and financial impacts through various activity sectors. It also highlights the interdependence of sectors and cascade risks.
In this context, an operational model of geomagnetically induced currents (GIC) in power grids is being developed, based on our understanding of the available literature combined with G2ELAB's expertise in electrical engineering. This presentation will outline the development of this model, which enables the calculation of GIC in a power line or grid using data from magnetometers. Furthermore, based on a statistical study of the frequency of occurrence of dB/dt data per cycle, as well as the correlation between dB/dt and GICs (max dB/dt --> max GIC), we can construct GIC vs probability of occurrence diagrams for a given power line.
This presentation aims to share the progress of our work with the community, as well as our current thoughts and the difficulties we have encountered.

Date: Thursday, November 05, 2026

Session Info: SWI: SW EFFECTS ON INFRASTRUCTURE - ADVANCES IN THE ASSESSMENT OF GEOMAGNETICALLY INDUCED CURRENTS AND GROUND GEOELECTRIC FIELDS

GEOMAGNETICALLY INDUCED CURRENTS DURING THE SSC OF THE OCTOBER 2024 GEOMAGNETIC STORM IN EUROPE.

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Geomagnetically induced currents (GIC) are electrical currents caused by variations of the geomagnetic field due to space weather phenomena. These currents can affect numerous infrastructures, such as pipelines and power grids, becoming particularly hazardous during magnetic storms.

This study investigates the Storm Sudden Commencement of the October 2024 magnetic storm by analyzing solar wind data from WIND, ARTEMIS, and GOES satellites, alongside ground-based magnetometer data from the European quasi-Meridional Magnetometer Array (EMMA) network. We reconstructed the interplanetary shock's normal and the Earth's magnetosphere state thanks to the TS04 and Shue et al. model. Magnetospheric-ionospheric currents were evaluated and the geoelectric surface field was estimated to compute GIC magnitudes using the MAIGIC model (Piersanti et al., 2019).

This research contributes to understanding how GIC are coupled with interplanetary shocks and when such phenomena can pose significant risks to modern technology.

Date: Thursday, November 05, 2026

Session Info: SWI: SW EFFECTS ON INFRASTRUCTURE - ADVANCES IN THE ASSESSMENT OF GEOMAGNETICALLY INDUCED CURRENTS AND GROUND GEOELECTRIC FIELDS

COMPUTING LARGE GEOELECTRIC FIELDS IN THE UK: A 43-YEAR EXTREME VALUE ANALYSIS

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Rapid geomagnetic field variations induced by solar activity generate large geoelectric fields at Earth's surface, posing significant risks to critical grounded infrastructure. High-voltage power transformers are potentially vulnerable to damage from geomagnetically induced currents (GICs). Utilizing recent magnetotelluric (MT) surveys combined with legacy measurements for 68 sites across the island of Britain, we model continuous geoelectric field time series at these location for the past 43 years. We derive the geoelectric field by convolving 1-minute cadence magnetometer data at three UK observatories (1983-present) with MT impedances at each location spanning the digital era of geomagnetic data.

Using extreme value statistics, we present 100-year return value estimates revealing very strong spatial variability across Britain driven by the local geoelectrical response due to geology. The highest estimated 100-year geoelectric fields are found in Northern England and Southern Scotland (54-56N), with values modelled in West Yorkshire as large as 13.57 V/km, which far exceeds those from Lerwick, Shetland at the most northerly latitude (4.35 V/km, ~60N). We benchmark these estimated return values against those measured in significant geomagnetic storms such as the March 1989 event and the more recent May 2024. These results highlight the importance of including the local electrical conductivity structure in determining the geoelectric hazard, and the value of dense MT surveying for accurate space weather impact assessment.

Date: Thursday, November 05, 2026

Session Info: SWI: SW EFFECTS ON INFRASTRUCTURE - ADVANCES IN THE ASSESSMENT OF GEOMAGNETICALLY INDUCED CURRENTS AND GROUND GEOELECTRIC FIELDS

GEOELECTRIC FIELDS IN SOUTHWESTERN CANADA DURING SEPTEMBER 2017: A COMPARISON OF DIRECT MEASUREMENTS, DATA-SPACE PREDICTIONS, AND MODEL-SPACE PREDICTIONS

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Long-period magnetotelluric (MT) data collected at 7 sites in SW Canada in 2017 were used to investigate geoelectric fields during a 13-day period which included the strong geomagnetic storm on Sept 8. Data from 5 variometers surrounding the MT survey area were used to conduct a leave-one-out analysis of magnetic field interpolation. Interpolations at the 7 MT locations were validated using the measured MT data, then they were used to predict geoelectric fields using the MT data-space method, 3D model-space method and 1D model-space method. These predictions were compared to the simultaneous MT measurements. The 3D method outperformed the 1D method. Following validation at the 7 primary MT sites, geoelectric fields were estimated at 31 secondary MT sites nearby.

Nine sites (2 primary and 7 secondary) had peak geoelectric field magnitudes > 2 V/km, all at ~14:04 UT on Sept 8. At 7 of these 9 sites, geoelectric field magnitudes > 1 V/km were sustained continuously for 2-6 minutes. GIC prediction is beyond the scope of this study, but we note that a series of 230 kV transmission lines connect substations near 4 population centres within the study area.

Analysis of geoelectric field directions revealed consistent polarization at each of the 38 MT locations, but with a range of directions from site to site, suggesting an important role of 3D subsurface conductivity. Analysis of magnetic local time (MLT) bins revealed unidirectionality dependent on MLT at many sites. E.g., the field was more likely to be W-directed at 01:00-07:00 and E-directed at 17:00-23:00. Peak geoelectric field magnitudes occurred on the dawn flank; their directions were mostly between W and N.

It is rare for 7 MT data loggers and 5 nearby variometers to be recording simultaneously during a major geomagnetic storm, such as the one on Sept 8, 2017. This unique dataset allowed a novel investigation of data usage and data limitations, regarding magnetic field interpolation and geoelectric field prediction.

