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Integrating plasmasphere, ionosphere and thermosphere observations and models into a standardised open access research environment: The PITHIA-NRF international project

Anna Belehaki [a,*], Ingemar Häggström [b], Tamas Kiss [c], Ivan Galkin [d,e], Anders Tjulin [b], Mária Miháliková [b], Carl-Fredrik Enell [b], Gabriel Pierantoni [c,1], Yin Chen [f], Gergely Sipos [f], Sean Bruinsma [g], Viviane Pierrard [h], David Altadill [i], Antoni Segarra [i], Víctor Navas-Portella [i], Emanuele Pica [j], Luca Spogli [j], Lucilla Alfonsi [j], Claudio Cesaroni [j], Vicenzo Romano [j], Sara Mainella [j], Pietro Vermicelli [k], Tobias Verhulst [l], Stefaan Poedts [m,n], Manuel Hernández-Pajares [o], Dalia Buresova [p], Jan Rusz [p], Jaroslav Chum [p], Fabien Darrouzet [h], Edith Botek [h], Hanna Rothkaehl [q], Barbara Matyjasiak [q], Mariusz Pożoga [q], Marcin Grzesiak [q], David Chan You Fee [c], Dimitris Kagialis [c], Ioanna Tsagouri [a], Angeliki Thanasou [a], Themistocles Herekakis [a], Jean-Marie Chevalier [r], Nicolas Bergeot [r], Alexandre Winant [h], Maaijke Mevius [s], Ben Witvliet [t], Victoria Graffigna [o], Aurélie Marchaudon [u], David Wenzel [v], Martin Kriegel [v], Jürgen Matzka [w], Guram Kervalishvili [w], Tero Raita [x], Reko Hynönen [x], Jurgen Watermann [y]

[a] Iaasars, National Observatory of Athens (NOA), Metaxa and Vas. Pavlou, Palaia Penteli, 15236, Greece
[b] Eiscat Scientific Association (EISCAT), Rymdcampus 1, Kiruna 981 92, Sweden
[c] The University of Westminster LBG (UOW), Regent Street 309, London W1B 2UW, United Kingdom
[d] Borealis Global Designs Eood (BGD), BLVD Maria Louisa 24 Entr A FLOOR 1 AP 1, Varna 9000, Bulgaria
[e] Center for Atmospheric Research, University of Massachusetts Lowell (UML), 600 Suffolk Street, Lowell, MA 01854, USA
[f] Stichting EGI (EGI), Science Park 140, Amsterdam 1098 XG, the Netherlands
[g] Centre National D'etudes Spatiales (CNES), Space Geodesy Office, 18 Avenue E. Belin, 31401 Toulouse, France
[h] RoyaI Belgian Institute for Space Aeronomy (BIRA), AVENUE CIRCULAIRE 3, Bruxelles 1180, Belgium
[i] Observatorio del Ebro Fundacion, CSIC - Universitat Ramon Lull, Roquetes 43520, OE, Spain
[j] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Via di Vigna Murata 605, 00143, Rome
[k] SpacEarth Technology (SET), Viale dell'Astronomia 18, 00144 Rome, Italy
[l] Royal Meteorological Institute of Belgium(RMI), AVENUE CIRCULAIRE 3, Bruxelles 1180, Belgium
[m] Katholieke Universiteit Leuven (Ku Leuven), Dept. of Mathematics/CmPA, Oude Markt 13, Leuven 3000, Belgium
[n] University of Maria Curie-Skłodowska (UMCS), ul. Marii Curie-Skłodowskiej 1, 20-031 Lublin, Poland
[o] Universitat Politecnica de Catalunya (UPC), Mod. C3 Campus Nord UPC, c/ Jordi Girona 1-3, 08034 Barcelona, Spain
[p] Ustav Fyziky Atmosfery AV CR, v.v.i. (IAP), BOCNI II 1401, PRAHA 4 141 31, Czech Republic
[q] Centrum Badan Kosmicznych Polskiej Akademii Nauk (CBK PAN), Bartycka 18A, 00-716 Warsaw, Poland
[r] Koninklijke Sterrenwacht van Belgie (ROB), Avenue Circulaire 3, Bruxelles 1180, Belgium
[s] The Netherlands Institute for Radio Astronomy (ASTRON), Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands
[t] University of Twente, Faculty of EEMCS, Radio Systems, Enschede, the Netherlands
[u] Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse, ROUTE DE NARBONNE 118, TOULOUSE CEDEX 9 31062, France
[v] Deutsches Zentrum Fuer Luft - und Raumfahrt ev (DLR), Kalkhorstweg 53, 17235 Neustrelitz, Germany
[w] Helmholtz Zentrum Potsdam Deutsches Geoforschungszentrum GFZ, TELEGRAFENBERG 17, Potsdam 14473, Germany

* Corresponding author at: IAASARS, National Observatory of Athens, Palaia Penteli 15236, Greece.
E-mail address: belehaki@noa.gr (A. Belehaki).

[1] Deceased, December 2023.

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[x] Oulun Yliopisto (SGO), Pentti Kaiteran Katu 1, Oulu 90014, Finland
[y] Jfwconsult (JFW), LA Tetrade Chemin De Pichot, Tourrettes 83440, France

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Abstract

The PITHIA-NRF project "Plasmasphere Ionosphere Thermosphere Integrated Research Environment and Access services: a Network of Research Facilities" aims at building a European distributed network that integrates observations from space and ground, data processing tools and models to support scientific research on the Plasmasphere-Ionosphere-Thermosphere system. PITHIA-NRF is designed to provide formalised open access to experimental facilities, data and models, standardised data products, and training services. Participating organisations that operate these facilities, formed twelve nodes in eleven European countries. These nodes work on optimising their observing facilities and offer *trans*-national access to scientists and engineers. The PITHIA-NRF e-Science Centre is a core element of the project. Its design and evolution are controlled by a systematic ontology which governs the collection of scientific observations and research models, jointly termed data collections, which are registered with the e-Science Centre. Several tens of data collections are being registered. Data collection registrations adhere to FAIR principles and transparent quality measures to a large extent. The e-Science Centre facilitates the execution of research projects proposed by researchers from inside and outside the PITHIA-NRF consortium which require *trans*-national access to and understanding of data collections (observations and models) residing at one or several PITHIA-NRF nodes. Upon completion of the project a comprehensive collection of observations and models will have been gathered by the e-Science Centre for the benefit of efficient scientific research which relies on Europe-wide collaboration.

1. Introduction

Physical processes in the Earth's ionosphere, thermosphere, and plasmasphere result in an extremely complex physical system which is the source of many scientific, operational, societal, and environmental challenges that affect the smooth and uninterrupted operation of technological systems. Some indicative affected applications are: (1) high-frequency (HF) radio communication and localisation (Knipp, 2016; Witvliet, 2016), geolocation systems and associated ground- and satellite-based augmentation systems (Roy, 2013); (2) space-based communications (Dorman, 2005), communication between the Earth and ground stations and rovers on the Moon, on Mars and other planets (Barbieri, 2004; Bergeot et al., 2019); (3) communication with deep space missions (Woo, 2007); (4) low-frequency radio astronomy and Synthetic-Aperture Radar (SAR) observations (Pi, 2015).

The importance of the socioeconomic impact of these effects (Vermicelli et al., 2022) indicates the need to release improved nowcasting and forecasting tools for the upper atmosphere and the plasmasphere. To meet this goal, a first fundamental step is to advance access to science data, analysis tools and scientific models and facilitate the transition of models from research to operational status; this is the main objective and the ambition of the Research Infrastructure project PITHIA-NRF, implemented with funding from the European Commission Horizon 2020 Programme. PITHIA-NRF, the Plasmasphere Ionosphere Thermosphere Integrated Research Environment and Access services: a Network of Research Facilities, aims to build a European distributed network integrating observing facilities, data collections, data processing tools and prediction models dedicated to ionosphere, thermosphere and plasmasphere (ITP) research. PITHIA-NRF is designed to provide formalised access to experimental facilities, to Findable, Accessible, Interoperable, Re-usable (FAIR) data, to standardised data products and to training and innovation services. PITHIA-NRF paves the way for the establishment of a research environment that provides new observing technologies, procedures and tools that support transition of research models to high-level data products tuned to meet the requirements of the technologies concerned, linking best-in-class R&D facilities for the provision of seamless multi-technology services.

European institutions operate a large number of world-class ground- and space-based instruments dedicated to observing the Earth's ionosphere, thermosphere and plasmasphere. The management and processing of the data collections acquired by these heterogeneous instruments is not standardised and the policies for access and exploitation are different and mainly tuned to national priorities. Due to this fragmented operation, and different access policies, researchers in Europe and worldwide cannot exploit the full potential of these important research assets, despite the significant investments made mainly through national and regional funds.

The PITHIA-NRF integration scheme unites the research facilities, databases and models in a single research environment and renders them easily accessible to the European researchers and to all interested individuals and organisations, ensuring their optimal use and promoting cooperative development.

The research facilities serve the following fundamental scientific demands:

1. Access to the network facilities by scientists and engineers, for the implementation of user-design projects, using the unique observing capabilities that PITHIA-NRF offers.
2. Access to long-term observational data of the near-Earth space environment to build a comprehensive view of the Ionosphere – Thermosphere – Plasmasphere system, and also to develop and validate models.
3. Access to validated models and their results and to relevant training material on the modelling concepts, and on the physics principles embedded in the empirical models, addressed to the new generation of researchers.
4. Access to a platform that provides tools for the development and integration of new models for near-Earth space, which are indispensable for describing, explaining and ultimately forecasting the behaviour of this complex system, and mitigating adverse space weather effects on vulnerable technologies.

From its inception, PITHIA-NRF has been an integral part of the global network of research infrastructures (Ishii et al., 2024), as its foundation is based on integration principles set by EGI (a pan-European e-infrastructure), URSI, and ESA (SSA and EO Programmes) regarding data model standards and maturity scales. It relies on data collection and management standards and policies set by the EOSC, mainly provided by URSI, the IGS GNSS network (such as raw GNSS RINEX- and global VTEC IONEX- formats) and CCMC/NASA. The adoption of specific standards is considered in the PITHIA-NRF data policy definition, which is necessary given the particularities of the upper atmosphere data sets that are a mixture of ground-based and space-borne data and contain a variety of data products extracted from models or processed with data curation tools.

Fig. 1 shows the structure of PITHIA-NRF. An advanced level of integration is obtained via the alignment and use of common standards, observation strategies, data management strategies, data formats, scientific models, and e-infrastructures.

The integration is achieved through:

- The establishment of the e-Science Centre (eSC) for the registration of data collections, their discovery, access and re-use. Data collections registered in the eSC are available with open access. However, registrations in the eSC are accepted by authorised users either from the project beneficiaries or from any other party, such as TransNational Users or institutions willing to use the eSC as a central repository for data and models.
- The development of policies for common data management and quality control.
- The creation of a space physics ontology and community metadata standard facilitating the establishment of a shared language, essential for streamlined data integration.
- The optimisation of the operation of the observing facilities operated within the PITHIA-NRF nodes and the provision of standardised access to scientists and engineers to conduct Research and Development projects.

Models and data made available at the Nodes are made compatible with national e-infrastructures brought together in EGI. The integrated system provides an extended exploitation potential for users regarding observing facilities, data, application models and workflows. Delivery towards users is done via the PITHIA-NRF e-Science Centre and is promoted by EOSC.

The following sections provide details about the implementation of integrated activities and the outlook for the sustainability of the PITHIA-NRF Research Infrastructure on a long-term perspective.

2. The network of research facilities

The Network of Research Facilities consists of 12 nodes that provide access to key observing and data processing infrastructures for the investigation and modelling of physical processes acting in the Earth's upper atmosphere.

2.1. Research priorities in PITHIA-NRF nodes

Table 1 provides a short description of the research specialisation of each node and the indicative research topics for project implementation by external research users.

The PITHIA-NRF nodes provide access to the data collections through its local databases. Within the course of the project the majority of these local databases are upgraded to meet the FAIR requirements and their metadata are registered in the eSC. In this way, the eSC became the central node of the network of local databases and it is the end point from where PITHIA-NRF data collections can be discovered with open access. However, the data itself are hosted and maintained by the nodes. It depends on the policy of each node whether the registered data collections are updated in real-time, or with a latency which is again defined by the policy of the data owners.

The eSC, as the main access point for the data collections, provides access also to global data bases of key interest for the PITHIA-NRF community such as the GIRO database for Digisonde data, the IGS database for GNSS data, and the GFZ and DTU databases for geomagnetic and solar indices. The eSC is continuously updated with new registrations and hopefully more data collections will be accessible in the near future to facilitate Research and Innovation projects implemented in the nodes.

