



Services for Spacecraft Operations support within the ESA Space Situational Awareness Space Weather Service Network.

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Abstract— Spacecraft operations are by nature complex and every satellite's operational environment poses a range of potential risks, often a unique combination for a given orbit. The implications of interruptions of operations, data transfer and service provision, are serious, both in terms of cost and capability, thus it is imperative to mitigate against all operational risks to the fullest extent possible.

In the frame of its Space Situational Awareness (SSA) programme, the European Space Agency (ESA) is establishing a Space Weather Service Network to support end-users, in a wide range of affected sectors, in mitigating the effects of space weather on their systems, reducing costs and improving reliability. This service network is currently in a test and validation phase and encourages user engagement and feedback.

The network is organised around five Expert Service Centres (ESCs) focusing on Solar Weather, Heliospheric Weather, Space Radiation Environment, Ionospheric Weather and Geomagnetic Conditions. Each ESC is connecting different expert groups, federating their space weather products, and ensuring the quality and consistency of the provided information. The service network also includes a central Data Centre and the SSA Space Weather Coordination Centre (SSCC).

In this presentation we give an overview of the current status of the network (<http://swe.ssa.esa.int/>), the targeted end-user groups and Expert Service Centres with a focus on the space community.

Keywords—space weather, space situational awareness, service network

I. INTRODUCTION

The objective of the ESA Space Situational Awareness (SSA) programme is to support Europe's independent utilisation of, and access to, space through the provision of timely and accurate information, data and services regarding the space environment, and particularly regarding hazards to infrastructure in orbit and on the ground.

The SSA programme will, ultimately, enable Europe to autonomously detect, predict and assess the risk to life and property due to man-made space objects (remnant debris, re-

entries, in-orbit explosions and release events, in-orbit collisions, disruption of missions and satellite-based service capabilities), potential impacts of Near-Earth Objects (NEOs), and the effects of space weather phenomena on space- and ground-based infrastructure.

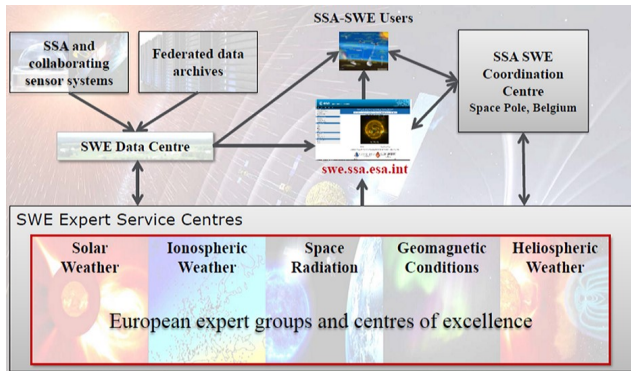
The programme is currently in its Period Three [1] and is active in three main areas:

- Space Weather
- Near Earth Objects
- Space Surveillance and Tracking

Within this framework, the focus in the Space Weather Segment (SWE) of the SSA Programme is on developing a system capable of providing space weather services to end users. The system under development is based on a federated architecture where the service provision will be carried out by Expert Service Centres (ESCs) in the Programme Member States. These collaborative centres bring together European expertise and assets. Five ESCs focusing on Solar Weather, Heliospheric Weather, Space Radiation Environment, Ionospheric Weather and Geomagnetic Conditions are being established. In parallel to the provision of the current services, the ESCs are introducing new, innovative products and developing the necessary processes in order to provide these in a reliable manner. Consequently, the SSA SWE Service Network is expected to grow substantially within SSA Period 3. The overall structure of the network is shown in Figure 1

For the development of the SWE Service Network, two distinct approaches are followed. The first approach is a bottom-up approach where existing space weather assets in Europe are deployed and further developed into a set of representative and essential precursor services. In addition to providing accurate and timely information, the deployment and operation of this set of precursor services allows the gathering of feedback from the user community, to make assessments of the Network's performance and to provide key inputs for its further service development. The second approach is a top-down approach starting with the definition of the customer

Figure 1 SSA SWE Service Network structure [1]



requirements [2] from which system requirements [3] have been derived in succession. The top down design process benefits from the experience and feedback gained from the pre-operation of the SWE Service Network set up by the first approach. The second approach has defined eight service domains — Spacecraft Design (SCD), Spacecraft Operation (SCO), Human Space Flight (SCH), Launch Operation (LAU), Transionospheric radio link (TIO), SSA Space Surveillance and Tracking (SST), Non-space systems operation (NSO), and General data service (GEN) — for which 39 services have been identified (see Appendix).

Since space weather is a rapidly evolving domain, with users gaining more in-depth knowledge of how space weather affects their systems and new user groups becoming aware of the potential impact of space weather, it is important to establish a close relationship with the different potential user communities. Such a relationship enables user awareness and ensures its progress from awareness, to agreement, and from agreement to adoption of evidence-based practices. In the approach to establish a close relationship with the end-users of space weather services, the SSA Space Weather Coordination Centre (SSCC) — which provides the user helpdesk and first line user support for the SWE network — conducts three main actions:

- bringing the network to the users to increase its awareness,
- identifying key persons within the different user communities
- setting up end user meetings to learn the user requirements and to translate them into a user tailored space weather service.

Members of the SSCC team attend workshops, conferences etc. to promote the network and to meet end users, and the team also organises visits to the SSCC premises upon invitation and/or request (helpdesk.swe@ssa.esa.int).

In what follows, for each ESC their mission statement, contributing expert groups, provided services and corresponding user types and provided products are described. The SSCC tailoring of some products for space mission support is also described.

II. THE EXPERT SERVICE CENTRE – SOLAR WEATHER

A. Mission statement

The mission of the Solar Weather Expert Service Centre (S-ESC) is to provide and develop the functionalities, capabilities and expertise in the domain of Solar Weather that are needed within the ESA SSA SWE Network to achieve as a collaborative enterprise its mission of demonstrating and assessing the influences of Space Weather and informing and supporting end-users through the provision of accurate, reliable and timely products and (pre-) operational services, tailored to their requirements.