Date: Thursday, November 05, 2026

Session Info: SWI: SW EFFECTS ON INFRASTRUCTURE - ADVANCES IN THE ASSESSMENT OF GEOMAGNETICALLY INDUCED CURRENTS AND GROUND GEOELECTRIC FIELDS

ASSESSING THE IMPACT OF GEOMAGNETICALLY INDUCED CURRENTS ON HIGH VOLTAGE POWER TRANSMISSION SYSTEMS THROUGH HARMONIC DISTORTION MEASUREMENTS MADE IN NEW ZEALAND, UK, AND CANADA

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Geomagnetic disturbances can result in geomagnetically induced currents (GIC) flowing in electrical power grids. Quasi-DC GIC can lead to asymmetric half cycle saturation in transformer cores. The observation of even-order harmonic distortion is a key indicator of GIC-induced transformer saturation, and recent publications have advanced our knowledge of the value of such measurements. GIC threshold levels (also known as 'headroom'), at which transformers begin to experience half cycle saturation, are dependent on the transformer type and design. The responsiveness to increasing GIC levels is also dependent on operational voltage. Even-order harmonic distortion observations can be used to infer both the headroom and response gradient.

Much of the high time resolution analysis of GIC-induced harmonic distortion data has come from very low frequency (VLF) measurements made close to the Halfway Bush substation in Dunedin, New Zealand working with the power grid operator, Transpower New Zealand Ltd. Supporting measurements made with lower time resolution have come from Transpower power quality meters located within the substation. Grid-wide power quality meter data has allowed regional analysis of harmonic hotspots in New Zealand.

Here we extend the New Zealand harmonic analysis to measurements made in Glasgow, Scotland by Scottish Power Energy Networks, and in Ottawa, Ontario by Natural Resources Canada (NRCan). We focus on the two large geomagnetic disturbances that occurred in 2024, where enhancements of even-order harmonic intensity were observed at all three locations. Local neutral DC current measurements are also presented. Scottish Power measurements were supplemented by very high time resolution reactive power observations made during the storm sudden commencement on 10 October 2024. NRCan measurements of even-order harmonic distortion during the May 2024 Gannon Storm are compared with local magnetic field perturbations in the absence of supporting local GIC.

Date: Thursday, November 05, 2026

Session Info: SWI: SW EFFECTS ON INFRASTRUCTURE - ADVANCES IN THE ASSESSMENT OF GEOMAGNETICALLY INDUCED CURRENTS AND GROUND GEOELECTRIC FIELDS

OBSERVING GEOMAGNETICALLY INDUCED CURRENTS IN THE MEXICAN POWER GRID DURING THE MAY 2024 EXTREME STORM

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On May 10, 2024, an extreme geomagnetic storm lasting approximately 40 hours, affected the Mexican power grid. The storm was monitored in real time at three locations using the REGMEX magnetometer network, where horizontal component variations exceeded -400 nT and local K = 9. Fluctuations were so intense that the automatized algorithm considered them as data gaps. Notably, red aurora borealis were sighted as far south as magnetic latitude ~30N over northern Mexico. For the first time, direct measurements of geomagnetically induced currents (GIC) during an extreme geomagnetic storm were obtained from GIC sensors installed at four substations of the Mexican power grid, through a collaborative effort between the National Space Weather Laboratory and the Federal Electricity Commission (CFE). The recorded GIC data, reaching up to 40 A, reveal previously unknown vulnerabilities in the power system and provide critical benchmarks for risk assessment in low-latitude regions typically considered less susceptible to space weather effects.

Date: Thursday, November 05, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

ROPE: A REDUCED-ORDER PROBABILISTIC EMULATOR FOR FAST AND UNCERTAINTY-AWARE HIGH-FIDELITY THERMOSPHERIC DENSITY EMULATION

Daniele Sicoli [1], Anirudh Tapedia [1], Sriram Narayanan [1], Piyush Mehta [1], David Vallado [2]

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In the last 10 years the interest of operators in sending satellites to low Earth orbit (LEO) has risen and the overall value of LEO assets is expected to go from $630 billion in 2023 to $1.8 trillion by 2035. Thus, high fidelity orbit determination of LEO assets and debris, and real-time intelligent maneuvering has become of primary interest for stakeholders.
The largest source of uncertainty for operators in LEO is thermospheric density, which is highly nonlinear due to the Sun's activity. The two main alternatives used by the community to address the challenge are physics-based models (TIEGCM, WAM), which are high fidelity models with high computational cost and with which doing uncertainty quantification is challenging, and empirical models (MSIS), with lower computational cost, lower fidelity and no uncertainty quantification coming along naturally. There is a third alternative given by HASDM, which is limited in use to DOD and the U.S. Space Force.
To address the LEO challenge, we have built a Reduced-Order Probabilistic Emulator (ROPE) framework, a data-driven complement to physics-based and empirical models for high fidelity emulation with uncertainty quantification.
ROPE outputs have been compared to SLR CPF reference orbits, a gold standard truth source for orbital position: the models outperformed MSIS, and preliminary results indicate that ROPE can outperform HASDM.
ROPE is a data-driven framework compressing global three-dimensional density fields into a compact latent representation using various encoding methods preserving essential structures and variability.
To further enhance robustness and generalization, and to better capture geomagnetically active intervals, ROPE employs a neural-network-based meta-modeling framework. Complementary to the data-driven framework based on Physics-Based models, we leverage Data Assimilation to retrain using observationally informed latent states containing the physics that measurements incorporated.