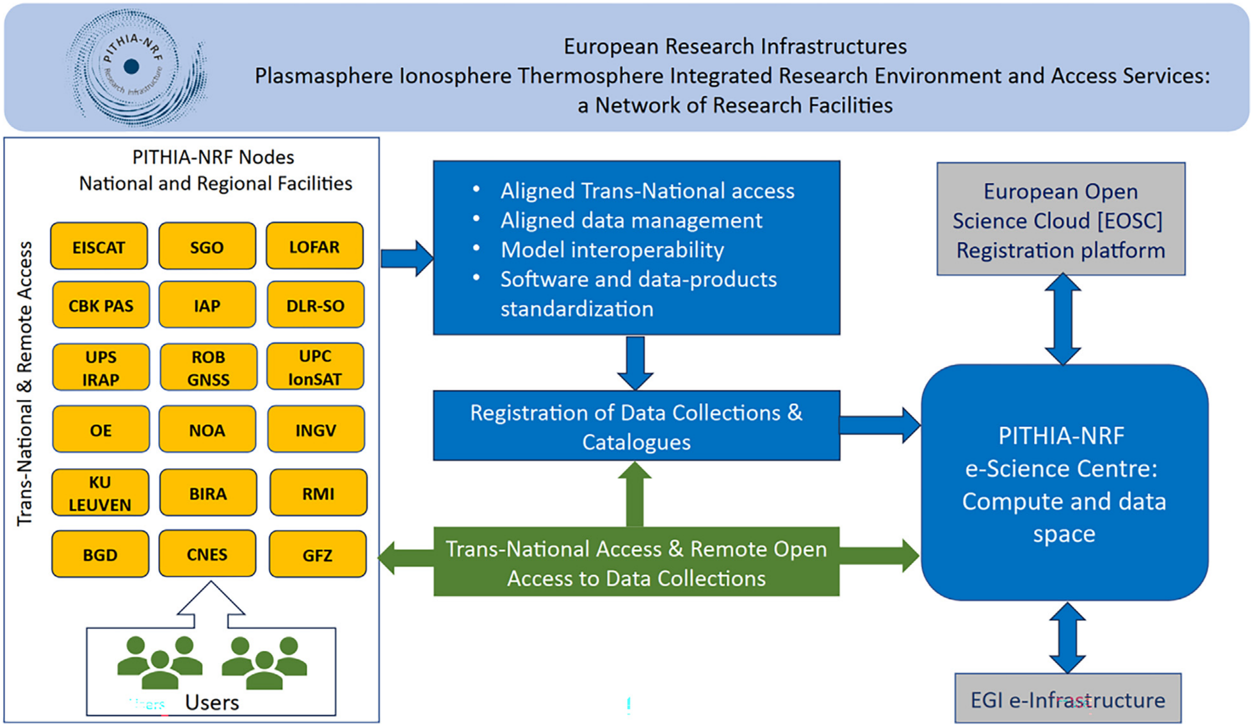

Fig. 1. PITHIA-NRF integration concept.

2.2. Guided access to PITHIA-NRF nodes via TNA projects

Access to PITHIA-NRF nodes is provided to selected users after the successful evaluation of their Transnational access (TNA) research proposals. The access can be granted for projects requiring on-site work and/or remote execution.

Once a proposal is positively evaluated and accepted for implementation in a PITHIA-NRF node, the TransNational Access (TNA) project is implemented. The PITHIA-NRF TNA programme has released seven open calls since the start of the PITHIA-NRF Horizon 2020 project. These calls are detailed on the project web site, regarding the commitments from the side of the project and the side of the applicants and the evaluation criteria. In the frame of the PITHIA-NRF TNA programme 47 projects are completed or currently implemented.

The choices available to the applicants are summarised in Fig. 2.

The user gets access to observing facilities operated by the node (in case of on-site access) and to local databases and/or to the eSC (for on-site and remote implementation). Depending on the specific TNA project, the first phase usually includes the collection of the required data either through special campaigns or through the databases and the eSC.

The second phase includes the processing of the collected data:

– If scientific observations are collected for a special campaign, data (*acquisitions*) can be evaluated regarding the quality (see section 5) and can be registered in the eSC as a new data catalogue.
– If the collected data are used for the development of a scientific model, then after the completion of an iterative procedure that includes model design – development – verification – validation, the results of the model (*computations*) can be registered in the eSC as a new data collection. The PITHIA-NRF ontology (Galkin, 2023) supports the registration of several types of scientific models, including empirical and physics-based models. The model execution and the storage of results depend on the data collection interaction method that will be chosen by the user (see Section 4.2).
– If the collected data are used for the calibration of an instrument, the results can be published (registered) in the eSC in the form of a catalogue and/or can be transformed to a new high level data product and be used for a new innovation project.

High level data products result from intensive data processing applied over a set of data (acquisitions and computations) and very often require a chain of scientific models to be used in the processing chain (workflows).

2.3. Research results obtained from TNA projects

The operation of PITHIA-NRF nodes as a network of research facilities provides a framework for exchange of expertise, new ideas and concepts. Through this activity, interfaces are being developed with innovation actions, reaching out to the engineering community, and the space agencies which have specific requirements for technology readiness and standardisation in instrumentation and soft-

Table 1
Nodes research specialisation.

PITHIA-NRF nodes	Indicative research topics for implementation by scientific users
NOA node: HF VI experiments and ionospheric models *Operated by NOA, Athens (Palaia Penteli), Greece*	• Ionospheric modelling for nowcasting and forecasting purposes: Modelling formulation of ionospheric storm effects at middle latitudes driven by solar wind input; Data – driven ionospheric specification models, using different training data sets and/or deep-learning techniques; Reconstruction of electron density profile ingesting ground and space-based observations • Validation of ionospheric specification models compatible with international practices • Ionospheric data quality control: development of higher-level data-products based on ionospheric autoscaled data filtering algorithms • Ionospheric irregularities and travelling ionospheric disturbances (TIDs): identification and propagation patterns for TIDs in the bottomside and topside ionosphere; identification of post-seismic effects in the ionosphere • Digisonde experiments: vertical soundings in autonomous and synchronised modes; joint experiments/special campaigns with bistatic HF sounders' operations.
EISCAT node: Incoherent scatter radar (ISR) and other VHF/UHF high power large aperture radar experiments, HF ionospheric heating experiments, Dynasonde data *Operated by EISCAT, Kiruna, Sweden*	• Auroral and polar cap electrodynamics • Space environment – atmosphere coupling at the statistical southern edges of the polar vortex and the auroral oval • Thermosphere-ionosphere coupling • Combined ISR and active HF Heating experiments • ISR WorldDay collaboration • Meteoroids, dust particles and near-Earth objects • Ionospheric 3D imaging • Dynasonde database (DSND/NeXtYZ parameters, ionospheric irregularities)
LOFAR node: low-frequency radio observations *Operated by ASTRON, The Netherlands*	Ionospheric scintillation at low radio frequencies: • Assessment of any association with scintillation seen by GNSS • Assessment of any association with large-scale structures (e.g., TIDs) detected and modelled by other instruments.
CBK/PAS node: multi-instrument diagnostics of plasma structures *Operated by CBK/PAS, Warsaw, Poland*	• Quantification of the impact of magnetosphere–ionosphere coupling on auroral region boundary layers behaviour using satellite in situ measurements from DEMETER, RELEC, COSMIC, as well as measurements from ground-based infrastructures • Implementation of novel techniques based on LOFAR diagnostics for determining the characteristics of small and middle scales ionospheric irregularities
SGO node: High latitude ionosphere physics experiments *Operated by the Sodankyla Geophysical Observatory, Finland*	• Auroral electrodynamics using entire Finnish Pulsation Magnetometer network, comparison to visual auroral oval and exploitation of IL and IU indices • Electron precipitation from KAIRA, comparison to model results • Ionospheric D region cosmic noise absorption using riometer network and KAIRA observations
UT3 IRAP node: Plasmasphere- Ionosphere Thermosphere modelling *Operated by UT3-IRAP, Toulouse, France*	• Validation of the IRAP Plasmasphere-Ionosphere Model (IPIM) results especially during solar eclipses, solar flares, CIRs or CMEs, using data from ionospheric stations, SuperDARN radars and GNSS satellites signals; • Quantification of Joule heating and energetic particle precipitation heating at auroral latitudes through IPIM modelling fed with realistic inputs such as SuperDARN convection, satellites particle precipitation; • Assessment of the thermosphere characteristics during perturbed periods (CIRs, CMEs) and their effect on the IPIM ionosphere modelling at high and middle latitudes. Comparison with ionospheric observations (ionosondes, EISCAT radars…).
ROB GNSS node: GNSS hardware calibration and data processing facility *Operated by the ROB GNSS group, Brussels, Belgium*	• Adaptation of the ROB-IONO software process global data. • Post-processing and nowcasting products on vTEC and sTEC at ionospheric pierce points. • Test for Galileo inclusions in the processing • Multi-GNSS comparison to test interoperability of the different systems. • GNSS hardware delay estimation

Table 1 (*continued*)

PITHIA-NRF nodes	Indicative research topics for implementation by scientific users
UPC IonSAT node: Precise GNSS modelling for new scientific and technical applications. *Operated by UPC IonSAT group, Barcelona, Spain*	• Global Tomographic modelling of the ionosphere computed with multifrequency GNSS phase-carrier observations. • Electron density profiles derived from LEO based GNSS radio-occultation measurements. • GNSS-Ionosphere Measurement of Extreme UltraViolet (EUV) solar flux variation during solar flares
OE node: HF Digisonde-to-Digisonde (D2D) experiments *Operated by OE, Roquetes, Spain*	•HF D2D experiments to improve ionospheric specification in west Europe. • Identification and specification of Large Scale Travelling Ionospheric Disturbances (LSTIDs). • Identification and specification of Plasma Depletions by means of GNSS data. • Solar flare absorption effects on radio signals.
IAP node: Ionosphere-lower atmosphere coupling, *Operated by IAP, Prague, Czech Republic*	• Analysis of wave coupling processes and consequences in the whole atmosphere and ionosphere using CDSSs and European Digisonde network measurements • Validation of medium scale TIDs detection techniques • Ionosphere/gravity wave climatology • Troposphere - upper atmosphere - solar wind coupling studies exploing atmospheric electricity, ionosphere and solar wind data
INGV node: ionospheric irregularities: specification, modelling and mitigation *Operated by INGV, Rome, Italy*	• Ionospheric scintillations: Monitoring, modelling, forecasting and climatological analysis. • Mitigation algorithms/techniques for HF. communications (Ray tracing) and for ionospheric scintillations on high accuracy positioning (PPP, NRTK) and Synthetic Aperture Radar Imaging; • Ionospheric correction for augmentation systems in challenging areas (high and low latitudes).
DLR-SO node: Space weather impact in the ionosphere and plasmasphere and mitigation of the effects *Operated by DLR, Neustrelitz, Germany*	• Solar flare monitoring and analysis of the ionospheric response. • Impact analysis for HF communication and GNSS performances by combination with GNSS measurements (TEC, TEC rates) • Spectral analyses to study radiation impacts on the lower ionosphere • Research and analysis of D-Layer ionosphere disturbances from below (Gravity waves, Earthquakes, Hurricanes, radiation sources) • Analysis of ionospheric response during Solar Eclipse events • Cross correlation with external data sets from users (e.g. in the domain of GNSS-positioning or communication) to check the vulnerability of their systems to solar flare events • Specification of topside ionosphere and plasmasphere electron density using NPSM

ware. In this framework, specific activities have already been carried out in PITHIA-NRF nodes to promote the networking concept and the design of new scientific services based on the needs expressed by the scientific/engineering community and by the space industry.

The objectives and some results from selected TNA projects, organised in four research areas, are summarised here below:

2.3.1. Multi-instrument data analysis for detection and modelling of ionospheric storm effects and irregularities

The majority of projects belonging to this group address topics relevant to the analysis of multi-instrument data for the study of the coupling of the lower atmosphere with the ionosphere, the coupling of the bottomside and topside ionosphere and the detection of upper atmosphere disturbances triggered by earthquakes, solar storms and solar flares.

1. Upward Propagating Gravity Waves in the lower and middle ionosphere (UPGW)

Gravity waves (GWs) are an important class of atmospheric waves that can propagate from the troposphere up to the upper atmosphere, where they can contribute significantly to dynamical changes in the ionosphere. The aim of the UPGW project was to gain a deeper understanding of the coupling between the lower and the middle ionosphere via gravity waves by the concurrent analysis of narrowband VLF (characterising GWs in the lower ionosphere), continuous HF Doppler (characterising GWs in the middle ionosphere) and lightning data provided by the World Wide Lightning Location Network (WWLLN). Thereby, the research is expected to contribute to a better understanding and mitigation of the distorting effects of atmospheric waves on satellite communications and global GNSS-based positioning.

The project aims at investigating the simultaneous occurrence of GWs in the lower ionosphere and in the F layer, by studying the nighttime ionosphere using narrow-band VLF measurements (characterising GWs in the E layer) carried out at Tihany, Hungary and the multi-point and multi-frequency continuous Doppler sounding system, characterising GWs in the F layer (Chum et al., 2023) operated by the Institute of Atmospheric Physics, Czech Academy of Science (IAP Node). Due to the oblique propagation of GWs, multiple VLF propagation paths are analysed (Fig. 3) to find the path where the occurrence of GWs shows the highest correlation with the detection of GWs by the Doppler system. The goal is not to identify strictly the same GW in the lower ionosphere and in the F layer, but to explore the statistical relationship between the occurrence of GWs in the two ionospheric regions.

2. Characterization of Plasma Depletions and Effects on Geodetic Applications (CPD&EGA)

In this work, local features of the ionosphere are identified, monitored, and characterised from ionosonde measurements at Ebro Observatory, satellite ultraviolet images from Special Sensor Ultraviolet Spectrographic Imager (SSUSI), total electron content (TEC) index (ROTI) (Pi et al., 1997) from GNSS, and all-sky 630 nm images at Oukaïmeden Observatory (Morocco). This TNA project is implemented in the OE node. The dynamics and coupling processes of plasma depletions in relation to upper atmosphere and space weather conditions are studied for the geomagnetic storm of 28 February 2014.