The S-ESC thus provides, implements and supports the Solar Weather products and capabilities of the ESA SSA SWE. This includes the observation, monitoring, interpretation, modelling and forecasting of Solar Weather conditions with an emphasis on Solar (sub-)surface and Solar coronal features, events and processes that drive Space Weather in our Solar System.

B. Expert groups

The current network of Expert Groups contributing to the S-ESC network are:

- Solar Influence Data analysis Centre (SIDC), Royal Observatory of Belgium (ROB), Belgium
- Kanzelhöhe Observatory (KSO), University of Graz (UniGraz), Austria
- Research Center for Astronomy and Applied Mathematics, Academy of Athens, Greece
- Osservatorio Astrofisico di Catania (CAO), Istituto Nazionale di Astrofisica (INAF), Italy
- Institute of 4D Technologies, University of Applied Sciences North Western Switzerland

C. Services and user types

The functionalities and responsibilities of the S-ESC are located at the start of the causality chain of Space Weather events starting from the Solar origin up to the effects on Geospace, Earth and, eventually, the impact on user infrastructure. Hence, the focus of the S-ESC is very much on the production and assessment of synoptic Solar data.

Solar Weather products can have direct relevance to the end-user (e.g. a general probabilistic forecast on the likelihood of solar events given the current Solar Weather conditions). In addition, Solar Weather ESC products are often digested by other Centres that, based on their subsequent expertise in the physical systems impacted, further specify and predict the more precise characteristics of these impacts.

D. Products

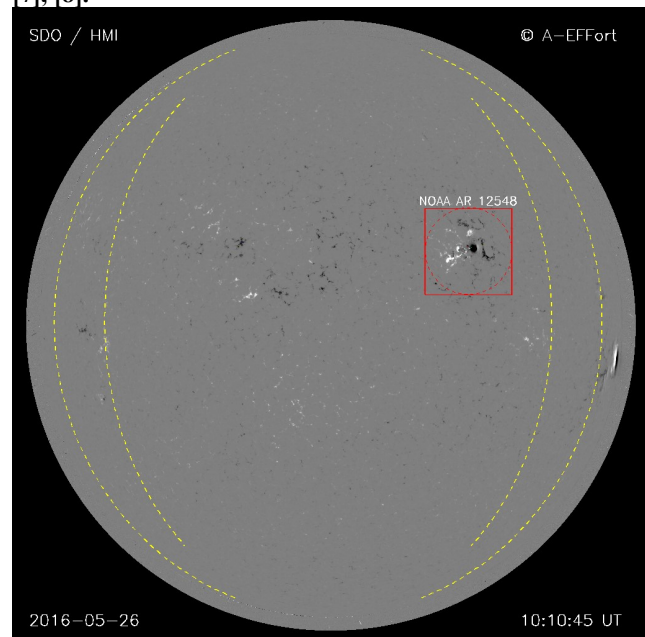
Below we give a list of products provided by the S-ESC, illustrated with the CACTus CME detection (Figure 2) and a full disk magnetogram with eligible active regions (Figure 3)

produced by Athens Effective Solar Flare Forecasting (A-EFFort).

- Solar Imaging:
 - White light continuum images from ground based stations (SIDC/USET, UniGraz/KSO, INAF/CAO)
 - H-Alpha images from ground based stations (USET, KSO, CAO)
 - PROBA2/SWAP EUV images
 - European mirror of SDO imagery
- Spectral Radio observations:
 - Radio spectra from the Humain radio station, Belgium
 - Radio spectra from the eCallisto Global network
- Solar irradiance:
 - PROBA2/LYRA 4channel (E)UV irradiance
 - Recalibrated LYRA data as proxy for X-ray flare magnitudes
- Solar feature and event detections/characterisation:
 - Characterisation of Sunspot Groups: from USET and CAO
 - Automated Radio Burst detections on SIDC/Humain radio observations
 - (CACTus) Automated CME detection in SoHO/LASCO coronagraphic images
 - Optical flare detections from KSO
 - X-ray flare detections based on NOAA/GOES flux measurements
 - Filament detections from KSO
 - Human operator (7d/7d, 16h/24h) moderation and expert annotation and alerting complementing the above automated event detections
 - Solar Activity indices
 - International Sunspot Number
 - Solar activity and indices forecasts
 - 3-day forecast of radio flux F10.7 index
 - Probabilistic Solar Flare predictions (2 distinct methods)
- Service Products:
 - Email alerts associated to the feature and event detections
 - Image browsing with Solar Active Region annotations
 - All quiet Alert: marking times with exceptionally low Space Weather risk. This product is targeted at Satellite operators.
 - Daily bulletin on Solar (and Heliospheric and Geomagnetic) Weather (Human operator generated)

Figure 2: CACTus CME detection in SoHO/LASCO coronagraphic image [4], [5].

Figure 3: Eligible active regions identified on full-disk SDO/HMI line-of-sight magnetogram (from A-EFFort) [6], [7], [8].



III. THE EXPERT SERVICE CENTRE – HELIOSPHERIC WEATHER

A. Mission statement

The mission of the Heliospheric Weather Expert Service Centre (H-ESC) is to provide and develop the functionalities, capabilities and expertise in the domain of Heliospheric

Weather that are needed within the ESA SSA SWE network to achieve as a collaborative enterprise its mission of demonstrating and assessing the influences of Space Weather and informing and supporting end users through the provision of accurate, reliable and timely products and (pre-)operational services, tailored to their requirements.

The specific goal of the H-ESC is to fully exploit heliophysics assets and expertise from Europe, and further afield, to provide, improve and support the provision of alerts, forecasts and post event analysis of space weather conditions both near to the Earth and at other locations within the heliosphere.

This will be accomplished through the use of remote-sensing and in situ monitoring to identify and track key transient features (including coronal mass ejections, high-speed solar wind streams and solar energetic particles), combined with the use of advanced modelling and analysis techniques to predict their arrival at various points of interest in the heliosphere.