Date: Thursday, November 05, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

MONTE CARLO SIMULATION OF THE RADIATION DOSE ABOARD ORION DURING ARTEMIS I: A CDF-BASED EQUIVALENT SHIELDING METHODOLOGY

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As human space exploration moves beyond Low Earth Orbit, accurate assessment of the radiation environment becomes increasingly critical for astronaut safety. Future crewed missions to the Moon and Mars will expose astronauts to prolonged radiation from Galactic Cosmic Rays (GCRs) and trapped particles in the Van Allen belts, demanding reliable predictive tools and validated simulation frameworks.
In this context, the Artemis I mission offers a unique validation opportunity: the Orion capsule carried radiation dosimeters along a translunar trajectory, providing flight measurements against which models can be benchmarked. This work presents an end-to-end Monte Carlo simulation workflow to estimate the radiation dose received by the HERA dosimeter aboard Orion. The pipeline integrates AP9/AE9 trapped particle models and GCR spectra, modulated for geomagnetic cutoff rigidity and Earth shadowing, with Geant4 transport, including a normalization procedure to convert simulated energy deposition into time-dependent dose rates along the trajectory.
Since no detailed geometric model of Orion was publicly available, radiation transport is performed using an equivalent spherical aluminium shielding derived from the areal density distribution of the HERA dosimeter environment. Dose-rate profiles and cumulative dose values are compared with published flight measurements, showing good overall agreement and providing a quantitative assessment of the capabilities and limitations of this approach across different mission phases.
Beyond the flight data comparison, the simulation chain produces a species- and energy-resolved dose response function for the HERA dosimeter, allowing rapid dose estimation for future translunar scenarios without repeating the full simulation chain. The work contributes to the broader effort of validating space radiation models for early mission design and radiation risk evaluation for future crewed deep-space exploration.

Date: Thursday, November 05, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

DEMONSTRATING THE OPERATIONAL VALUE OF SWE SERVICES: A NEW TOOL TO QUANTIFY THE IMPACT OF A SPACE WEATHER EVENT OVER THE EU ECONOMY

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The domain of Space Weather has a clear direct social and economic impact on the lives of our citizens and affects multiple interconnected sectors. However, quantifying the impact of space weather events remains a critical challenge for justifying space weather research and forecasting services. While community recognizes space weather influence on modern infrastructure, entities with exposed systems remain naturally unwilling to disclose operational vulnerabilities, creating a significant knowledge gap. To bridge this gap, we developed a computer model that provides the socio-economic impact of a space weather event on the most vulnerable sectors of the EU economy (power supply, spacecraft operations, telecommunications, aviation, etc.). This model is based on results provided by a large-scale consultation (lead by PwC France, coordinated by ESA and funded by the European Commission) and has been refined by the ESA Space Weather Office to provide realistic economic projections. It accounts for event severity and forecasting service availability, allowing a direct comparison of scenarios with and without forecasting services, showing how space weather early warnings can reduce economic impact with metrics that stakeholders understand and value. This tool can also be used to justify research plans and consequently help towards ESA long-term strategy for transitioning research activities into operational services. Here we present the first results, along with an overview of the underlying logic, and invite community expertise to validate assumptions and improve model justifications.

Date: Thursday, November 05, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

SPACE WEATHER CAPABILITIES ASSESSMENT AT DIFFERENT STAGES OF THE RESEARCH-TO-OPERATIONS TRANSITION PIPELINE

Maria Kuznetsova [1], Martin Reiss [1], Edmund Henley [2], Leila Mays [1], Jia Yue [1], Jack Wang [1], Lutz Rastaetter [1]

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The presentation will discuss recommendations on space weather capabilities assessment and transition to operations from the recently published COSPAR Space Weather Roadmap. We will present examples of validation projects at different stages of the research to operations (R2O) transition pipeline and highlight model validation platforms maintained by the Community Coordinated Modeling Center (CCMC) to support like-for-like comparisons and to track progress in performance and operational readiness level over time.

Date: Thursday, November 05, 2026

Session Info: OTH1 OTH1.01: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

VALIDATION OF ICAO SPACE WEATHER ADVISORIES FOR AVIATION: FROM GLOBAL PATTERNS TO THE ICELAND HF CASE STUDY

Judith De Patoul [1], Yana Maneva [1], Elisabeth Dom [1], Dimitrios Millas [1], Daria Shukhobods [1], Tobias Verhulst [2]

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ICAO space weather advisories provide operational information to aviation users on HF communication degradation, GNSS degradation, and radiation environment enhancement. As these products are used to support operational decision-making, their validation must assess whether they reflect physically meaningful conditions and provide reliable information for aviation users.

Based on a first global exploratory analysis of ICAO advisories from November 2019 to September 2025, we will examine whether advisory occurrence is consistent with broad space weather behaviour, including Solar Cycle 25 evolution, major disturbed periods, seasonal enhancement around the equinoxes, and the expected geographic distribution of GNSS and HF COM impacts. This provides a first physical credibility check, while also showing why advisory volumes and centre-to-centre differences cannot be interpreted as performance metrics without a proper validation framework.

Based on recorded HF communication conditions over Iceland, we will then discuss a regional validation case study. We will assess the role of timing, duration, regional filtering, and spatial scale by comparing HF condition reports with ICAO HF advisory chains and space weather drivers, including proton flux, geomagnetic activity, X-class flares, and daylight conditions.

Using the Iceland case, we will discuss what an operational validation framework should include: false alerts, missed local impacts, geographically broad advisories, user-relevant regions, uncertainty, and feedback from operational outcomes. The contribution frames ICAO advisories as a successful R2O achievement, while emphasizing the need to close the O2R loop through systematic validation and user-centred metrics.