This work verifies that ionosonde, satellite UV imaging, GNSS-ROTI, and all-sky imaging data can be combined to investigate and characterise ionospheric plasma depletions at local and regional scales (Calabia et al. 2024). In this scheme, the low latitude plasma depletion that appeared in Spain during the geomagnetic storm of 27 February 2014, is investigated and characterised (Fig. 4); its variations in space and time are interrelated with the different multi-instrument data.

3. Comparisons and validation of the TIDs occurrence in the ionospheric tilt measurements with the GNSS observations (CVTIDs)

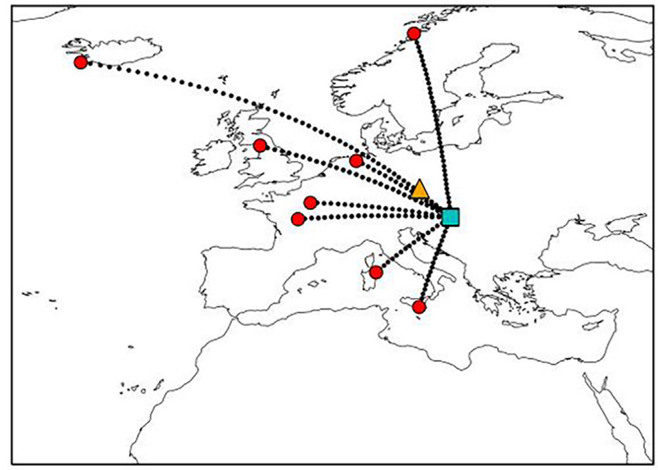

Fig. 3. Map showing the different geophysical measurements to be used in the project. The orange triangle indicates the location of the continuous Doppler sounding system (Czech Republic), while the blue square indicates the location of the narrowband VLF receiver system (Tihany, Hungary). Red circles mark military VLF transmitters, which are connected to the Hungarian VLF receiver by dotted lines.

The main objective of this project is to compare the capabilities and limitations of various observational techniques for studying MSTID over the European sector. Furthermore, these techniques will be used to quantify the causes and sources of MSTIDs and to identify the potential indicator for developing the MSTID forecasting.

To attain the main objective, the following specific objectives are proposed:

- Compare and validate the ionospheric tilt measurement results with the GNSS-dTEC estimated MSTIDs and explore the physical reasons relating ionospheric gradients with ionospheric tilt.
- Quantify the role of Es and F region coupling on the generation of TIDs under inter-hemispheric perspectives.

The project is under implementation in the OE node.

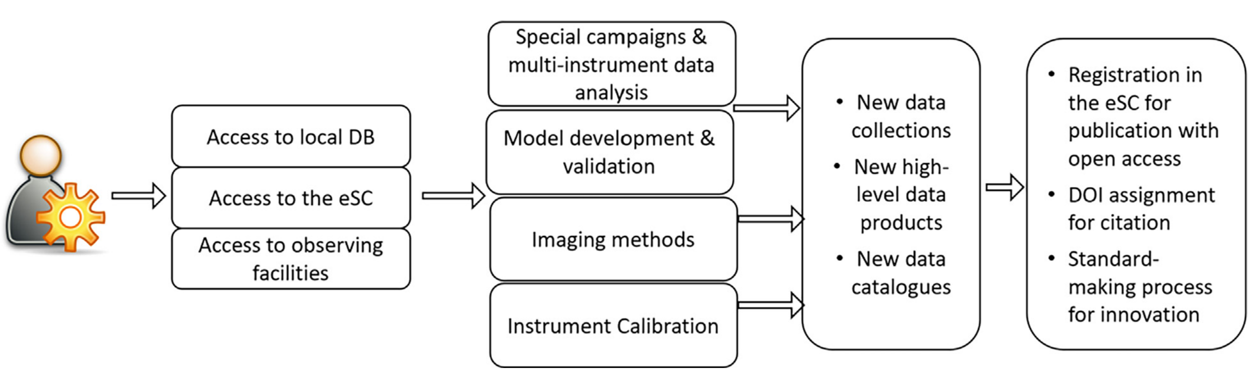

Fig. 2. PITHIA-NRF TNA choices.

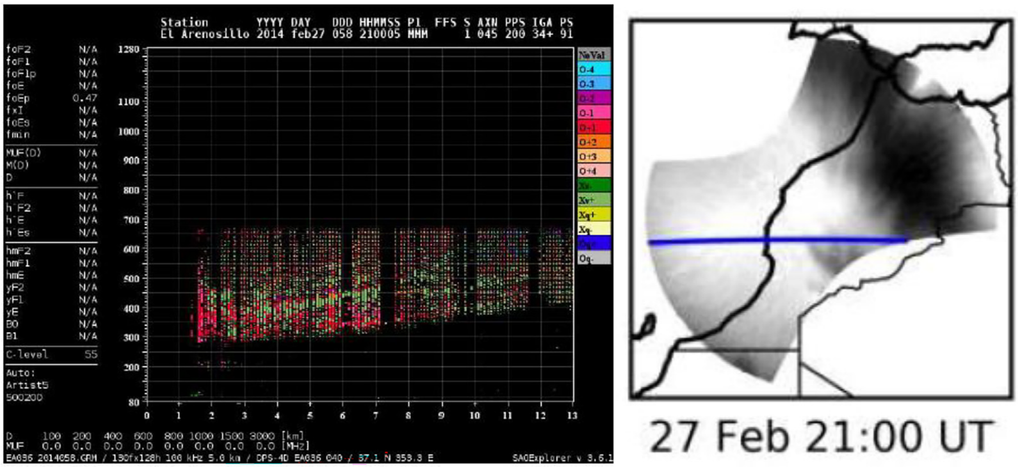

Fig. 4. Left panel shows the ionogram from El Arenosillo Observatory (EA036), Spain, for 27 February at 21:00 h UTC, where range spread F reveals the presence of a plasma depletion. Right panel shows an all-sky OI 630.0 nm image captured at Oukaïmeden Observatory (OO), Morocco, on 27 February 2014, where spatial characteristics of the plasma depletion can be observed.

4. Longitudinal differences in travelling ionospheric disturbance characteristics at middle latitudes (LONG)

Thanks to the TNA programme, two groups of researchers from the Ionosphere Institute (Kharkiv, Ukraine) and the Institute of Atmospheric Physics, Czech Academy of Science (IAP Node), using a combination of various radiophysical methods studied ionosphere dynamics above Europe during the 22–24 September 2020 moderate geomagnetic storm. The results obtained in the project allow us to expand our knowledge about the regional characteristics of TIDs and improve the prediction capabilities of ionospheric models.

Three ionosondes located in Juliusruh, Pruhonice and near Kharkiv, and the Kharkiv incoherent scatter radar were employed to study temporal and spatial TID signatures in ionospheric F2 peak density and height and electron density variations at the heights of 100–300 km (Fig. 5). TIDs were observed during enhancemed auroral activity and local sunrise terminator passage and the following specific characteristics were recorded: diurnal occurrence at each location, predominant period, vertical and horizontal phase velocity and wavelength, relative amplitude of electron density fluctuations and propagation direction. With increased storm intensity day-to-night variations of hmF2 and NmF2 increased at all three sites (Panasenko et al., 2023; Aksonova et al., 2024).

5. Wave-like structures in the ionosphere between Athens and Sopron (WIONAS)

Travelling Ionospheric Disturbances (TIDs) detection software codes and relevant data collections, provided by the NOA node, have been exploited by the WIONAS project to identify wave structures propagating within the ionosphere above the South-East European region, in the area between Sopron and Athens Digisonde stations. Ionosonde measurements, including ionograms and Digisonde-to-Digisonde TID observations between the two Digisonde stations were analysed. Based on the data availability from the two Digisonde stations, some recent geomagnetic storms and lower atmosphere dynamic events were selected for further study. TID results from the TechTIDE database (Belehaki et al.,2020) obtained from Digisonde measurements, and HF Interferometry method (based on the spectral

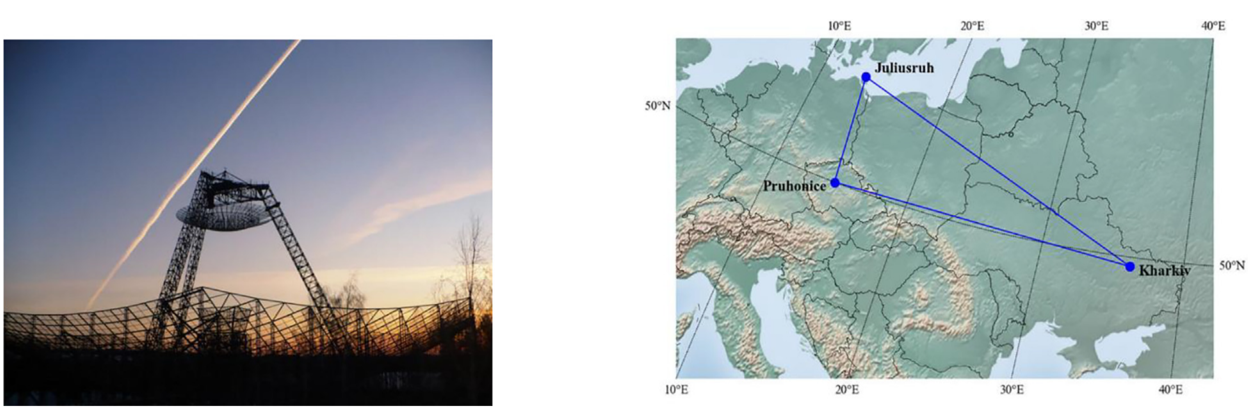

Fig. 5. Kharkiv incoherent scatter radar (on the left) and location of the instrumentation involved in the analysis (on the right).

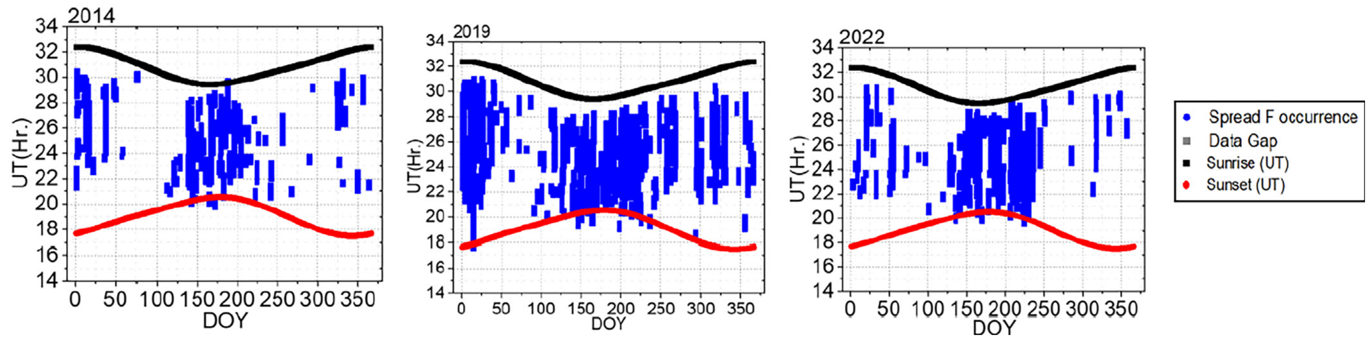

Fig. 6. Diurnal nighttime spread F occurrence over Ebro for (a) 2014, (b) 2019 and (c) 2022.

analysis of the MUF) and the GNSS gradient method, were analysed to obtain information about different triggering sources of the observed TIDs and their propagation characteristics.

6. Height-time-intensity (HTI) application and validation in TID and Es signatures on extended datasets (HAVES)

HAVES has three main objectives, nighttime spread F characterization over the Ebro Observatory (OE), comparison of two methods to detect LSTIDs – the HF-INT (Altadill et al., 2020) and the HTI (Haldoupis et al., 2006), and a long-term study of intermediate descending layers (IDLs). The project is implemented in the OE node. The first objective, the characterization of nighttime spread F, was based on an extended ionogram dataset recorded by the OE digisonde during the interval 2012–2022 (Fig. 6). These ionograms were analysed to identify nighttime spread F events and evaluate any seasonal and solar activity trends. Clear seasonal characteristics and yearly inverse solar activity spread F dependence was identified. The second objective, LSTID activity over OE has been studied in terms of the HF-INT and HTI techniques (exploiting ionograms at a 5-min resolution recorded from 2016 to 2022). Similarities and differences in the diurnal LSTID occurrence were noted over Ebro as extracted by these two different techniques. The third objective of HAVES was a long-term study of intermediate descending layers (IDLs) over OE by applying the HTI methodology.

7. Validation AND Assessment of near-real time detection and forecasting of LS-TIDs in Europe (VANDALS-TIDE)

The main scientific purpose of the project is to study specific LSTID activity to validate and assess the methods of the detection and forecasting of LSTIDs and define potential early indicators of LSTID activity. LSTID detection and forecasting products will be cross validated with analysis of independent data providing clear TIDs signatures. As part of the validation process, the forecasted events need to be compared with measured data like HF-INT, detrended Total Electron Content (dTEC), detrended isodensity contours (dNe(h)), and D2D products (from Digisonde measurements) over Europe. The project is under implementation in the OE node.