B. Expert groups

The H-ESC network consists of eight Expert Groups. The H-ESC network coordination is provided by STFC RAL Space, UK. The full list of H-ESC Expert Groups is:

- STFC RAL Space, UK (Coordination, scientific QA and service assessment)
- Met Office, UK (operational forecasting service, MHD modelling)
- University of Graz, Austria (solar wind and CME propagation)
- DTU, Denmark (near-Earth solar wind transient detection)
- IRAP, France (AMDA and propagation validation tools)
- KU Leuven, Belgium (European modelling assessment)
- DH Consultancy, Belgium (Existing service assessment)
- University of Göttingen, Germany (CME propagation)

C. Services and user types

The H-ESC has responsibility for three service areas falling within the general data, spacecraft operations and spacecraft design service domains:

- GEN/mod – End-to-end modelling capability for space weather
- SCO/pla – Spacecraft operations for interplanetary missions
- SCD/pla – Spacecraft design for interplanetary missions

The SCO/pla and SCD/pla are two new service areas with a specific focus on the support of ESA interplanetary science missions.

D. Products

The portfolio of products, and their institutional providers, within the H-ESC include:

UK Met Office (MET)

- H.101a Solar Wind Near-Earth Forecasts H.102a Near Real Time Solar Wind
- H.103a CME Near-Earth Arrival Forecast
- H.105a Near Real Time Near-Earth Energetic Particles
- H.106a Near-Earth Space Weather Alerts
- H.107a Solar wind Tailored Heliospheric
- H.108a CME Tailored Heliospheric arrival predictions
- H.110a Tailored Heliospheric Space Weather Alerts

Technical University of Denmark (DTU)

- H.106b Automated Near-Earth NRT Alerts (AWARE)

Centre de Données de la Physique des Plasmas (CDPP)

H.103c Propagation Tool

- H.114a AMDA

RAL Space (STFC)

- H.112a Archive Product Assessment Report (HPARC-PAR)
- H.113a Archive Product Browser (HPARC-PB)

University of Graz (UNIGRAZ), Institute of Physics

- H.101b Forecast of solar wind high-speed streams (ESWF)
- H.103b CME near-Earth arrival time predictions (Drag Based Model Tool)

Figure 4: Example of the WSA/ENLIL MHD heliospheric modelling that is being provided by UK Met Office as part of the H-ESC forecasting centre [9].

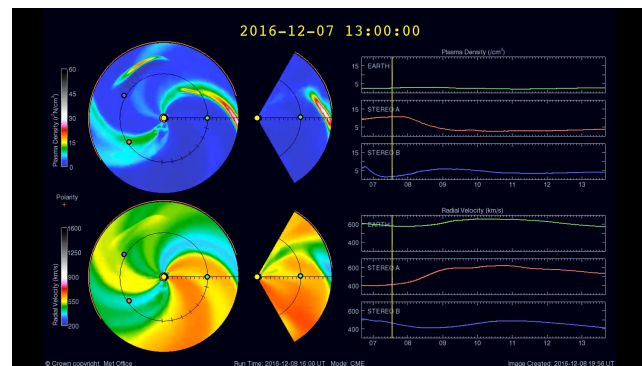


Figure 5: Example of the empirical modelling products provided by University of Graz. (left) coronal hole based near-Earth solar wind estimates [10], (right) drag based model forecast of CME arrival [11].

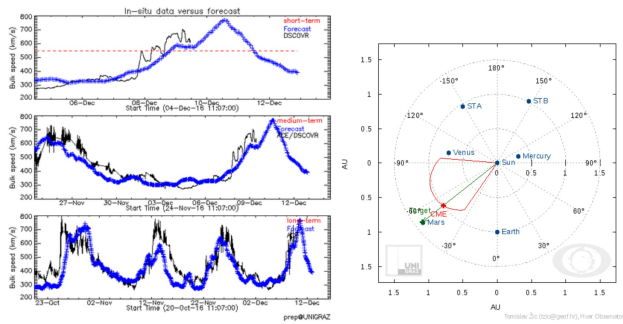


Figure 4 shows an example of the WSA/ENLIL MHD heliospheric modelling. Empirical modelling products are shown in Figure 5 (left: coronal hole based near-Earth solar wind estimates, right: drag based model forecast of CME arrival).

In addition the H-ESC will provide a range of ancillary and support products and capabilities including:

- Case study and special event modelling.
- Assessment report on near-Earth forecast and alerting performance.
- Archive of H-ESC products.
- Integrated access to science archive (CDPP, UKSSDC) on near-Earth and interplanetary measurements in support of post event analysis.
- Long term statistical products on heliospheric weather conditions.

IV. THE EXPERT SERVICE CENTRE – SPACE RADIATION

A. Mission statement

The mission of the Space Radiation ESC (R-ESC) is to provide and develop the functionalities, capabilities and expertise in the domain of Space Radiation that are needed within the ESA SSA SWE Network to achieve as a collaborative enterprise its mission of demonstrating and assessing the influences of Space Weather and informing and supporting end users through the provision of accurate, reliable and timely products and (pre-) operational services, tailored to their requirements.

The R-ESC ensures that the monitoring, modelling and forecasting of space particle radiation (ambient plasma, solar energetic particles, radiation belts, galactic cosmic rays), micron-size particulates (from meteoroids and space debris), as well as all types of phenomena induced effects on technologies and biological systems, are fully covered in regard to the near-Earth space environment.

B. Expert groups

The R-ESC is currently a network of twelve Expert Groups comprised of eight product providers and four consultants with expertise in charged particle radiation. Expert group names and their associated countries in alphabetical order are listed below. During P3-SWE-I the R-ESC is being coordinated by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB).