Date: Thursday, November 05, 2026

Session Info: SCL1 LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS

VALIDATING THE ESPERTA MODEL FOR FORECASTING SOLAR ENERGETIC PARTICLES AT OFF-EARTH LOCATIONS

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Solar flares and shocks driven by Coronal Mass Ejections (CMEs) are major accelerators of Solar Energetic Particles (SEPs) that interact with planetary environments and our technological infrastructure, posing space weather hazards. Critical in our ability to assess and mitigate the impacts of space weather is the development and/or upgrade of reliable SEP forecasting models. ESPERTA (Empirical model for Solar Proton Events Real Time Alert) is an empirical model that provides the yes/no occurrence of an SEP event by simply using the longitude of the flare, the fluence of the flare's soft X-ray emissions, and the fluence of solar radio bursts. To this date, the radio measurements used for the ESPERTA model were obtained from ground- and space-based detectors only at Earth's location. In this work, we incorporate radio measurements from the solar-orbiting STEREO spacecraft into ESPERTA, and compare the results at different longitudes to that of Earth with the results from near-Earth measurements. We evaluate the ability to exploit radio data as a reliable short-term warning of SEP events onboard spacecraft at any longitude, a crucial requirement for the protection of spacecraft cruising the heliosphere and wider space exploration. We also confirm that solar radio measurements are useful diagnostic tools for SEP events and thus for space weather forecasting models.

Date: Friday, November 06, 2026

Session Info: SCL1: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS

TEMPORAL EVOLUTION OF BIPOLAR MAGNETIC REGIONS: SUPPORT OF THIN FLUX TUBE MODEL

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The solar convection zone is characterized by the birth of the concentrated magnetic field regions known as Bipolar Magnetic Regions (BMRs), which are tilted with respect to the equatorial line.
These regions are key drivers of solar magnetic activity and play an important role in shaping space weather, influencing the heliospheric environment. The thin flux tube model, employing the rising of magnetically buoyant flux loops tilted by the Coriolis force, is a popular paradigm to explain the formation of the tilted BMRs. In this study, we assess the validity of the thin-flux tube model by analyzing the tracked BMR data obtained through the Automatic Tracking Algorithm for BMRs (AutoTAB). Our observations reveal that the tracked BMRs exhibit the expected collective behaviors, and the polarity separations of BMRs increase over their lifetimes, supporting the assumption of the rising omega-shaped flux tubes from the CZ. Furthermore, we observe an increasing trend of the mean tilt with the flux of the BMR, suggesting that rising flux tubes associated with lower flux regions are primarily influenced by the drag force and the Coriolis force, while in higher flux regions, magnetic buoyancy dominates. Additionally, we observe Joy's law dependence in the tilts of the emerging BMRs from their early emergence, indicating that the tilts in the BMRs are formed below the photosphere, and the tilts observed in BMRs can be attributed to the Coriolis force. Thus, all these results support the thin-flux tube model.

Date: Friday, November 06, 2026

Session Info: SCL1: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS

CONSTRAINING SOLAR CYCLE VARIABILITIES WITH ENSEMBLE FLUX TRANSPORT MODELING

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Predicting the strength of future solar cycles remains one of the longstanding challenges in solar physics. The growing societal reliance of modern technological systems including space-based infrastructure has significantly increased the need for accurate and early predictions of solar activity. Although several precursor methods exist for predicting the amplitude of an upcoming cycle, robust estimates often require waiting until the declining phase or minimum of the current cycle, when the polar magnetic field becomes a reliable predictor. Surface Flux Transport (SFT) models provide a promising pathway for earlier predictions by simulating the evolution of the Sun's large-scale magnetic field and forecasting the polar field years before solar minimum. Early prediction capability is particularly valuable for strategic planning of space missions and mitigation of space weather risks. In this work, we combine the Advective Flux Transport (AFT) model with a statistical Synthetic Active Region Generator (SARG) to perform ensemble simulations of past solar cycles. Using constraints derived from these simulations, we carry out a global sensitivity analysis of the coupled AFT+SARG framework. This approach enables probabilistic solar cycle modeling with quantified uncertainties. The insights obtained from this analysis are then used to develop forecasts for Solar Cycle 26.

Date: Friday, November 06, 2026

Session Info: SCL1: LONG-TERM SOLAR VARIABILITY: OBSERVATIONS, PROXIES, AND MODELS

RECONSTRUCTING THE GROUP SUNSPOT NUMBER WITHOUT THE NEED FOR INTERCALIBRATING OBSERVERS

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The group sunspot number is a key quantity for reconstructing past solar activity over daily to centennial time scales. However, the present record is based on a large set of heterogeneous data, collected by observers who often did not count sunspot groups in the same way. For this reason, one of the major challenges lies in intercalibrating the different observers, which is a necessary step before the various data records can be merged to produce one single composite sunspot number record. The FARSUN project precisely aims at producing a new version of that composite.

Here, we present a new approach that bypasses the need for intercalibration, as well as avoiding the artificial introduction of 'backbone' observers to stitch records together. First, we combine partly overlapping records by using a statistical method called expectation maximisation. The second novelty is the use of rank order statistics to eliminate the need for intercalibration.

Tests performed with synthetic data confirm the robustness of the method. We apply the method to real data and propose a new reconstruction of the group sunspot number, for which the exact spot-to-observer scaling can now be freely determined.

Date: Friday, November 06, 2026

Session Info: PL1 - INSIGHTS FROM AN OPERATIONAL PERSPECTIVE: CHALLENGES AND LESSONS LEARNED FROM SEVERE EVENTS IN SOLAR CYCLE 25

A NEW DECLINING PHASE PRECURSOR IN THE SUNSPOT NUMBER RECORD AND AN EARLY PREDICTION FOR CYCLE 26 MAXIMUM

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The overall level of solar activity as seen in the sunspot number (SSN) record paces both the state of the ionosphere and the amplitude and occurrence rates of extreme space weather events. SSN predictions on solar cycle timescales are problematic given the variability in cycle amplitude and duration. The Hilbert transform of 13 month smoothed SSN since 1749 is used to construct a uniform clock for the Schwabe solar cycle which establishes a clear switch-on and off of geomagnetic activity seen at earth and which correlates with long-timescale solar cycle morphology. Here [1], cycle SSN maxima are shown to correlate with the SSN at the switch-off of the preceding cycle. The switch-off is found to occur when solar eruptions change in character from coronal mass ejections to high speed streams, correlating both with the sunspot active regions moving to lower solar latitudes with reduced differential rotation, and the switch-off of extreme space weather at earth [2]. This correlation between the SSN and the following SSN maximum provides a method for predicting the upcoming cycle maximum on a 6-7 years time horizon. The maxima of solar cycles 1-25 are hindcasted with ~ 7 year lead time with good fidelity by this method with coefficient of determination r2 >0.7 and Pearson correlation rho>0.8. Projecting the current SSN forward to the switch-off of cycle 25 gives an early prediction of a moderate upcoming cycle 26 maximum, of intensity less than, or of order, cycle 25. A more precise prediction will be possible in 2.5-3.5 years when the switch-off of cycle 25 will occur.