8. STorm-related Study of Ionospheric iRRegularities over southern Europe using digisondes and GNSS Data (STIRRED)

STIRRED aimed at highlighting some of the characteristics of the ionosphere by studying irregularities during disturbed geomagnetic conditions, focusing on southern Europe at geomagnetic latitudes of 35°-40°. Specifically, the objectives deal with the investigation of Spread-occurrence F in ionograms from El Arenosillo, Roquetes, Gibilmanna, and Athens ionosondes; and the study of TEC and ROTI behaviour from GNSS receiver networks in the Iberian Peninsula, Morocco, Italy, and Greece during geomagnetic storms. Additionally, the evolution of the Equatorial Ionisation Anomaly (EIA) during selected geomagnetic storms using data from global ionosphere maps of TEC (GIMs) has been addressed, to correlate observations of Spread-F, TEC, and ROTI with EIA evolution. The project's scope extended beyond the analysis of a few specific storms, with plans to expand the study to include storms of varying intensities occurring at different Universal Time (UTC). By assessing the ionosphere effect signatures in latitude, longitude, and local time, the project aims at providing insight into the broader impact of geomagnetic storms on the ionosphere above southern Europe. STIRRED project was implemented in the INGV node.

Irregularities observed during several storms occurred in 2014, characterised by high solar activity, appear to be linked to the limited northward extension of the EIA during the storm's main phase, as evidenced by GIMs. This localised expansion of the EIA underscores the importance of monitoring this area during storm phenomena to better understand its specific effects. Irregularities observed during several storms occurred in 2021, occurring during a period of low solar activity, could be attributed to Perkins instabilities, involving irregularities propagating from low to middle latitudes within discrete longitude sectors. This finding resonates with previous research in the North American sector. An example of the ROTI analysis for the 2021 storm is given in Fig. 7.

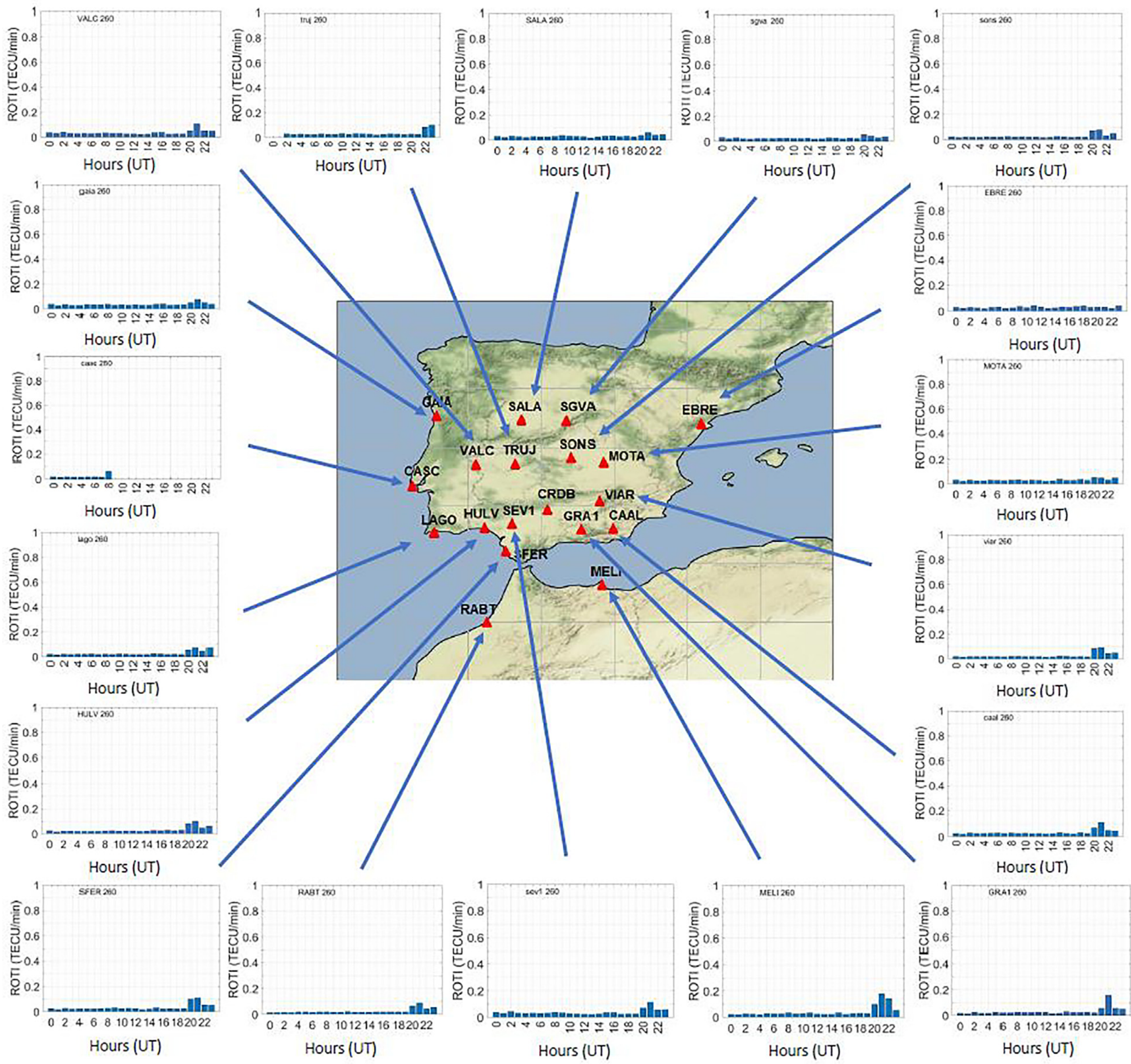

Fig. 7. Map of receiver stations and hourly averaged ROTI plots during the day of the main phase of the 17–18 September 2021 geomagnetic storm (24 h on 17 September 2021).

9. The F2-Layer Peak Height Response at mid-latitudes to Space Hurricane (FLPHR)

A Space Hurricane was observed for the first time on 20 August 2014 (Zhang et al., 2021). Different from the storm scenarios, Space Hurricanes occur under extremely quiet interplanetary conditions, with low solar wind speed, density, and northward interplanetary magnetic field. The extremely quiet interplanetary condition results in efficient lobe reconnection which leads to the formation of the space hurricane. The space hurricane opens a rapid energy transfer channel from space to the ionosphere and thermosphere, and would be expected to lead to important space weather effects. At the height of the ionosphere, it has a strong circular horizontal plasma flow with a nearly zero-flow centre and a coincident cyclone-shaped aurora caused by strong electron precipitation. The data analysis has shown negligible effect in VTEC maps and its topside component. However, different LSTID features between day 231 and day 232 of 2014, can be seen especially in the mid-latitudes in the morning sector. This provides the motivation to explore the changes of hmF2 and NmF2 during the Space Hurricane, to try to answer one question "Can ionospheric response to a Space Hurricane be identified in GNSS and Ionosonde data?" The project is accepted for implementation in the OE node.

10. SOlar Flare-induced Absorption in the ionosphere Research (SOFAR)

The primary objective of the SOFAR TNA project, implemented in the OE node, was to study the effect of solar flares on the ionosphere by comparing two different methods from the HUN-REN Institute of Earth Physics

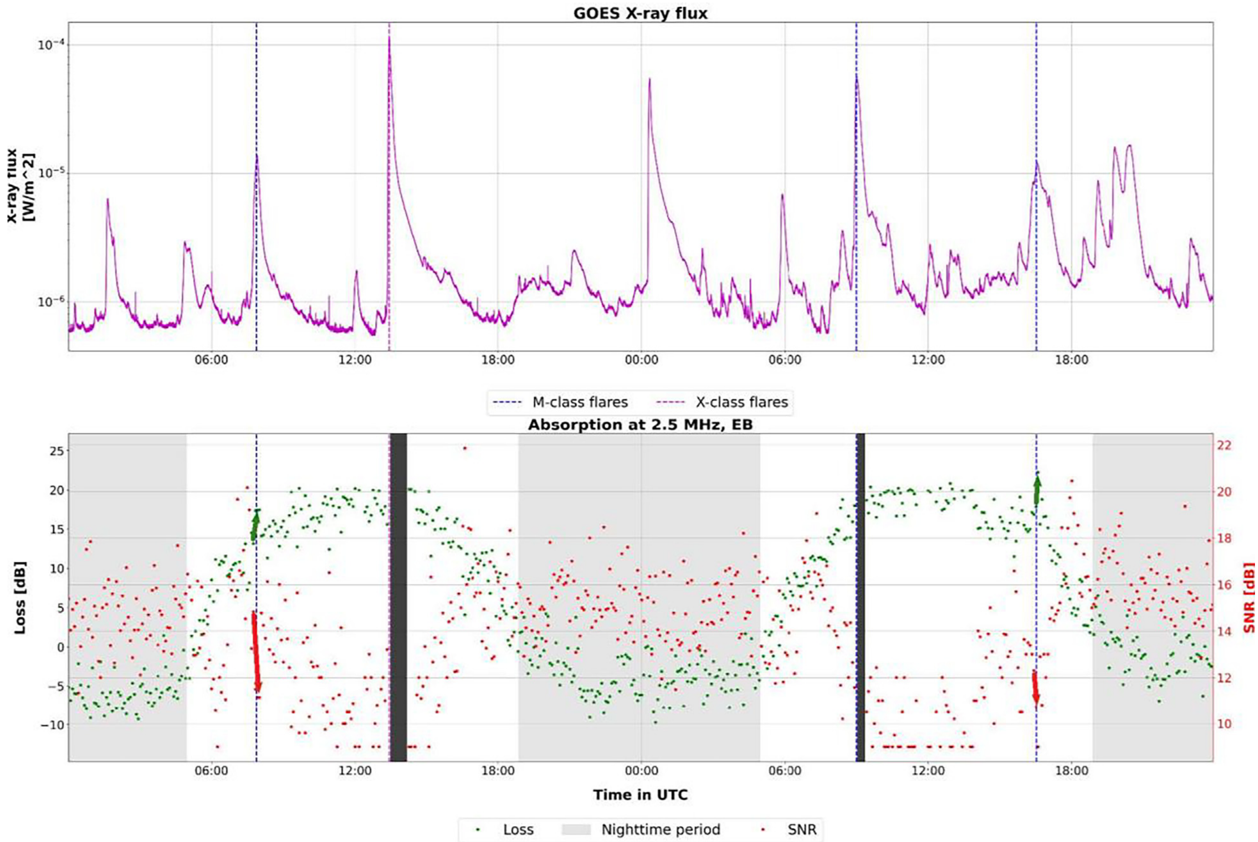

Fig. 8. The calculated absorption (green stars) and SNR (red stars) values at the 2.5 MHz frequency band (2.5 MHz+/-200 kHz) on the 3rd and 4th May 2022. The grey-shaded area represents the local nighttime periods, whereas the black areas denote the complete radio fade-outs. Green and red arrows mark the points when there was a clear increase or decrease associated with the flares in the absorption or SNR values, respectively. The corresponding GOES-16 X-ray flux is plotted on the upper panel by a magenta line.

and Space Science (EPSS) and from the OE. At EPSS, a novel method to calculate the ionospheric absorption of EM waves based on the amplitude data of Digisonde was used. The results derived from this so-called amplitude method were subsequently compared to the ones derived from the SNR (Signal-to-Noise Ratio) method developed by the OE. In the framework of the SOFAR project, 7 solar flare events were selected and analysed based on the data collected by the OE Digisonde. Both the absorption based on the measured amplitudes and the SNR values of the reflected EM waves were calculated for these flare events (Fig. 8). Subsequently, the temporal variation of the absorption and SNR data were compared with each other, and the effects of the solar flares were studied in the cases of both parameters.

11. Sensitivity of Ionospheric Disturbance detection by Swarm in time of strong Earthquakes in Aegean region (SIDSEA):

The earthquakes result from tectonic processes, which generate the so-called Lithosphere-Atmosphere-Ionosphere Coupling (LAIC). The tectonic plate boundaries are weak zones of the Earth's crust, where various chemical and physical processes contribute to LAIC. These are processes affecting the ionosphere from below, but their imprints in the ionosphere are mixed with those coming from different processes from above, related to the solar forcing and magnetic field variations. Acoustic Gravity Waves (AGW) occur in close time proximity to the largest crustal movements, whereas Electric Field Modifications (EFM) can last for days, and moreover, can be precursory to the largest mainshocks.