Providers:

- Radiation Hardness Assurance and Space Weather (RAS), Seibersdorf Laboratories GmbH (Austria)
- Paul Buehler (Austria)
- Centre for Space Radiations (CSR), Université Catholique de Louvain (Belgium)
- Space Physics Division (BIRA-IASB), Royal Belgian Institute for Space Aeronomy (Belgium)
- Space Research Laboratory (SRL), University of Turku (Finland)
- Department Radiation Biology (DLR-IAM), DLR Institute of Aerospace Medicine (Germany)
- Athens Neutron Monitor Station (ANeMoS), National and Kapodistrian University of Athens (Greece)
- Mullard Space Science Laboratory (MSSL), University College London (United Kingdom)

Consultants:

- Ondrej Santolik, Institute of Atmospheric Physics (IAP) (Czech Republic)
- Ilya Usoskin, Sodankylä Geophysical Observatory (SGO), University of Oulu (Finland)
- Clive Dyer, CSDRadConsultancy Ltd (United Kingdom)
- Keith Ryden, Univ Surrey, UK

C. Services and user types

Seventeen services from five of the service domains introduced in section I fall under the responsibility of the R-ESC. Domains and their respective services are listed here :

- Spacecraft design
 - SCD/arv – Data archive
 - SCD/orb – In orbit verification
 - SCD/pst – Post event analysis
- Spacecraft operation
 - SCO/orb – In orbit environment and effects monitoring
 - SCO/pst – Post event analysis
 - SCO/for – In-orbit environment and effects forecast
 - SCO/ana – In-orbit mission risk analysis
- Human space flight
 - SCH/orb – In-flight crew radiation exposure
 - SCH/pstb – Cumulative crew radiation exposure
 - SCH/for – Increased crew radiation exposure risk
- Launch operation
 - LAU/orb – In-flight monitoring of radiation effects in sensitive electronics
 - LAU/pst – Estimate of radiation effects in sensitive electronics
 - LAU/for – Forecast of radiation storms
 - LAU/drg – Atmospheric density forecast
 - LAU/ios – Risk estimate of service disruption caused by ionospheric scintillations

- LAU/mcp – Risk estimate of microparticle impacts
- Non-space systems operations
 - NSO/air – Service to airlines

D. Products

The R-ESC provides users with an extensive range of products that are available at the R-ESC homepage on the SSA SWE portal (<http://swe.ssa.esa.int/web/>) and are listed below:

Seibersdorf Laboratories

- R.101 Radiation exposure estimation at aircraft altitude (AVIDOS 2.0)

Athens Neutron Monitor Station (ANeMoS), NKU Athens

- R.102 Ground Level Enhancement (GLE) Alert service
- R.108 Multi-station Neutron Monitor data

Department Radiation Biology (DLR-IAM)

- R.123 Radiation environment outside the ISS
- R.124 Radiation environment inside the ISS
- R.125 Accumulated dose in human phantoms on board the ISS
- R.127 SEP post-event analysis for aviation radiation exposure

BIRA-IASB Space Weather Services

- R.103 Space Environment Information System (SPENVIS)
- R.134 The COMESEP Alert System
- R.136 SWIFF Plasmasphere Model (SPM)

Paul Buehler

- R.118 PROBA-1/SREM radiation rates
- R.119 Integral/SREM radiation rates
- R.120 Rosetta/SREM radiation rates
- R.121 Herschel/SREM radiation rates
- R.122 Planck/SREM radiation rates

Mullard Space Science Laboratory (UCL)

- R.131 Electron Population Model (GEO)
- R.132 Electron Population Model (MEO)

Center for Space Radiations (CSR)

- R.109 PROBA-V/EPT electron flux spectra time series
- R.110 PROBA-V/EPT proton flux spectra time series
- R.111 PROBA-V/EPT helium flux spectra time series
- R.112 PROBA-V/EPT electron flux geographical maps
- R.113 PROBA-V/EPT proton flux geographical maps
- R.114 PROBA-V/EPT helium flux geographical maps

- R.115 PROBA-V/EPT auroral electron energy spectrum characterization
- R.116 PROBA-V/EPT SAA proton energy spectrum characterization
- R.117 PROBA-V/EPT SAA helium energy spectrum characterization

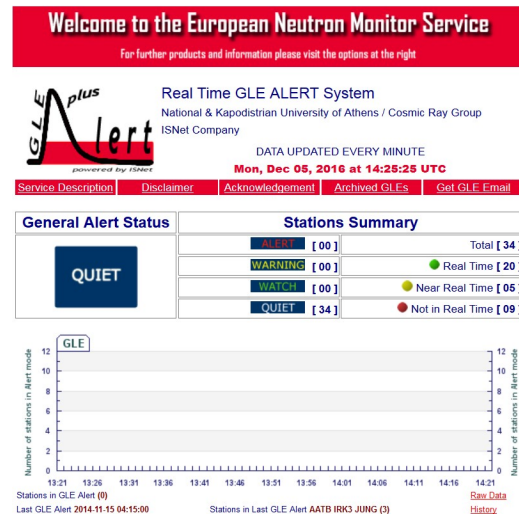
Hosted by the SWE Data Centre

- R.104 Space Environment Data System (SEDAT)
- R.106 Space Environment System for Mission Operations (SEISOP) [UNDER MAINTENANCE]
- R.107 European Debris Impact Database (EDID)

These products provide users with a large spectrum of applications ranging from technologies to biological systems covering different orbits as well as airline altitudes.

Figure 6 displays two of these products, respectively the GLE alert service (upper panel) and AVIDOS that provides radiation exposure estimation at aircraft altitudes (lower panel).

Figure 6: Example of two Space Radiation ESC products. Upper panel: GLE alert service provided by the University of Athens [12]. Lower panel: Radiation exposure estimation at aircraft altitude (AVIDOS) provided by Seibersdorf Laboratories [13]. Courtesy of the ESA SWE Portal (<http://swe.ssa.esa.int/space-radiation>).