[1] S. C. Chapman, A new declining phase precursor and an early prediction of cycle 26 maximum, Ap. J. in press (2026)
[2] S. C. Chapman, T. Dudok de Wit, A solar cycle clock for extreme space weather. Sci Rep 14, 8249 (2024). doi:10.1038/s41598-024-58960-5

Date: Friday, November 06, 2026

Session Info: PL2 - THE FUTURE OF SPACE WEATHER PREDICTION: INTEGRATING ARTIFICIAL INTELLIGENCE, PHYSICAL MODELS, DATA AND OPERATIONS

THE VIGIL MISSION AND A PATHWAY TO AI/ML OPERATIONAL CAPABILITY

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The ESA Vigil mission, planned for launch to the Sun-Earth L5 point in 2031, will provide a new operational perspective for monitoring solar activity and forecasting space weather at Earth. Beyond its operational objectives, Vigil also provides an opportunity to establish a long-term roadmap toward the use of artificial intelligence and machine learning (AI/ML) systems in future heliophysics and operational space-weather missions.

This presentation will introduce the Vigil mission and its payloads, highlighting how the mission's multi-instrument observations may support future AI/ML applications for both scientific and operational use cases. A phased pathway toward AI-enabled operational capability will then be outlined, beginning with the identification of operational and scientific needs, followed by the development of ground-based AI/ML tools using multi-mission datasets and synthetic proxy observations derived from existing assets, including Solar Orbiter, STEREO, and Earth-based observatories, as well as synthetic datasets.

These datasets can be used prior to launch to develop and validate forecasting tools, event-detection algorithms, and operational support systems. Initially, such AI/ML capabilities are expected to support ground-segment operations and space-weather forecasting activities, including event identification, calibration scheduling, event tracking, and data prioritisation. Through an R2O2R framework, successful ground-based implementations may later mature toward onboard applications, where autonomous systems could support adaptive observing strategies, telemetry prioritisation, and onboard forecasting support.

The presentation will discuss how multi-instrument/mission data integration, operational requirements, and phased AI development strategies can provide a realistic pathway toward increased onboard autonomy in future operational space-weather missions.

Date: Friday, November 06, 2026

Session Info: PL2 - THE FUTURE OF SPACE WEATHER PREDICTION: INTEGRATING ARTIFICIAL INTELLIGENCE, PHYSICAL MODELS, DATA AND OPERATIONS

TEN YEARS OF MACHINE LEARNING IN SPACE WEATHER: SUCCESSES, CHALLENGES, AND FUTURE PERSPECTIVE

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Exactly ten years ago, at the 13th ESWW, a new session entitled Machine Learning and Statistical Inference Techniques was introduced. At the time, the session description noted that 'the ease of accessing and processing large volumes of data makes these techniques very attractive for the space weather community.'

Since then, machine learning and AI have evolved rapidly and are beginning to reshape the way we conduct and think about science. Some refer to AI as the fourth pillar of the scientific method.
Today, many of the most accurate forecasting approaches are fundamentally data-driven. This makes it an opportune moment to reflect not only on the progress achieved over the past decade, but also on the challenges and opportunities that lie ahead.

In this talk, I will present a personal and, inevitably, biased perspective, while striving to remain grounded in scientific rigour and evidence. Topics intended to stimulate discussion for the subsequent panel will include: the widening gap between space weather and AI-driven terrestrial weather forecasting; the major unresolved questions limiting progress in AI-based space weather; and an appreciation of the unsung hero behind the machine learning revolution - automatic differentiation - together with how our heavily physics-based community can better exploit its potential.

Date: Friday, November 06, 2026

Session Info: IOM1 PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

PREPARING FOR THE L5 PHOTOSPHERIC MAGNETIC FIELD OBSERVATIONS TO IMPROVE SPACE WEATHER MODELING AND PREDICTIONS AT NOAA

Nai -Yu Wang [1], Andrew R. Marble [2,3], Eric Adamson [3], Mark Miesch [2,3], Alessandra Pacini [3], Carl J. Henney [4], Samuel J. Schonfeld [4], Sara Housseal [3,5]

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The sun's photospheric magnetic field drives models of solar corona magnetic field, ambient solar wind, and the interplanetary magnetic field (IMF) polarity. Recent studies show integrating far-side magnetic field data from the Solar Orbiter Polarimetric and Helioseismic Imager (SO/PHI) with near-side observations from the Solar Dynamics Observatory Helioseismic and Magnetic Imager (SDO/HMI) and the Global Oscillation Network Group (GONG) significantly improves the accuracy of global magnetic field maps, solar wind modeling and Coronal Mass Ejection (CME) propagation. The European Space Agency (ESA) Vigil Mission to Lagrange 5 (L5) is designed to provide a side view of the Sun from 60 degrees behind Earth. This additional vantage point acts as an early warning system, allowing forecasters to see active regions before they rotate into view from Earth, and an alternate view for disambiguating CMEs. The Photospheric Magnetic Field Imager (PMI) on the Vigil provides continuous, real-time magnetic field mapping of the Sun's east limb. Data assimilative models like ADAPT (Air Force Data Assimilative Photospheric flux Transport) enable the ingestion of these magnetograms and blend them with earth-facing data. This presentation highlights NOAA's current uses of magnetograms and the plans for the future Vigil mission magnetogram data to improve space weather modeling and forecasting.