Thanks to the Trans-National Access (TNA) programme of PITHIA-NRF, a group of researchers from the UWM had the opportunity to work in the NOA node, in the framework of the SIDSEA project. SIDSEA investigated the sensitivity of various frequencies of the ionospheric observations' spectrum to the seismic activity. The data analysis performed for the SIDSEA project was focused on the Aegean Sea and over two years of moderate to strong seismic activity in 2020——2021. The project employed ionospheric observations from the Athens Digisonde AT138, TEC from co-located ground-based GNSS receivers and electron density from the in-situ observations collected by the Swarm satellites in the topside ionosphere. The Fourier-based band-pass filtering method was applied to all data series, after preliminary inspection of the spectrograms and initial assessment of these spectral bands, which showed a higher degree of correlation with seismic

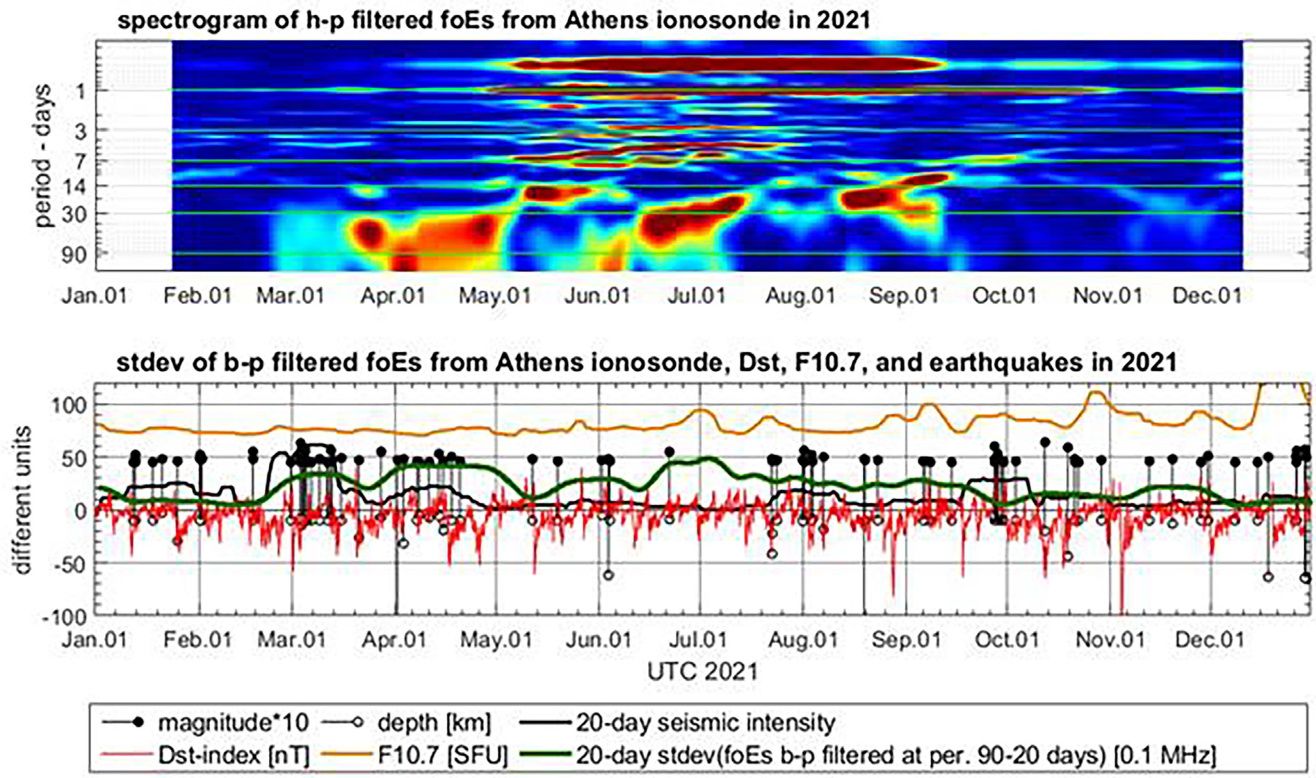

Fig. 9. Results from the sporadic E layer maximum frequency spectrogram from Athens Digisonde presented together with the seismic intensity recorded in the Aegean Sea.

sources in comparison to respective correlation with solar or geomagnetic variations (Fig. 9). It was observed that the use of long time series can help in the discussion on the evolution of LAIC processes. The variability of ionospheric characteristics appears to be different at different frequencies, which exhibit various sensitivity to seismic, solar-driven and magnetospheric factors. The sensitivity levels at analysed over-diurnal periods, rather suggested EFM channel of LAIC, as AGW channel is better detectable at much shorter wavelengths. The results of band-pass ionospheric data filtering in the Aegean Sea focused on LAIC are preliminary, but indicate the possibility of detection of relatively weak signals, which can be important in the observation of LAIC.

2.3.2. Development and validation of scientific models

Projects belonging in this group propose new models and/or validate existing ones with data from PITHIA-NRF.

1. Magneto-ionospheric modelling through Faraday rotation in Pulsar data (MaMo-FaRo)

’Broadband pulsar radiation can be effectively used to monitor the properties of the magneto-ionic media through which it propagates. Faraday rotation calculated from polarised pulsar observations provides an integrated product of electron densities and the line-of-sight component of the magnetic field in the intervening plasma. In particular, a time-variable effect mainly associated with the rapidly changing column density of the Earth’s ionosphere and plasmasphere heavily dominates the observed Faraday rotation of pulsar radiation. In this work, a performance test is carried out for three GNSS-based models of the ionosphere using observations of PSR J0332 + 5434 taken with the LOw Frequency ARray (LOFAR). This TNA project is accepted for implementation in the UPC-IonSAT node. As it was shown by Porayko et al. (2019), the conventional single layer model (SLM), which assumes that the ionosphere is a thin slab at a fixed effective height, is not capable of fully accounting for the ionospheric Faraday rotation in pulsar data. The simplified physics of the SLM is upgraded within IRI-Plas (International Reference Ionosphere and Plasmasphere) extended SLM and the dual-layer voxel TOmographic Model of the Ionosphere (TOMION), both of which partially account for the thickness and vertical dynamics of the terrestrial plasma. Although the last two improve the reconstruction of the ionospheric Faraday rotation, none of the considered models completely purge the observed residual variations. This study shows that the long term LOFAR observations of Faraday rotation of pulsars provide an excellent tool to test and improve models of the magneto-ionic content of the Earth’s atmosphere (Porayko et al., 2023).

2. Feasibility study of data-driven Autonomous Service for Prediction of Ionospheric Scintillations (ASPIS)

The ionosphere is the most important atmospheric layer that affects the radio signal between space-based missions and ground-based stations. Disturbances that can rapidly modify the amplitude and phase of the radio waves are called ionospheric scintillations. They represent a high-risk effect for the signal from GNSS (Global Navigation Satellite System) used for high-precision calculation of position and time. The ASPIS activity is supported by the European Space Agency (ESA) and is dedicated to study the feasibility of developing a data-driven service autonomously providing an assessment of ionospheric scintillation in a specific time ahead, based on available solar, space weather, geomagnetic, ionospheric, and thermospheric data for a particular location.

The objectives within the TNA program, implemented in DLR-SO node, were to:

1. become familiar with data of ionospheric scintillation (S4, $\sigma\phi$, ROTI) and other ionospheric parameters provided by DLR-SO;
2. incorporate these data into an existing data-driven approach;
3. investigate the performance of ASPIS in comparison with other current prediction models of ionospheric parameters;
4. compile user needs and requirements for ionospheric prediction service for future demonstration purposes and for potential operation purposes.

The main advantage is that the input from ASPIS TNA is self-consistent and has a straightforward temporal and spatial interpretation, in contrast to trying to put all raw data into the data-driven approach. An example of the projection of scintillation data is given in Fig. 10. All these aspects are known thanks to the TNA program and have not been considered before the start of ASPIS/ESA activity.

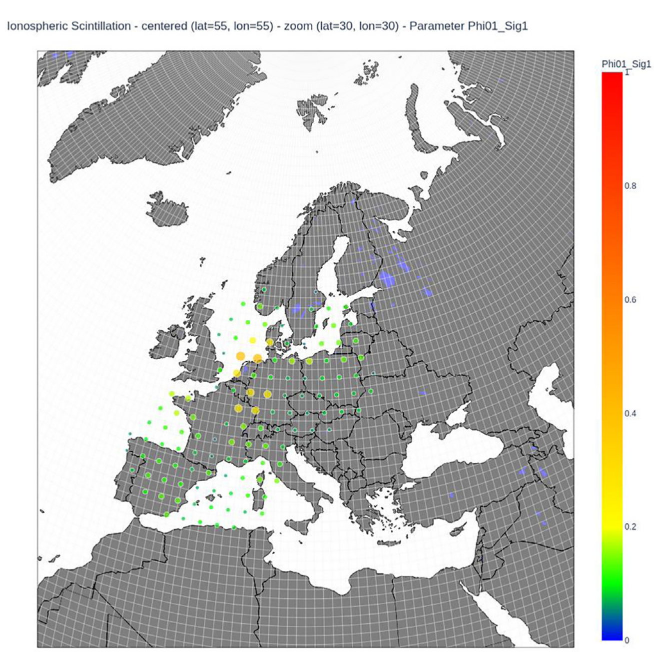

Fig. 10. The example of the projection of the scintillation data provided by DLR-SO to geographical coordinates for the three locations Toulouse (France), Neustrelitz (Germany) and Kiruna (Sweden).

3. Portuguese Regional Ionosphere MAps (PRIMA)

Instituto de Astrofísica e Ciências do Espaço at the University of Coimbra (IA-UC) has a small group (and only one working permanently on this subject in Portugal) of researchers working in the area of ionospheric studies. Up to now, no systematic studies of the ionospheric response to space weather disturbances (i.e., disturbances of solar and magnetospheric origin) were performed for Portuguese regions, neither continental nor insular (Azores and Madeira). One of the reasons is the lack of good quality data. Thus, the compilation of a database of ionospheric parameters including the total electron content (TEC) for the whole Portuguese region will be a necessary step for any study: data analysis, development of regional models to predict ionospheric response to different space weather events, development of regional ionospheric maps or other products that can be used by national service providers and end users.

Significant amount of the GNSS data from the Portuguese geodetic GNSS networks (as RAEGE-Az and RENEP) cannot be added to such a database because these data are available only as GNSS raw or pre-processed data formats (e.g., RINEX) and have to be converted to TEC data. Unfortunately, IA-UC team members did not have sufficient experience in such data processing. The PITHIA-NRF TNA call was a perfect opportunity for the IA-UC team members to obtain new knowledge working in the UPC-IonSAT node, where extensive experience exists in collecting and processing GNSS data from different GNSS systems.

As a result of the collaboration with UPC-IonSAT team, the IA-UC team obtained necessary knowledge and software to process the files and significantly enlarged the Portuguese ionospheric parameters database using high quality data from the Azores Archipelago. An example of TEC variations over Portugal during a geomagnetic storm is given in Fig. 11. The new data allowed us to perform comparative studies of ionospheric disturbances observed during geomagnetic storms at different longitudinal sectors (Barata et al., 2023).

4. Total Electron Content global and regional forecasting maps using artificial intelligence techniques (AI4TEC)

The AI4TEC project aimed to explore ionospheric forecasting through the utilisation of advanced Machine Learning (ML) algorithms. The primary emphasis was on improving the current model operated at the INGV node, which forecasts Total Electron Content (TEC) globally 24 h in advance. The main goal is to examine ionospheric variability caused by Space Weather conditions and to

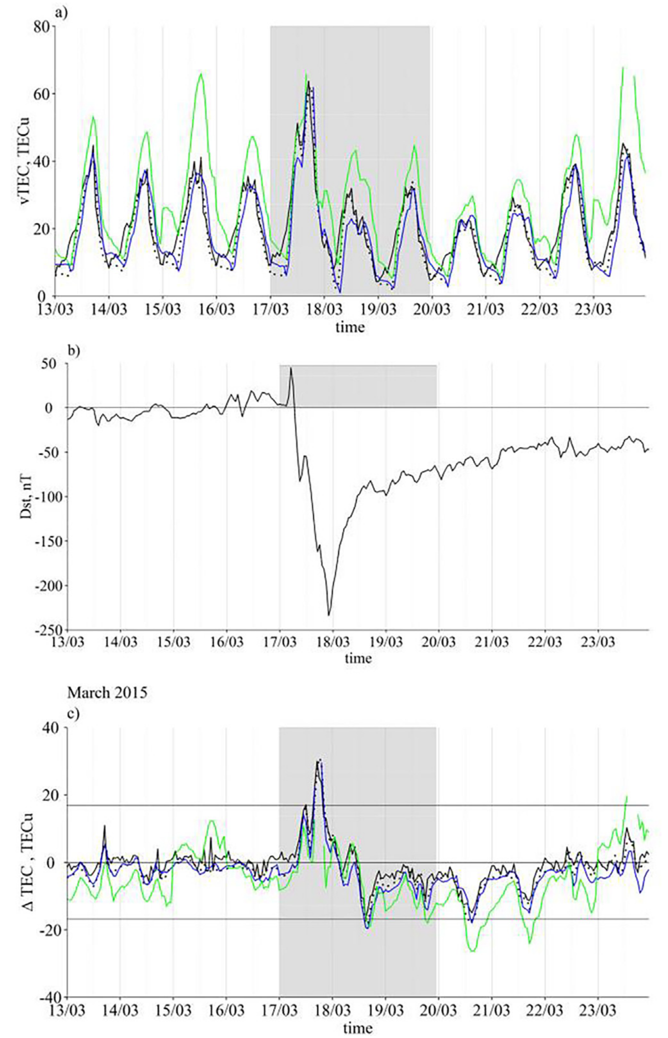

Fig. 11. Variations of TEC and Dst during March 2015: (a) variations of TEC measured at the three locations: Lisbon (black lines: Lis-SCINDA- solid line, Lis-SWAIR- dashed line, Lis-RENEp—dotted line), Azores (blue lines: Az-RAEGE—solid line, Az-RENEP— dashed line), and Madeira (Az-Madeira—green solid line). (b) Variations of Dst. (c) Variations of ΔTEC for the three locations. Horizontal lines mark ± 2σ limits for ΔTEC (extracted from Barata et al. 2023).

develop a predictive ML-based model for TEC. The project focused on two models: a global TEC forecasting model and a regional TEC model tailored for low latitude stations.

The experience gained from this project was instrumental in understanding the challenges associated with data limitations, leading to the identification of optimal datasets and parameters suitable for various ionospheric scales. Through thorough analysis, the complex relationships between solar activity, solar wind parameters, geomagnetic indices, and various ionospheric parameters were extensively investigated. This comprehensive analysis laid the foundation for meticulous feature selection and hyperparameter tuning, facilitating the implementation of ML models in real-time scenarios and for operational purposes.