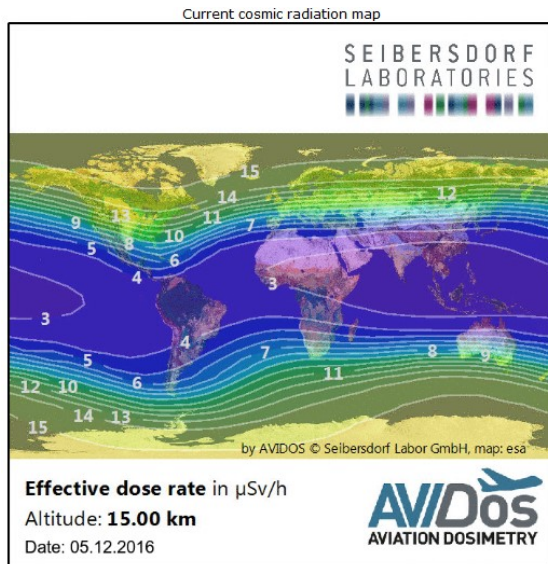
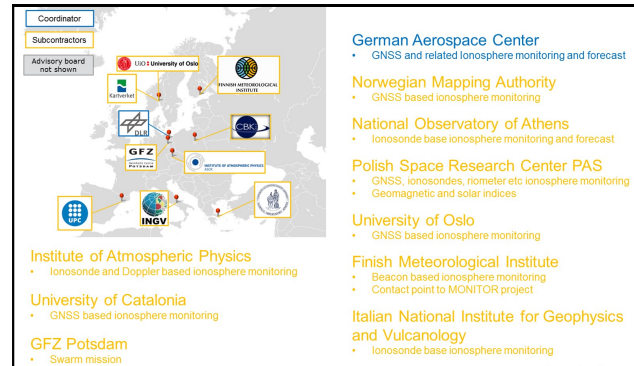


Figure 7: Overview of currently contributing expert groups in the I-ESC.



V. THE EXPERT SERVICE CENTRE – IONOSPHERIC WEATHER

A. Mission statement

The mission of the Expert Service Centre Ionospheric Weather (I-ESC) is to provide and develop the functionalities, capabilities and expertise in the domain of ionosphere and upper atmosphere weather that are needed within the ESA SSA SWE Network to achieve as a collaborative enterprise its mission of demonstrating and assessing the influences of Space Weather and informing and supporting end-users through the provision of accurate, reliable and timely products and (pre-) operational services, tailored to their requirements.

B. Expert groups

Currently, nine expert groups are contributing by product provision or development to the services for GNSS users in the I-ESC. An overview of these expert groups is shown in Figure 7.

The coordination of the I-ESC is performed by DLR. The currently nine expert groups are complemented during Period 3 through new expert groups, data and products. An I-ESC advisory board is constantly supporting the I-ESC coordinator in his duty to organize the development and operation of the I-ESC services. The vision of the ESC includes a continuous network extension and development. Therefore, the initial assets and expert groups involved in the ESC will be complemented by additional experts and assets extending the network and integrating additional and new products into the I-ESC.

C. Services and user types

The I-ESC is responsible for a number of services in the Transionospheric Radiolink (TIO) domain and the SWE services to the Space Surveillance and Tracking (SST) domain. In the TIO domain the I-ESC is providing services mainly to different kinds of GNSS users:

- Users of GNSS single frequency services with average accuracy, no integrity (e.g. typical GNSS mass market user)
- Users of GNSS single frequency services with average accuracy, using integrity (e.g. EGNOS user)
- Users of multi-frequency GNSS systems with average multi-frequency accuracy, no integrity (commercial services, public regulated services)
- Users of multi-frequency GNSS systems with average accuracy, integrity (aeronautical multi-frequency)
- Users of multi-frequency GNSS systems with very high accuracy (e.g. GNSS geodetic users, Real-Time Kinematics)
- Users of satellite data communications with high availability / continuity (e.g. Search-and-Rescue, Air Traffic Control/Management via Satellite, high availability/continuity data networks such as Galileo Ground Segment Data Network).
- Other space-based services/products users affected by the ionosphere (UHF - C-band radars, GNSS-R altimetry, UHF/low microwave radio astronomy and deep space communications). For these users, the I-ESC is providing the following services:
 - TIO/tcr – Provide near real-time Total Electron Content (TEC) maps
 - TIO/tcf – Provide forecast TEC maps
 - TIO/qua – Provide information on whether standard corrections to GNSS signal are applicable (Quality assessment of ionospheric correction)
 - TIO/sci – Provide near real-time estimate of ionospheric scintillation maps
 - TIO/for – Provide estimate of the occurrence risk of ionospheric disturbances (monitoring and forecast of ionospheric disturbances)

The SWE services targeting the the SST domain are mainly addressed to users in the following areas:

- Surveillance and tracking centre(s), stations and services

- Spacecraft operators
- Collision warning services
- Re-entry risk assessment services

For these users the I-ESC will provide the following services:

- SST/atm – Provide estimates of atmospheric density in the past years and predicted in near real-time.
- SST/arv – Provide a database of past values of solar and geomagnetic indices relevant to drag calculation
- SST/for – Provide forecast of geomagnetic and solar induces for drag calculation
- SST/ion – Provide nowcast of ionospheric group delay to estimate effects on radar signals.

D. Products

The I-ESC provides a large variety of products serving the needs of the addressed users and contributing to the provision of the mentioned services. The relation between the products and services is described in the documents [2] and [3] and will be presented in this way on the I-ESC homepage on the SSA SWE portal (<http://swe.ssa.esa.int/web/>). Below is the current list of all products hosted by the I-ESC:

Norwegian Mapping Authority (NMA)

- I.107 RTIM VTEC maps (Northern Europe)
- I.108 RTIM GIVE maps (Northern Europe)
- I.109a RTIM ROTI maps (Northern Europe)
- I.109b RTIM ROTI@Ground maps (Fennoscandia)
- I.110a RTIM S4 maps (Northern Europe)
- I.110b RTIM SigmaPhi maps (Northern Europe)
- I.110c RTIM S4 maps (demo service, not assigned to services)
- I.110d RTIM SigmaPhi maps (demo service, not assigned to services)
- I.127 RESOSS ROTI at ground time series (selected locations in northern Europe)

National Observatory of Athens (NOA)