Date: Friday, November 06, 2026

Session Info: IOM1: PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

COMBINING VIGIL WITH SUB-L1 MISSIONS ON DISTANT RETROGRADE ORBITS

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As a potential further extension to interplanetary space weather forecasting missions after Vigil, there is currently a rising interest in spacecraft on distant retrograde orbits (DRO). With these orbits, spacecraft can be temporarily placed at a position near the Sun-Earth line, but closer to the Sun than the L1 point. Such upstream in situ observations of the solar wind and coronal mass ejections may strongly extend forecast lead times, as knowledge of the southward magnetic field component Bz < 0 field is a decisive factor for forecasting geomagnetic storm intensity.
The ESA HENON mission is the first on a DRO and soon being launched (2027-). ESA is currently studying a fleet of spacecraft called SHIELD to provide sub-L1 data after Vigil (2031-). Given our current inability to remotely determine the magnetic structure of interplanetary coronal mass ejections, there have been some promising results that indicate the possibility for solving the problem of predicting Bz < 0 intervals with upstream in situ data.
We present an overview of observations made and lessons learned from sub-L1 (> 0.72 au) and far upstream observations (< 0.72 au), mainly from Solar Orbiter and STEREO-A. We determine which types of physics we need to understand better and which gaps to fill, by using an R2O2R approach, in order to optimally use HENON and SHIELD data for enhanced forecasts. We present some first ideas on how a space weather forecasting pipeline with Vigil, sub-L1 and L1 data may look like. With these missions, highly accurate space weather forecasts with strongly enhanced lead times could become reality.

Date: Friday, November 06, 2026

Session Info: IOM1: PREPARING FOR L5 AND BEYOND: OPERATIONAL AND SCIENTIFIC READINESS FOR THE ESA VIGIL MISSION AND FUTURE HELIOSPHERIC OBSERVATIONS

SUPPORTING SPACE WEATHER WITH NANOSATELLITES: THE ITALIAN SPACE AGENCY CONTRIBUTION

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Modern nanosatellites are increasingly capable platforms, incorporating advanced technologies that enable dedicated measurements and new observation concepts, complementing those provided by larger and more traditional space missions such as Vigil. The Italian Space Agency (ASI) is supporting a growing portfolio of nanosatellite missions addressing space weather through both national activities and ESA programmes. This contribution will present three missions, originally selected through the ASI ALCOR program, and currently under development: the CUbesat Solar Polarimeter (CUSP) and Sun CubE OnE (SEE) missions, developed at national level, and HEliospheric pioNeer for sOlar and interplanetary threats defeNce (HENON) mission, developed in the framework of ESA's General Support Technology Programme. The three missions address different aspects of the Sun-Earth environment, combining remote observations of solar activity with in-situ measurements of the solar wind, energetic particles and interplanetary magnetic field. Beyond their individual scientific objectives, these missions provide examples of how nanosatellite platforms can enable dedicated measurements, innovative observation concepts and new vantage points, complementing larger space missions. The presentation will provide an overview of their objectives, current development status and programmatic context, highlighting ASI's approach to nanosatellites as an increasingly relevant element of space weather observation capabilities.

HENON will provide the first empirical assessment of the scientific return, data quality, instrumentation concepts, telemetry strategies, and operational value of in situ measurements in the DRO, including a region between L1 and L5 environment. HENON will also provide benchmark datasets for model validation (e.g.,for the propagation of the solar wind and coronal mass ejections) and data assimilation frameworks. Therefore, HENON acts as a critical scientific and methodological bridge, transforming the yet-unexplored DRO-L5 region into a validated observational domain that can contribute to maximizing the scientific and operational return of Vigil.

Date: Friday, November 06, 2026

Session Info: HEL3: RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

NOAA'S SPACE WEATHER OBSERVATIONS AT L1 TO ADVANCE READINESS (SOLAR) PROJECT

Yaireska Collado-Vega [1], Ashley Greeley [2], Irfan Azeem [1], James Spann [1], Erin Lynch [1], James Morrissey [2], John Panek [2], Charles Delee [1], Richard Marlow [1], Richard Ullman [1], Eugene Guerrero-Martin [2]

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The Space Weather Observations Office from the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS), is implementing operational missions that have the capability to provide critical low latency data. Low latency data are essential for the successful implementation of forecasting capabilities and safeguarding the Nation, including our satellites and human exploration endeavors. The first project part of the Space Weather Next program is the Space weather Observations at L1 to Advance Readiness (SOLAR) project, composed of two spacecraft, SOLAR-A and SOLAR-B, with SOLAR-A currently planned to be launched by 2029. The Space Weather Next (SW Next) program was designed and is being implemented to provide continuity of observations from different vantage points, including the Lagrange point 1 (L1), the Geostationary and Low Earth orbits, as well as Lagrange 5 (L5), in collaboration with the European Space Agency (ESA). The main objective of the SOLAR project, already in phase B, is to provide continuity of observations beyond the SOLAR-1 former Space Weather Follow On - Lagrange 1 (SWFO-L1) mission launched in September 2025 with a design life of five years. In this presentation, we will describe the observational requirements from the L1 vantage point, how the project is working to continue critical observations, a description of the instruments acquired, how we will work together with different missions in different vantage points, and how these observations will support the space weather operational environment to safeguard the Nation and to support government and commercial human exploration missions.