The combined efforts of the team resulted in significant advancements, leading to the development of improved TEC models on a global scale, with a 24-hour forecasting capability. The ultimate goal is to operationalise these new models, making them accessible through the Tucuman Space Weather Center (TSWC) portal (spaceweather.facet.unt.edu.ar) and the eSWua portal (eswua.ingv.it).

To exemplify the model capabilities, Fig. 12 displays the time series of the mean TEC error for each investigated Deep Learning technique: Long-Short Term Memory, Gated Recurrent Unit, Convolutional Neural Network (upper left) during the case study of the September 2017 geomagnetic storm; related SymH geomagnetic disturbance index (bottom left); histogram of the mean TEC error for each technique (upper right); related whisker plots (bottom right).

5. Validating the Swarm S4 index over Africa using Eswua Database (VSS4AED)

The amplitude scintillation index S4 is a measure of the intensity fluctuations of Global Navigation Satellite System (GNSS) signals caused by ionospheric irregularities. Recently, a researcher from the Helwan University proposed a model to estimate S4 from the 16 Hz electron density data measured by the Swarm satellites. This model is based on Rino's theory of weak scattering and the NeQuick2 model of the electron density profile. The researcher is implementing the VSS4AED project in the INGV node, where Swarm data are used to derive the spectral slope and the variance of the electron density at the peak of the irregularity layer, which are the key parameters for the scintillation model. The NeQuick2 model is used to reconstruct the irregularity layer. In this project, the S4 model is validated against ground-based S4 data from several stations in South Europe as provided by eSWua web services, and stations in Africa such as Malindi station that intersect with Swarm trajectories. The proposed method can provide global information on scintillation, especially in areas where ground-based GNSS receivers are not available.

6. Climatology of Medium Scale Travelling Ionospheric Disturbances and development of a probabilistic forecasting model (MSTIDClima)

Medium scale travelling ionospheric disturbances (MSTID) are wave-like ionospheric plasma density perturbations with horizontal scale size range from 100 to 500 km (Hunsucker 1982). MSTID are caused by gravity waves and/or electrodynamic instability processes. MSTID are observed both in the daytime and in the nighttime, but the causative mechanism of daytime and nighttime MSTID is different. Investigations suggested that daytime MSTID are generated in association with primary and/or secondary gravity waves (Frissell et al., 2016) mainly originating in the lower and middle atmosphere, respectively. The nighttime MSTID is caused by the electrodynamical pro-

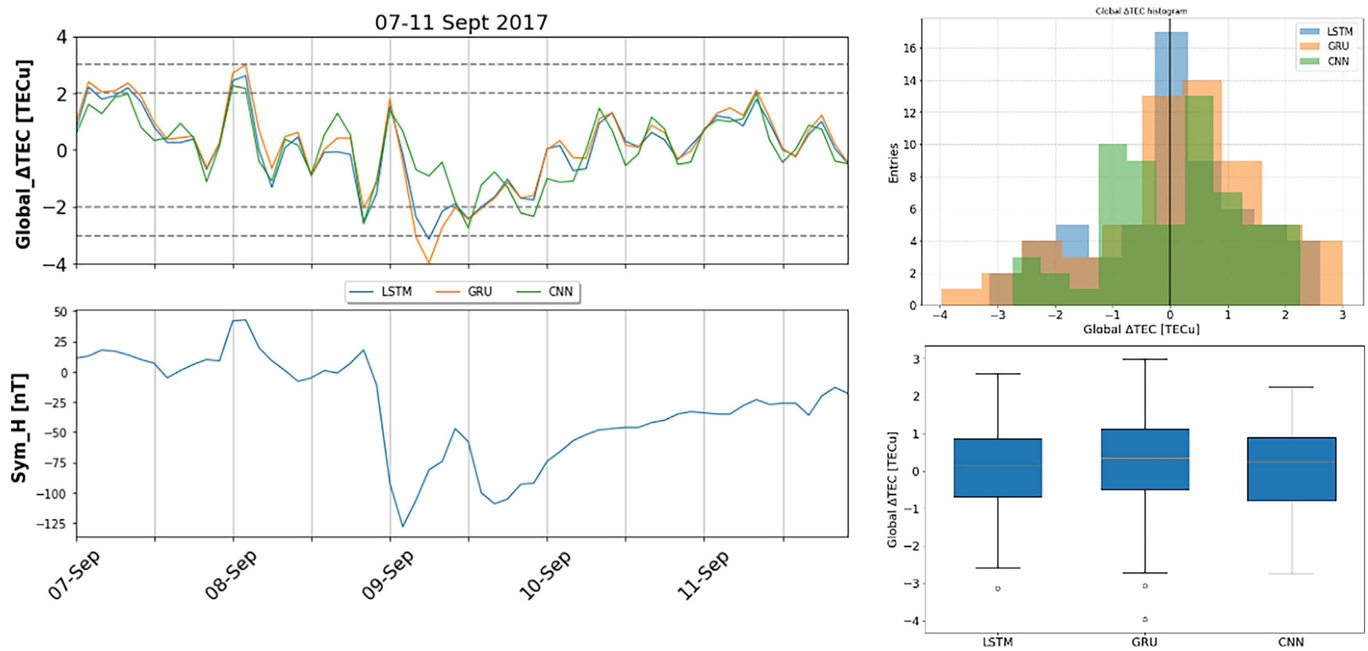

Fig. 12. Time series of the mean TEC error for each investigated Deep Learning technique: Long-Short Term Memory, Gated Recurrent Unit, Convolutional Neural Network (upper left) during the case study of the September 2017 geomagnetic storm; related SymH geomagnetic disturbance index (bottom left); histogram of the mean TEC error for each technique (upper right); related whisker plots (bottom right).

cesses i.e. Perkins instability associated with E- and F-region coupling processes. However, the climatology of the MSTID over the European sector is not explored well. In this TNA project, implemented in the NOA node, the main objective is to explore the MSTID characteristics such as occurrence, wavelength, phase speed and propagation direction as well as seasonal and solar cycle dependency. Furthermore, the development of a probabilistic statistical model is proposed.

2.3.3. Ionosphere-magnetosphere-plasmasphere imaging methods

1. Retrieving the ionospheric currents and magnetic field variations from the observation of the upper atmosphere emissions polarisation (CEP)

In recent years, a group led by Jean Lilensten of the Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) has discovered that many nightglow emissions are polarised and noted that it opens a new window for observing the space environment. In particular, it allows following the evolution of the electron density in the upper atmosphere, as well as the electric currents that flow either parallel or perpendicularly to the magnetic field. Up until now, the results could be proven only in the E-region (around 110 km altitudes), and only with the atomic oxygen green line. However, thanks to this experiment campaign, it could be proven that it also works at lower altitudes (85 km) and in the F region (220 km) by observing the purple nitrogen band and the red atomic oxygen line, while comparing to the data obtained by EISCAT data.

This measurement campaign, implemented in the EISCAT node, took place on four nights, from 1 to 4 March 2022 where 8 h of EISCAT observations were provided by the PITHIA-NRF TNA programme. The first night was very cloudy and was therefore used for calibration purposes. Since the weather forecast was bad for the rest of the week, it was decided to change the locations of the three polarimeters from the originally planned placements to an area west of Kilpisjärvi in Finland for better prospects. These were directed in different directions with 120° apart and were used under the assumption of a uniform sky – an assumption that is only valid during quiet geomagnetic conditions. The quietest conditions were met during a night when EISCAT could not operate in the preferred mode. However, some results could still be obtained from the campaign: The observed optical intensity follows the observed electron density quite well at all three observed altitudes, and the variations of the angle of linear polarisation (AoLP) agree well with those of the observed ion velocity.

This campaign would not have been possible to perform without the strong support of PITHIA-NRF, which provided EISCAT observation time for two (out of the four) nights of the campaign. Moreover, it made it possible to bring along three of the students who benefited from the introduction to the EISCAT radar systems and to ionospheric physics.

The CEP campaign (Fig. 13) confirmed that the polarisation of auroral emissions can be used as a new tool to monitor the ionospheric electron density and the ionospheric currents at different altitudes, allowing estimation

Fig. 13. The 3 polarimeters used in the CEP project study 3rd of March 2022.

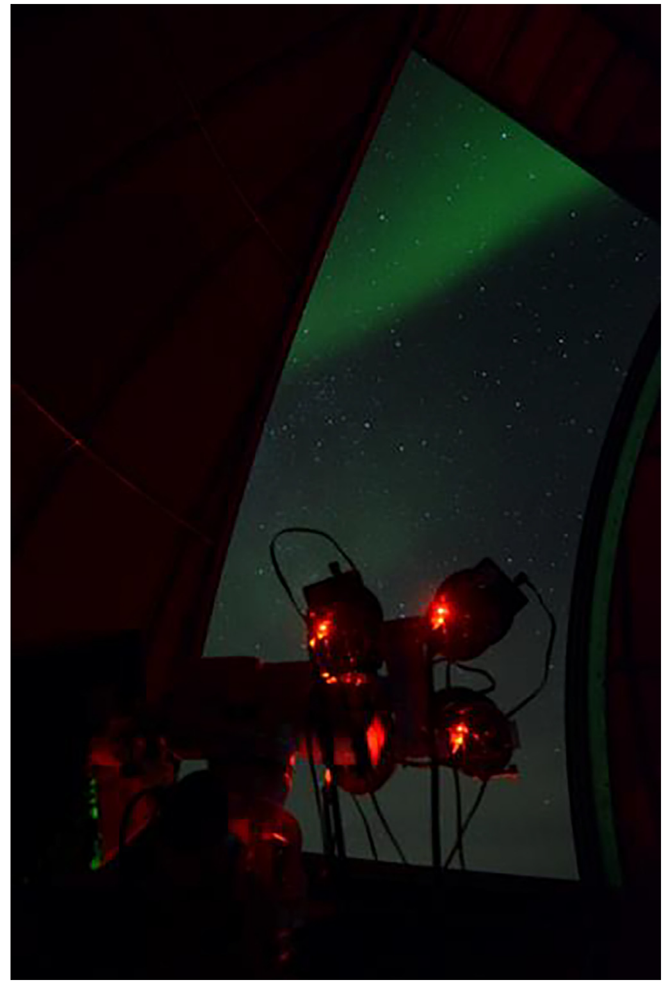

Fig. 14. The PLIP instrument used in the PRISMATIC project.

of their profiles. This monitoring can be processed in real time, at any latitude, provided a clear sky. It will therefore constitute a useful technique for monitoring and predicting the state of the ionosphere, particularly (but not exclusively) for HF communications in the frame of space weather.

2. Can PolaRISation Measurements of Auroral emissions Trace the Ionospheric Currents? (PRISMATIC)

A group of researchers at the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) led by Hervé Lamy developed an imaging polarimeter called PLIP (Polar Lights Imaging Polarimeter), presented in Fig. 14. It measures the Degree of Linear Polarisation (DoLP) and the Angle of Linear Polarisation (AoLP)) of the three main auroral emissions (green, red and blue) within a large field of view. With this instrument, one goal is to check if there is a link between the AoLP of the auroral emission lines and the directions of field-aligned and/or horizontal ionospheric currents.

To achieve this objective, the BIRA-IASB team requested complementary observations from the EISCAT node, to compute a 2-D reconstruction of field-aligned electron fluxes. This was possible using data from the ALIS_4D optical network and measurements from the UHF antenna of EISCAT in Tromsø, Norway.

Thanks to the TNA of PITHIA-NRF, they obtained 8 h of observations with EISCAT during a 10-day observation campaign with PLIP located at the Skibotn Observatory in Norway in November 2022. During this campaign, they received support from the EISCAT team who operated the necessary measurements with their infrastructure.

PLIP data are still being analysed, but the authors made an interesting observation: a strong decrease of DoLP and a clear rotation of AoLP occurred during the main phase of the geomagnetic storm clearly identified by ground-based magnetometer data from Tromsø and UHF radar data from EISCAT. The origin of this polarisation is still puzzling and could be related to ionospheric currents, either field-aligned or horizontal Pedersen/Hall currents. Additional work must be done to confirm these results and see if AoLP of auroral emission lines can become a tracer of ionospheric currents.

3. Study on ionospheric disturbances due to Space Weather in LOFAR data (iono-SW-LOFAR)

The iono-SW-LOFAR project, implemented in the LOFAR node, considered establishing a correlation between solar flares and the ionospheric response seen by the LOFAR telescope. This is not only interesting from a scientific perspective, but it also forced us to make the data and metadata more accessible. Two larger databases, all solar flares since 2013 on the one hand and the available LOFAR scintillation data on the other, needed to be cross-matched. Unfortunately, no common data were found for the brightest, X class, solar flares. But some intriguing correlation was found for the less bright events. This will lead to a follow-up study and a stronger collaboration between solar and ionospheric physics in the future.

4. Use of LOFAR data for ionospheric studies (ScintLO)

This TNA project, also implemented in the LOFAR node, was more focused on teaching external users how to extract ionospheric information from the LOFAR stations, specifically from all sky imaging capabilities of the station. In this TNA project support for two researchers to visit Astron was provided. The ultimate goal of the project, to establish a metric that could be used for dynamic scheduling of LOFAR, was not fully met. But satisfactory progress was made, new techniques developed, and the idea of using all sky imaging to determine the ionospheric state relevant for LOFAR observations is now being investigated further. The all-sky images are currently not considered as part of the e-Science Centre, but this could certainly be considered in the future.