- I.114 EIS European maps of foF2 long term predictions
- I.115 EIS Nowcast European maps of foF2
- I.116 EIS Maps of forecasted foF2 over Europe for the next 24 hours
- I.117 EIS Near real-time TEC maps for the European region
- I.118 EIS Alerts for ionospheric disturbances in the European sector (based on the Alert Algorithm of the SWIF model)
- I.119 EIS Current ionospheric conditions at each ionosonde location
- I.120 EIS Forecasted foF2 values for the next 24 hours over each ionosonde

Finnish Meteorological Institute (FMI)

- I.123a MONITOR:SISTED
- I.123b MONITOR:GSFLAI
-

Ionosphere Monitoring and Prediction Center (IMPC)

- I.101 IMPC TEC map (Europe), current
- I.102 IMPC TEC map (Europe), 1hr forecast
- I.103a IMPC TEC map (Global), current
- I.103b IMPC TEC map (Global), current, beta version (demo product not assigned to services)
- I.104 IMPC TEC map (Global), 1hr forecast
- I.105a IMPC Equivalent slab thickness, Juliusruh
- I.105b IMPC Equivalent slab thickness, Pruhonice
- I.106a CBK Local scintillation indices S4 & SigmaPhi Hornsund
- I.106b IMPC Local scintillation indices S4 & SigmaPhi Kiruna
- I.106c IMPC Local scintillation indices S4 & SigmaPhi Neustrelitz I.
- I.106d IMPC Local scintillation indices S4 & SigmaPhi Tenerife
- I.106e IMPC Local scintillation indices S4 & SigmaPhi Toulouse
- I.124 IMPC mean ROTI maps for Europe

Collecte Localisation Satellites (CLS)

- I.122c ISM S4 and Err(S4) nowcast modelled maps
- I.122d ISM SigmaPhi and Err(SigmaPhi) nowcast modelled maps
- I.122e ISM TEC and Err(TEC) nowcast modelled maps
- I.122f ISM S4 and Err(S4) 6-hour forecast modelled maps
- I.122g ISM SigmaPhi and Err(SigmaPhi) 6-hour forecast modelled maps
- I.122i ISM S4 and Err(S4) nowcast modelled values at a given location
- I.122j ISM SigmaPhi and Err(SigmaPhi) nowcast modelled values at a given location
- I.122k ISM TEC and Err(TEC) nowcast modelled values at a given location
- I.122l ISM S4 and Err(S4) 6h forecast modelled values at a given location
- I.122m ISM SigmaPhi and Err(SigmaPhi) 6h forecast modelled values at a given location
- I.122o ISM S4 observed map as quality data for ISM S4 nowcast modelled maps
- I.122p ISM SigmaPhi observed map as a quality data for ISM SigmaPhi nowcast modelled maps

Helmholtz-centre Potsdam (GFZ)

- I.128 Swarm Rate Of change of TEC (ROT)
- I.129 Swarm Total Electron Content (TEC)
- I.130 Swarm Electron Density (Ne)
- I.131 Swarm Ionospheric Bubble Index (IBI)

Space Research Centre (SRC)

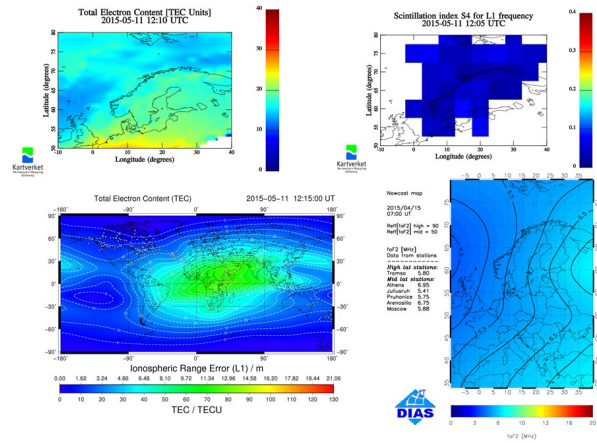
- I.125a SGIArv R - Daily Total Sunspot Number, archive
- I.125b SGIArv F10.7 index (measured, adjusted to 1AU, and URSI F10.7), archive
- I.125c SGIArv S10.7 index, archive
- I.125d SGIArv M10.7 index, archive

- I.125e SGIArv Y10.7 index, archive
- I.125f SGIArv F30 index (absolute), archive
- I.126a SGIArv Ap index (definitive), archive
- I.126b SGIArv Kp index (definitive), archive
- I.126c SGIArv Dst index (provisional and final), archive
- I.126d SGIArv IG12 index (provisional and final), archive
- I.126e SGIArv IMF (Bx_GSE, By_GSE, Bz_GSE, |B|_GSE), archive
- I.126f SGIArv Aa index(daily), archive

Hosted by the SWE Data Centre

- I.121 ESA IONMON TEC maps

A small subset of I-ESC products is shown in Figure 8.



- Technical University of Denmark – DTU Space
- Finnish Meteorological Institute (FMI)
- Swedish Institute for Space Physics (IRF)
- German Research Centre for Geosciences (GFZ)
- Polar Geophysical Institute (PGI)
- Solar Influences Data Analysis Center (SIDC)
- Norwegian Mapping Authority (NMA)
- University Alcalá (UAH)

C. Services and user types

Four user domains have been identified that fall under the responsibility of the G-ESC within the Non-Space System Operators Services (NSO) domain:

- NSO/pow – Service to power system operators (high priority)
- NSO/ppl – Service to pipeline operators (low priority)
- NSO/res – Service to resource exploitation system operators (high priority)
- NSO/tou – Service to auroral tourism sector (medium priority)

D. Products

The list of products provided by the G-ESC are listed below. In Figure 9 and Figure 10 respectively, a 27 days forecast of the daily global Ap index and 30-minutes dB/dt forecast map are displayed.