Date: Friday, November 06, 2026

Session Info: HEL3: RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

NEW INSIGHTS INTO CHROMOSPHERIC PROXIES FOR A PHYSICS-BASED FLARE FORECASTING MODEL WITH THE LARGE ITALIAN RADIO TELESCOPES

Sara Mulas [1], Alberto Pellizzoni [1], Marco Marongiu [1], Adriana Marcucci [2], Simona Righini [3], Giulia Murtas [4], Davide Napolitano [3]

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Solar flares and Coronal Mass Ejections (CMEs) are the most energetic phenomena in the Solar System. They greatly contribute to shaping the interplanetary medium and can cause serious hazards to human technologies. Predicting these events is particularly challenging, therefore a forecast system predicting them hours/days in advance is among the utmost goals of Space Weather research. Thanks to recently identified proxies through innovative high-frequency solar radio imaging, we are close to this goal.
Since 2018, high-frequency observations with the Italian network of large single-dish radio telescopes have resulted in ~600 solar images in K-band (18-26 GHz). Probing the Active Regions (ARs) at these frequencies reveals an emission associated with thermal free-free and an additional complex interaction between the plasma and the chromospheric magnetic fields. Anomalous spectral index values ($\alpha<1.5$) in the ARs brightness compared to pure free-free emission ($\alpha\sim2$) are associated with a steeper gyro-resonance component associated with enhanced magnetic fields up to 2000G and circular polarisation up to 40%.
In our work we demonstrated that the detection of AR spectral flattening implies a very high probability of a strong flare occurrence within 30 hours (89% statistical precision). With the inclusion of other relevant radio AR parameters, the precision improves up to 97%, proving a high reliability of our physics-based flare prediction method (Mulas et al. 2026 with a national INAF press release: www.media.inaf.it/2026/01/09/sundish-brillamenti-solari/). Our work also explores the possible coupling with photospheric elements, such as the magnetic complexity of the sunspots.
Our future goals are to corroborate this method with radio data of the solar maximum, find a synergy with other proxies in a multi-frequency approach, and integrate Deep Learning and AI models to further refine our method. We also intend to expand this work to include the forecast of CMEs.

Date: Friday, November 06, 2026

Session Info: HEL3: RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

PROBING THE CHARACTERISTICS OF A PRE-ERUPTIVE FLUX ROPE USING EUV AND RADIO DIAGNOSTICS

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Coronal Mass Ejections (CMEs) can cause large disturbances through their interaction with the Earth's magnetic field. Therefore, being able to tell when a CME will occur is a key aim of solar physics. To achieve this, we need to gain a complete understanding of the pre-eruptive magnetic configuration. Modelling of the pre-eruptive field suggests that there are sections of the structure not seen in soft X-ray and extreme ultraviolet (EUV) observations, likely as the density, and therefore emission, in these areas is too low to be seen. In order to study the full structure, observations at a wider range of wavelengths are required.
We present analysis of the formation and evolution of a pre-eruptive flux rope using both EUV and radio observations. The flux rope formed in AR 13590 on the 28th February 2024. Using radio imaging we found radio sources originating from altitudes between 0.34-0.47 R_s in the corona, above the diffuse EUV emission of the structure below. This work shows how a combination of EUV and radio imaging can give a more complete picture of the pre-eruptive magnetic field. These methods can be useful for CME forecasting as they allow features that affect the stability of a flux rope, such as the altitude, to be determined.

Date: Friday, November 06, 2026

Session Info: HEL3: RADIO INSTRUMENTS AND DIAGNOSTICS: FROM SOURCE REGIONS TO SPACE WEATHER APPLICATIONS

BEYOND TYPE III PRESENCE: RADIO MORPHOLOGY AS A DIAGNOSTIC OF HIGH-ENERGY SEP OCCURRENCE

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Type III radio bursts are widely used as signatures of escaping electrons, but for high-energy SEP events the question is not simply whether a burst was present. Major flares that do not lead to a near-Earth high-energy particle event can also be radio loud. We therefore ask whether the shape of the Type III emission, rather than its catalogue presence, carries information about which major flares are associated with high-energy SEP occurrence at Earth. We use an event-aligned, flare-conditioned comparison of major flares associated with near-Earth high-energy SEP occurrence and major-flare controls. The radio data are expressed as an event-specific excess over pre-flare background and summarized in broad frequency bands, so that the comparison focuses on persistence, contrast and time-frequency occupancy rather than absolute instrument level. We compare a flare-only reference, based on soft X-ray and geometric descriptors, with models that add low-frequency Type III morphology and radio-source products. The main finding is that low-frequency, post-peak Type III structure adds information beyond the flare description. It is most useful when interpreted as a measure of sustained electron escape and magnetic access into the heliosphere, not as a direct proxy for proton acceleration. Direction-finding, apparent source-size and localization products add a secondary layer, but their strongest value appears to come from the availability and stability of the radio source solution; we therefore treat them as product-level diagnostics rather than intrinsic source geometry.

Date: Friday, November 06, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

CHROMOSPHERE MODELING OF SOLAR ACTIVE REGIONS OBSERVED AT K-BAND FREQUENCIES USING INAF SINGLE-DISH RADIO TELESCOPES UNDER THE SUNDISH PROJECT

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Modeling the solar atmosphere at radio frequencies is essential for understanding the complex magnetic environments of active regions (ARs). By combining radiative transfer with magnetic field extrapolations and accounting for free-free and gyroresonance opacities, recent studies have significantly advanced our understanding of these regions (e.g. Selhorst et al. 2008; Pellizzoni et al. 2022; Oliveira e Silva et al. 2022; Marongiu et al. 2024), allowing for a detailed reconstruction of the thermodynamic and magnetic structure of the solar atmosphere, but the transition between the chromosphere and the corona remains a challenge. In this talk, we present a detailed modeling of AR total-intensity maps using high-resolution radio data from the SunDish project. We focus on observations in the under-explored K-band (18-26 GHz) using the INAF single-dish radio telescopes (Medicina 32-m and SRT 64-m). This work builds upon some ARs studied by Mulas et al. (2026), who analyzed their radio maps produced by the same radio telescopes up to some hours before/after the flare event. By performing linear force-free extrapolations using simultaneous SDO/HMI magnetograms, we coupled magnetic field configurations with radiative transfer modeling accounting for the aforementioned radio mechanisms. This approach ensures an accurate characterization of the chromosphere, the layer where gyroresonance develops. Following the approach of Amaro (2023), we included Doppler broadening for the 3rd and 4th harmonics of gyrofrequency, considering the gyroresonance sources. Our results show the kinect temperature, density, and magnetic profiles of ARs under different boundary conditions. By linking these physical parameters with the timing of eruptive events, we demonstrate how K-band radio observations can help identify important precursors of solar flares.