5. Radio scintillation studies for prospects of space weather forecasting and analyses (RadioScint)

The aim of the RadioScint TNA project is to determine if the methodology from Grzesiak et al. (2022) can be applied to a broader range of scintillation observations, specifically interplanetary scintillations (IPS). The described method uses multiple LOFAR station observations for ionospheric analysis. Scintillation measurements of specific radio sources are used to estimate ionospheric drift velocities and characterise the anisotropy of ionospheric irregularities. On the other hand, by observing a compact radio source (~0.1″) using a radio telescope, it is possible to determine the velocity with spectral analysis tools and density changes that are related to the changes in electron-density fluctuations (ΔNe) in the interplanetary medium. IPS data can be analysed using LOFAR single-site and multi-site observations (e.g. Chang et al., 2019).

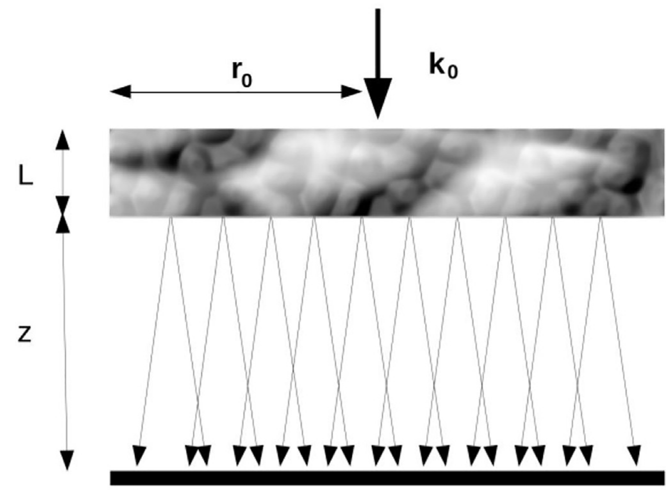

Fig. 15. Illustration of the scattering by a screen. From Grzesiak et al. (2022).

RadioScint will look into adapting the method proposed and described by Grzesiak et al. 2022 to datasets obtained in the LOFAR IPS campaigns and the possibility of calculating solar wind velocity estimates (Fig. 15). The project involves cross-comparing outputs from single-site and cross-correlation analyses for specific case studies or previous LOFAR campaigns for both methods. If successful, further plans can be developed to assess this approach for space weather purposes as a follow-up activity to the current project.

2.3.4. Calibration of new instruments

1. Study of the characteristics of ionospheric irregularities at high and low latitudes through coordinated observations of EISCAT and VHF Radar at Haringhata, India (CROLHL)

The University of Calcutta is developing a high power fully active phased-array radar at 53 MHz at Haringhata, India, situated near the northern crest of the Equatorial Ionisation Anomaly (EIA). The location of this radar is unique being the only one at this frequency in the south-east Asian longitude sector.

Within the framework of the PITHIA-NRF TNA programme, the University of Calcutta ST Radar team was given access to the EISCAT node, with training about the EISCAT radar systems through regular online sessions. This team consists of seven people led by professor Ashik Paul. The training contained an introduction to the system, data formats, analysis methods and some interpretation of the radar data, and it was performed from April until September 2022. A number of sessions were organised. After the initial few meetings, the focus was on a couple of specific cases of space weather impact on the ionosphere. For these cases the University of Calcutta project team conducted computationally intensive data analysis using data from the EISCAT radar systems as well as satellite data from different latitude sectors.

This project was the first step in the training process. It is followed by physical access, conducting coordinated experiments using the EISCAT UHF and University of Calcutta VHF radars, in September 2024.

The University of Calcutta ST Radar (CU STR) project team has gained immensely from the online training provided by the EISCAT node. Since CU STR is a new facility being established in an Indian University with limited resources, availability of online resources initially and physical access in future will be extremely helpful in advancing the studies of ionosphere using the radar, a topic in which EISCAT is a global leader.

2. Estimating ionospheric irregularity layer height and drift velocity with GNSS and incoherent scatter radar (IILHV)

The project is implemented in the EISCAT node and aims to increase the understanding of radio signal scintillation at high latitudes due to high-latitude ionospheric irregularities. A major uncertainty in current modelling and simulation efforts to understand ionospheric plasma instability mechanisms is due to the choice of input parameters regarding plasma drift speed and irregularity layer height and thickness. The project studies the high-latitude irregularity dynamics using a spaced GNSS receiver network in Svalbard, Norway, in conjunction with the EISCAT ESR incoherent scatter radar. The primary objective is to apply the spaced receiver technique to four receivers from different institutes located in Ny-Ålesund and test the feasibility of determining the plasma drift speed and height of the irregularity, using the incoherent scatter radar observations to verify the results and quantify the error.

3. Assessment of the ionospheric scintillation over Portugal (ALERT)

The ALERT project was implemented in the INGV node. The team possesses approximately four years of continuous ionospheric measurements taken in Lisbon and spanning between November 2014 and February 2019. These measurements were conducted using a GNSS receiver equipped with SCINDA software, yielding 1-minute data including TEC, scintillation indices such as S4 and ROTI, as well as satellite elevation and azimuth angles. However, since the receiver was not calibrated upon installation, the accuracy of its measurements requires verification, possibly through comparison with data from nearby receivers.

The objectives of ALERT concerned mainly the validation of the scintillation dataset from the Lisbon receiver to ensure accuracy and reliability. Additionally, a potential incorporation of those validated data into the INGV database, will enhance the collective scintillation monitoring capabilities. Lastly, scintillation events that occurred at middle latitudes in both Portuguese and Italian regions have been investigated, particularly during geomagnetic storms, with the objective to understand regional variations and dynamics.

As a result of the project, it was decided that site characterization and data validation procedures would be implemented for the Lisbon receiver dataset. Regrettably, upon examination, it was discovered that the data originated from a geodetic GNSS receiver equipped with SCINDA software operating at a 1-minute cadence. This receiver exhibits distinct design and data quality acquisition characteristics compared to the receivers available in the eSWua database, which are Ionospheric Scintillation Monitor Receivers (ISMRs) with different operational features.

A scintillation event that occurred on June 22–23, 2015, was selected as a case study. Results of the analysis of this event are shown in Fig. 16. It displays the S4 variation over time recorded by the Lisbon scintillation receiver during June 22–23, 2015 and the related azimuth-elevation distribution, highlighting the region of enhanced scintillation. The related study has been presented during the European Space Weather Week 2023 in Toulouse and the URSI AT-RASC 2024 meeting in Gran Canaria.

4. Caribbean Netherlands TEC measurement validation (CaNeTEC)

The project focused on collaboration between KNMI researchers and the INGV node to enhance understanding and capabilities in ionosphere measurements. The primary aim was to compare KNMI's GNSS receiver data in the Caribbean (Saba and Sint Eustatius stations) with ionosphere measurements from INGV and DLR. This comparative analysis aimed to comprehend calibration techniques and reproduce Total Electron Content (TEC) measurements from RINEX data files. Utilising INGV's calibration software, validation of KNMI's receiver output was achieved, leading to the attainment of initial scientific results. Notable observations included ionospheric disturbances caused by the Tonga volcanic eruption and the response to a solar flare. KNMI initiated sharing scintillation data with INGV, enhancing the global coverage of the latter's network. The project also discussed the potential benefits of integrating KNMI receivers into an international network, facilitating easier access to ionospheric observations for researchers. The project aimed also to establish a dedicated research group at KNMI, fostering long-term engagement and collaboration within the upper atmosphere research community.

Calibration of GNSS receiver output using INGV's TEC calibration software yielded promising results, with good agreement observed between measurements from Saba and Sint Eustatius stations and INGV and DLR TEC maps. An example of this is given in Fig. 17, which reports the vTEC measurements directly above the GNSS receiver at Saba (green) compared to INGV (blue) and DLR (orange) TEC maps evaluated at the receiver location over a period between 11 January and 19 January 2022

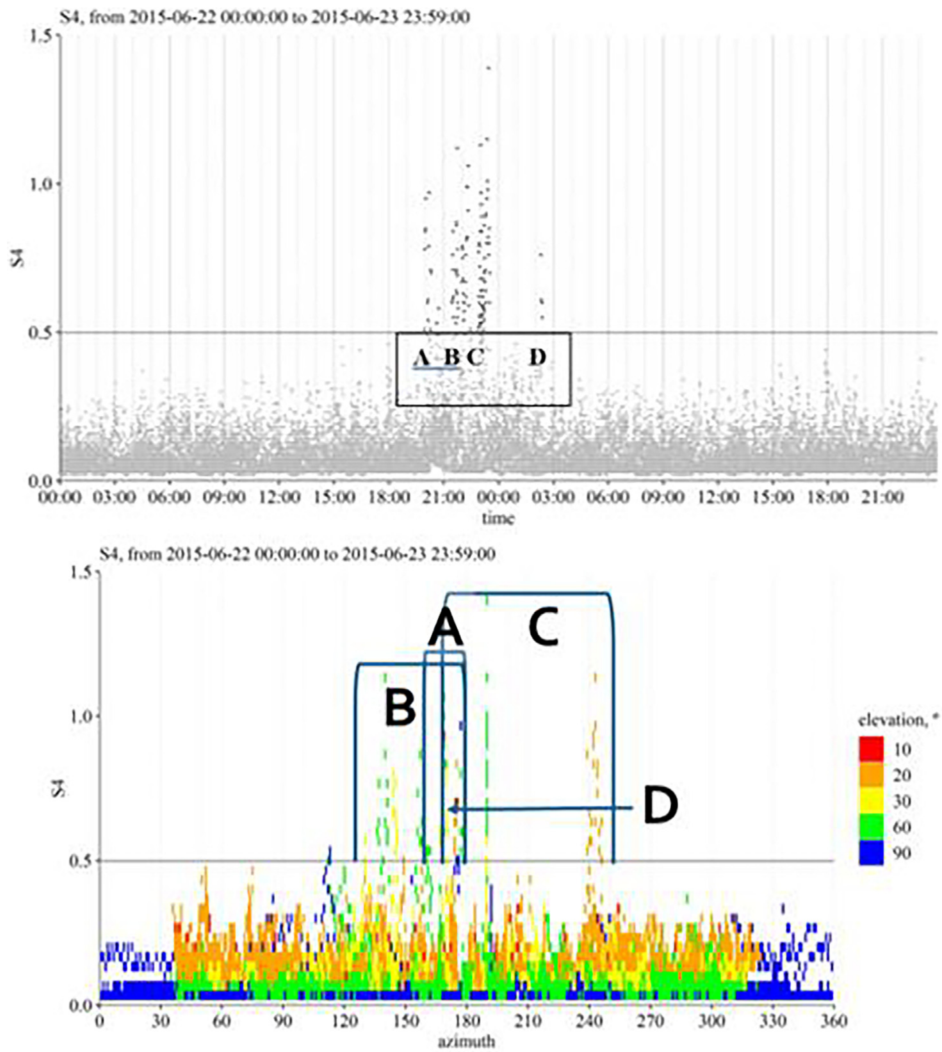

Fig. 16. (top) Time variations of S4 recorded by the Lisbon scintillation receiver during June 22–23, 2015. Letters A-D mark several scintillation sub-events that took place during the night of June 22–23. (bottom) Azimuth-elevation distribution of S4 during June 22–23, 2015. The colour code indicates the range of elevation angles of the observations.

UTC. This specific case serves to highlight a case in which discrepancies were found, which deserve further investigation to be conducted outside the CaNeTEC project.

The assessment of scintillation data produced by the receivers revealed no unexpected results, with discussions focusing on nuances such as the fixed cut-off frequency used in the equipment. Overall, the project facilitated rapid progress in KNMI's research activities, including practical aspects such as data integration and knowledge sharing.

3. PITHIA-NRF metadata Schema and ontology

PITHIA-NRF metadata are registered in the PITHIA-NRF e-Science Centre (see section 4) by the data providers. Descriptions of Resources are written as Extensible Markup Language (XML) documents that comply with three governing requirements:

- The PITHIA-NRF *Schema,* that controls the organisation of the registration documents:
  - *The Schema* is based on the International Standards Organization (ISO) 19,100 series of standards for geographic information, particularly 19156:2011 "Observations and Measurements" (O&M) standard;
  - ISO 19156:2011 was adapted and extended for the space physics domain by the data model team of ESPAS (Near-Earth Space Data Infrastructure for e-Science) European Commission FP7 project, during its 2014-2017 active period (Belehaki et al., 2016);
  - The ESPAS Schema has been adapted, simplified, and extended for PITHIA-NRF to meet specific project requirements.
- The PITHIA-NRF *Ontology,* that controls the standard vocabulary of terms specific to the domain of space physics:

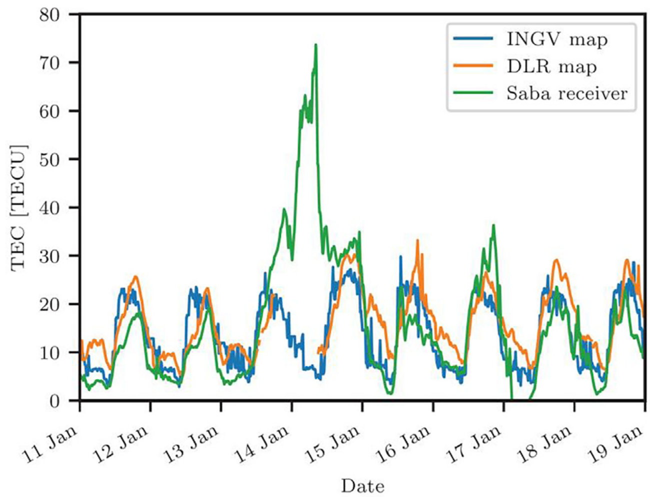

Fig. 17. Vtec measurements directly above the gnss receiver at saba (green) compared to ingv (blue) and dlr (orange) tec maps evaluated at the receiver location over a period between 11 january and 19 january 2022 utc.