Universidad de Alcalá (UAH)

- G.126 LDiñ
- G.127 LCiñ
- G.128 SolarHeed
- G.129 SolarHoldover
- G.130 UAH-SWE Subscription
- G.131 Sentinel G
- G.132 Sentinel C G.133 UAH-SWE Report

Solar Influences Data analysis Center (SIDC)

- G.105 Provisional AA index

Finnish Meteorological Institute (FMI)

VI. THE EXPERT SERVICE CENTRE – GEOMAGNETIC CONDITIONS

A. Mission statement

The mission of the Geomagnetic Conditions Expert Service Centre (G-ESC) is to provide and develop the functionalities, capabilities and expertise in the domain of geomagnetism that are needed within the ESA SSA SWE Network to achieve as a collaborative enterprise its mission of demonstrating and assessing the influences of Space Weather and informing and supporting end-users through the provision of accurate, reliable and timely products and (pre-) operational services, tailored to their requirements.

The G-ESC thus provides, implements and supports the geomagnetic products and capabilities of the ESA SSA SWE network for monitoring, interpreting, and forecasting variations of the geomagnetic field on various timescales, relying on in situ ground-based, as well as space-borne measurements and related derived quantities and models

B. Expert groups

Currently the G-ESC comprises the following eight expert groups:

Figure 8: Sample subset for ionospheric products provided in the I-ESC. Upper left: DLR TEC map [14], upper right: NMA S4 map [15], lower left: NMA TEC map [15], lower right: NOA Nowcast foF2 map [16], [17], [18].

- G.101 Magnetogrammes from North(west) Europe and Greenland
- G.106 Auroral alert and forecast service
- G.111 Maps for power and pipeline operators
- G.112 Table of modelled
- GIC G.114 PSP difference

Swedish Institute of Space Physics (IRF)

- G.113 Forecast of dB/dt

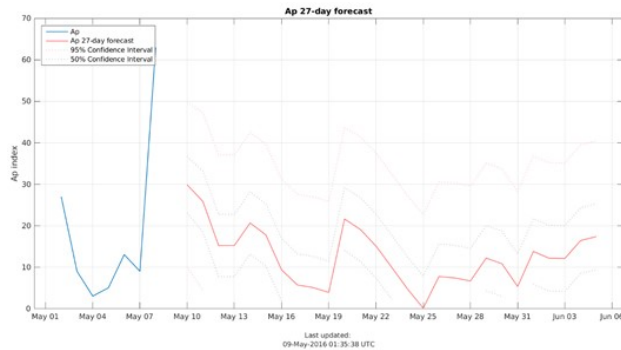
Tromsø Geophysical Observatory (TGO)

- G.102 Provisional K-indices from Northwest Europe
- G.103 Geomagnetic Activity index for auroral zone (AZ), last 33 days
- G.104 Geomagnetic Activity index for auroral zone (AZ), long term variation
- G.117 Day global forecast issued every 24 hours
- G.118 Short term (1 hour) Kp forecast
- G.119 Short term (1 hour) local geomagnetic forecast
- G.120 Real-time and historic geomagnetic activity plots and data files for geomagnetic surveying (Total field)
- G.121 Real-time and historic geomagnetic activity plots and data files for directional drilling (Total field, declination and inclination)
- G.122 E-mail alerts for geomagnetic disturbances

Helmholtz-centre Potsdam (GFZ)

- G.107 Quicklook Kp index (Nowcast Kp plot)
- G.108 Most recent definitive Kp index
- G.109 Kp and Ap index in tabular form
- G.110 Kp/Ap archive
- G.123 Swarm Polar Electrojets (PEJ)
- G.124 Swarm Field-Aligned Current (FAC)
- G.125 Swarm Vector Magnetic Field (MAG)

Figure 9: The 27 days forecast of the daily global Ap index, provided by the Norwegian Centre for Space Weather/Tromsø Geophysical Observatory at UiT [19]. In the figure the solid blue line depicts the Ap index data. The forecast, using linear prediction filter, is shown as solid red line with the corresponding upper and lower (50% and 95%) confidence limits in dotted lines.



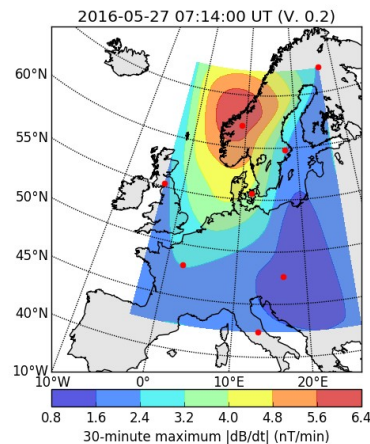
VII. TAILORING OF SPACE WEATHER PRODUCTS

In order to address specific requests from key users, SSCC is tailoring products of the SWE network into dedicated space weather bulletins. In particular such bulletins have been generated in support to the following ESA missions:

- Launch of GAIA spacecraft (16–20 December 2013) and L2 insertion manoeuvre (6–14 January 2014)
- Venus Express aerobraking campaign (May–July 2014)
- Rosetta mission (since October 2014) including the landing of the Rosetta’s sounder Philae on comet 67P/Churyumov–Gerasimenko (12 November 2014)
- Launch of the experimental spaceplane IXV (11 February 2015)

Figure 11 shows an illustration included in the space weather bulletin tailored for the Venus Express aerobraking operations.

Figure 10: 30-minutes dB/dt forecast map, provided by the Swedish Institute of Space Physics (IRF-Lund) [20]. The rate of change of the magnetic field (dB/dt) is indicative of the intensity of geomagnetically induced currents (GICs) flowing along electric power grid systems and other electrically conducting infrastructure, which can seriously affect normal operation.



VIII. FUTURE PERSPECTIVES OF THE NETWORK

The SWE network already provides access to ~140 products combined into 21 preliminary user-driven services. It is foreseen to undergo extensive development within the next few years.