Date: Friday, November 06, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

RE-FORECASTING THE ARRIVAL OF CORONAL MASS EJECTIONS WITH POOR NEAR REAL-TIME PREDICTIONS

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Numerical simulations like Enlil, EUHFORIA, and SUSANOO are routinely used by space weather agencies to forecast coronal mass ejection (CME) arrival times. We often encounter highly variable prediction accuracy. This study tries to re-evaluate and improve these forecasts by first reviewing unsuccessful CME predictions and missed events from solar cycles 24 and 25. We investigate the primary causes of these failures, focusing on uncertainties in ambient solar wind modeling (due partly to poor input magnetic maps), inaccurate eruption characterization based on compromised low-latency data, and inadequate incorporation of interactions of the CME with the solar wind and contemporaneous CMEs. To address these limitations, we utilize AWSoM simulations to re-forecast the arrivals of CMEs at L1 that were poorly predicted, aiming to significantly reduce and better control prediction uncertainties. Finally, we validate our simulation results using Interplanetary Scintillation (IPS) data, enabling us to track and verify CME structures at much larger heliospheric distances than sampled by standard white-light coronagraphs.

Date: Friday, November 06, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

THE VALIDATION OF THE SA SPACE WEATHER FORECAST MODELS

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The South African (SA) Space Weather Centre operates several models to characterise the ionosphere of the Earth. The model results are compared with the near-real-time total electron content measurements to evaluate the models' effectiveness and limitations. A discussion of the errors associated with the measurements and each model highlights the usability of the models. The models' predictability limits the usefulness for forecasting ionospheric conditions. Further validation of the models is done by comparing with digisonde ionospheric measurements.

Date: Friday, November 06, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

SPACE WEATHER FORECASTING USING NASA PUNCH WIDE FIELD IMAGER AND WIPSS DATA

Bernard Jackson [1], Eric Chen [1], Sam Nasri [1], Unity Listiak [1], Vishwas Tattala [1], Kazumasa Iwai [2], Ken'ichi Fujiki [2], Mario Mark Bisi [3], Richard Fallows [3], Craig Deforest [4], Sarah Gibson [4], Punch Team [4]

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The University of California San Diego (UCSD) has an iterative time dependent three-dimensional (3-D) reconstruction program that characterizes solar wind topology throughout the inner heliosphere. By editing the NASA Small Explorer Polarimeter to Unify the Corona and Heliosphere (PUNCH) heliospheric images in an automatic processing system, we now use these data to reconstruct solar wind density structure in 3-D over time with relatively low latency and high resolution. After obtaining images from PUNCH supplied to the US National Oceanographic and Atmospheric Administration, and by removing the major remnants of stellar signals and stray light, these data combined with interplanetary scintillation (IPS) observations, show exquisitely detailed results. Recent innovations using this system give analyses that can be set to the spherical resolutions desired and now combine the PUNCH data with World-Wide IPS Stations (WIPSS) networking data from ISEE, Japan, and the LOFAR UK system to provide outward flow velocities. The analyses make forecasts of solar wind density and velocity arrival several days in advance of their presence at Earth and continue to update as features within the solar wind get closer. Here we will show examples of the time dependent 3-D analysis for PUNCH- and IPS- observed coronal mass ejections (CMEs) and the background solar wind in comparison with plasma in-situ measurements from different interplanetary spacecraft. These analyses are also available in near real time on the UCSD website: https://stereo.ucsd.edu/PUNCH.

Date: Friday, November 06, 2026

Session Info: OTH1: VALIDATION OF SPACE WEATHER MODELS, FORECASTS, AND SERVICES: FROM RESEARCH TO OPERATIONS

CORNERSTONE: A REPRODUCIBLE INFRASTRUCTURE FOR SOLAR FLARE FORECASTING FROM SHARP MAGNETOGRAMS

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The CORonal mass ejection, solar eNERgetic particle and flare forecaSTing from phOtospheric sigNaturEs (CORNERSTONE) project implements a reproducible, operationally oriented framework for flare prediction based on SDO/HMI SHARP vector magnetogram data.
The project integrates ~15 years of solar observations (2010-2025) into a unified relational database combining SHARP magnetic parameters, GOES flare catalogs, NOAA active region metadata, and both definitive and near-real-time (NRT) data products. A central result is a systematic assessment of data reliability under operational conditions, showing that carefully designed quality-control criteria significantly reduce inconsistencies and non-physical variability in magnetic features.
Beyond data integration, CORNERSTONE is built around reproducibility as a core design principle. The framework implements standardized flare labeling, active-region-aware data splitting to avoid temporal leakage, and chronological validation strategies that reflect operational forecasting settings. All experiments are fully tracked, including preprocessing steps, model configurations, code versions, datasets, metrics, and outputs, ensuring complete transparency and reproducibility across runs.
A curated set of multivariate SHARP time-series datasets is constructed for predicting C-, M- and X- class and above flares within a fixed forecast horizon. Initial machine learning experiments show that performance is strongly dependent on both data quality and evaluation methodology, with carefully curated datasets yielding more stable and physically meaningful results than less controlled alternatives.
CORNERSTONE provides a scalable and extensible infrastructure for operational use of near-real-time data and establishes a foundation for reproducible machine learning in solar physics, enabling extensions toward CME and SEP forecasting within the European space weather ecosystem.