Specific implementation tasks for P3 include:

- Establish robust R2O process for models and tools developed within or outside the SSA Programme

- Mature elements of the SSA SWE system for transitioning to operations
- Develop and validate improved services for key user domains => develop required models and applications

This will ensure the consistent presentation of structured SWE services to the end users built on the wide range of European expertise and assets available, coupled with targeted developments. Constant user feedback and a programme of test campaigns will be used to highlight areas where user requirements are evolving. Second, substantial development of existing and new products will enlarge the capabilities of each ESC. Further product development activities are expected to be executed and as these developments mature, inclusion of relevant existing new or updated products into each ESC will be investigated in terms of their possible further contribution to meeting SWE user requirements. Following this assessment, their inclusion into the SWE Service Network may be foreseen. Two examples of ongoing developments foreseen to be integrated as products within the ESA SWE Service Network within 2018 are:

- Forecasts/hindcasts of atmospheric density (
- Figure 12), derived from the DTM2013 model [21] and targeted at users concerned with atmospheric drag within the SST domain.
- A forecasting tool, based on the British Antarctic Survey's Belt Radiation Model, to forewarn satellite users of likely radiation hazards.

Figure 11 Illustration of a space weather bulletin for Venus Express operations showing an extrapolation of the solar disk image, EUV background irradiation and F10.7 index matching Venus viewpoint.

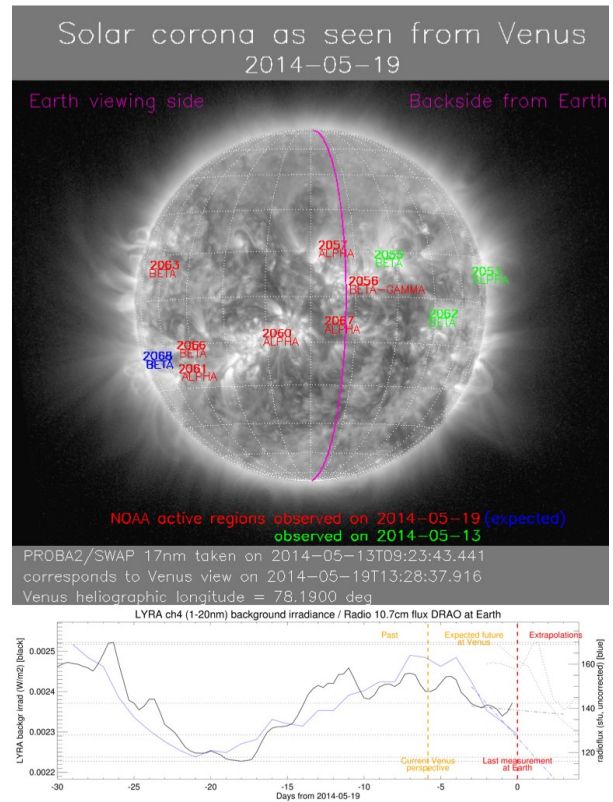
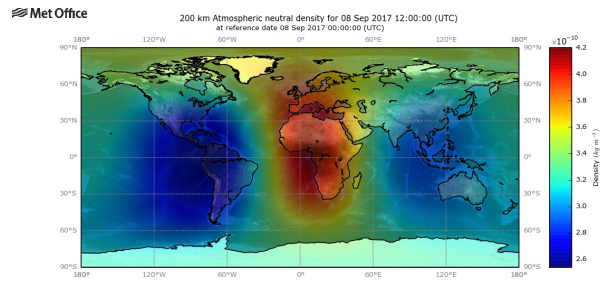


Figure 12 Overview of the predicted atmospheric density, at an altitude of 200 km, encountered during the period of increased space weather activity during September 2017 (provided by UK Met Office).



IX. CONCLUSION

The ESA SSA programme is driving the development of a system to monitor, predict and disseminate space weather information and alerts, including products and services available for use by both space and ground based user communities. This paper describes the SWE Service Network. In parallel, SSA space weather space segment developments address data needs to support enhanced space weather services, currently focussing on the design of a dedicated monitoring mission with target launch date of 2023 and a

distributed sensor system utilising hosted payloads operating within the magnetosphere.

The SWE Service Network development process is guided by regular assessments of the requirements and of the product quality, with end users in the loop. The challenge of this process is to understand the user needs and to translate them into targeted services providing accurate and timely space weather information. The spacecraft operations community is therefore invited to contribute with feedback and recommendations.

APPENDIX: LIST OF SSA SWE SERVICES

- *Spacecraft Design* -
- (1) Environment specification: data archive
- (2) Environment specification: in orbit verification
- (3) Post event analysis for satellite designers
- (4) Space Weather in the Solar System
- *Spacecraft Operation* -
- (5) In-orbit environment and effects monitoring
- (6) Post-event analysis for satellite operators
- (7) In-orbit environment and effects forecast
- (8) Mission risk analysis
- (9) Space Weather in the Solar System
- *Human Spaceflight* -
- (10) In flight crew radiation exposure
- (11) Cumulative crew radiation exposure
- (12) Increased crew radiation exposure risk
- *Launch Operation* -
- (13) In-flight monitoring of radiation effects in sensitive electronics
- (14) Estimate of radiation effects in sensitive electronics
- (15) Forecast of radiation storms
- (16) Atmospheric density forecast
- (17) Risk estimate of service disruption caused by ionospheric scintillations
- (18) Risk estimate of micro-particle impacts
- *Transionospheric Radio Link* -
- (19) Near real-time TEC maps
- (20) Forecast TEC maps
- (21) Quality assessment of ionospheric correction
- (22) Near real-time ionospheric scintillation maps
- (23) Monitoring and forecast of ionospheric disturbances
- *Space Surveillance and Tracking* -
- (24) Atmospheric estimates for drag calculations
- (25) Archive of geomagnetic and solar indices for drag calculation
- (26) Forecast of geomagnetic and solar indices for drag calculation
- (27) Nowcast of ionospheric group delay
- *Non-space systems Operation* -
- (28) Service to airlines
- (29) Service to resource exploitation system operators
- (30) Service to auroral tourism sector
- (31) Service to power systems operators
- (32) Service to pipeline operators
- *General Data Service* -
- (33) Latest data service
- (34) Space weather nowcast and forecast products
- (35) Event based alarms
- (36) Space weather data archive
- (37) Space Weather Support Material
- (38) Virtual space weather modelling system
- (39) Guaranteed data service for third-party/added-value service providers

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