  - The Ontology is based on the original ESPAS Ontology design (Galkin & Belehaki, 2017), with extensions specific to PITHIA-NRF datasets and models.

- The XML *Syntax,* that controls formatting of registration documents per World Wide Web Consortium (W3C) definitions.

Registration of new metadata in PITHIA-NRF is described in more detail in section 4.1.

3.1. PITHIA-NRF schema

The ISO 19156:2011O&M standard provides the following core properties for an observation (or a computational model that predicts an observation):

- Feature of Interest: a real-world object that carries the property which is observed or modelled to produce a Data Collection, such as the Earth's ionosphere;
- Observed Property: description of a physical Phenomenon obtained by means of observation or modelling that generates an estimate of its Measurand value, such as critical frequency;
  - Phenomenon is a physically observable entity; the top-level Phenomenon categories are Particle, Field, and Wave;
  - Measurand is the quantitative or qualitative attribute of the Phenomenon to be evaluated, such as velocity, flux, density, etc.
- Result: data generated by the act of observation or modelling;
- Procedure: a sequence of Acquisitions and Computations that lead to a Result.

The ESPAS Schema provides a significant extension to the ISO O&M standard needed to describe space physics observations in detail, and particularly to allow each Observation result to be registered with its individual Phenomenon Time, Spatial Extent, and particular subsets of Procedure as well as Observed Properties that were used during the Observation.

The PITHIA-NRF Schema underwent a significant simplification of the ESPAS design. To improve its scalability to collections of multi-million observations (that would each have required an individual metadata registration document), the PITHIA-NRF Schema introduced a new concept of Data Collection, that captures the exhaustive set of possible Procedures' Acquisition and Computation components, with all possible Observed Properties, and all Platforms that host the registered sensor Instruments. Thus, the PITHIA-NRF Schema omits the specifics of each individual Observation act, including their Phenomenon Time, Spatial Extent, and used components of Procedure. This simplification has delegated all functionality of data search by coincidence or conjunction to the original data providers, who remain responsible for the service functions that respond to incoming queries for temporal and spatial availability of data in the Data Collections. Instead, the PITHIA-NRF Schema adds a new Resource Catalogue for registration of Data Collection subsets of interest in a specific underlying physical event, investigation, or academic publication. Only Data Collections registered in PITHIA-NRF can contribute to Catalogues. The Catalogue data subsets are provided with particular Phenomenon Time and Spatial Extent descriptions, as well as a standard Digital Object Identifier (DOI) to meet FAIR requirements.

3.2. PITHIA-NRF ontology

Most of the PITHIA-NRF Ontology definitions are the original RDF (Resource Description Framework) documents developed by the ESPAS ontology team. As the PITHIA-NRF data registration proceeds, new terms and definitions are added to the Ontology that were not required previously. The most active areas of such extensions are Computation Type, Phenomenon, and Dimensionality vocabularies to describe data collections generated by models and sensors that were not available in ESPAS.

The Space Physics Ontology option in the e-Science Centre offers dynamic browsing of the ontology, allowing scientific users to find definitions for terms in the ontology, and understand how the various terms relate to each other. This is a very important function as all the registered metadata relate to each other based on ontology terms.

4. The e-science centre

In addition to the 12 nodes that provide access to research infrastructures, the PITHIA-NRF e-Science Centre (eSC[2]) is established as a central service that enables

[2] https://esc.pithia.eu/.

registration of, access to and use of Data Collections, Catalogues and Workflows.

Data collections can be either sets of raw or processed observations, offered by providers inside or outside PITHIA-NRF.

Catalogues are smaller sets of data that describe a certain event, or set of events, related to, for example, a publication. Data Collections can be live and changing/growing constantly. Catalogues refer to fixed sets of data that can also be assigned a DOI and referenced in scientific publications to support reproducibility.

Workflows are a combination of already registered models where the output of one model can be fed to other models as input, and the execution is automated.

eSC services are organised in five main categories, as illustrated in Fig. 18. The bottom box of Fig. 18 shows the various Security Services, such as authentication, authorisation, data protection and privacy management. These services are essential and required, and provide the basis for the other, higher-level services. On top of the Security Services, the e-Science Centre provides the User Account Management services. While access to most material and resources is open in the PITHIA-NRF eSC a specific User Account Management is necessary for establishing and managing accounts of some user groups (e.g., Data Collection owners and eSC administrators).

PITHIA-NRF e-Science Centre users are presented with three main categories of services: Information and Community Services, e-Learning Services, and Scientific Services. Information and Community Services provide mainly static information about the community in the form of news items or blogs, but this service category also incorporates more dynamic services that enable networking and collaboration between scientists or even with the general public. E-Learning Services provide access to learning and research material in an organised and systematic way. PITHIA-NRF e-Science Centre users are able to search for learning and research material based on an associated ontology, and could design and create learning graphs and paths that make them better understand and follow the various scientific and technical concepts associated with the resources of the e-Science Centre.

Finally, Scientific Services allow users to access e-Science Centre resources, namely Data Collections and Catalogues. Such resources are published by resource owners (i.e. Data Collection and Catalogue owners) using a rich set of metadata, and made available for scientific users to search, find and utilise them based on their scientific goals and requirements. Users will also get access to a general helpdesk and ticketing system https://ggus.eu/, which is especially important if questions arise when accessing Data Collections or executing Models.

The eSC is under constant development, and the roadmap has been set for adding new features and functionalities. At the time of writing this article, the eSC offers three main functionalities. Its home page is shown in Fig. 19.

The three main categories of functionalities are:

1. The Search & Browse category is accessible to Users without the requirement to log in and allows any user to:
   - Search for Data Collections by specifying a selection of ontology terms, or by simple freetext search.
   - ; Browse all registered Data Collections.
   - Browse all registered Catalogues.
   - Browse all registered Metadata related to the twelve-step registration process.

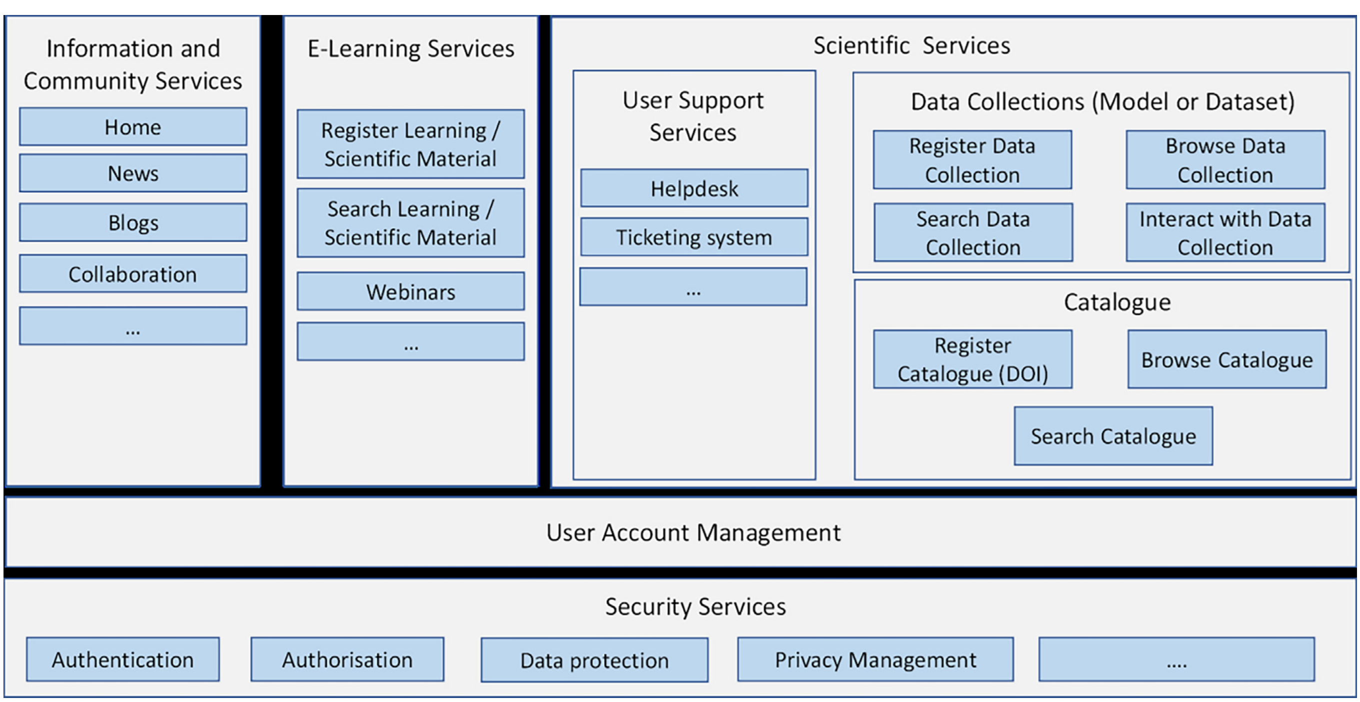

Fig. 18. PITHIA-NRF e-Science Centre Services.

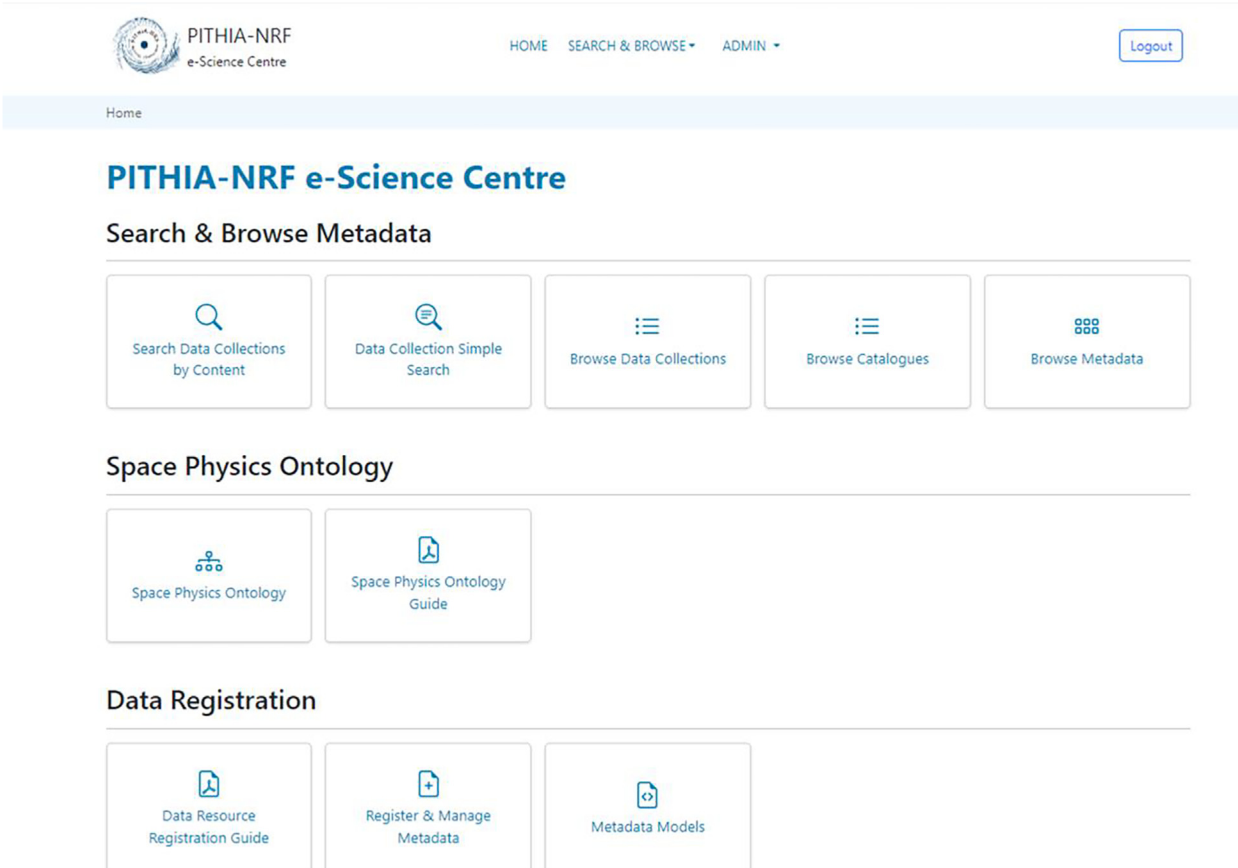

Fig. 19. E-science centre home page. The 2nd and 3rd blocks under Data Registration are only visible to authenticated users upon login.

2. The Space Physics Ontology category allows any User to:
   - Search for terms and their definitions.
   - Access the Space Physics Ontology Guide.
3. The Data Registration category allows:
   - Any user to access and download the detailed Data Resource Registration Guide.
   - Authenticated users (after logging in) to register new Data Collections through associated XML-based metadata.
   - Authenticated users to modify or delete existing Data Collections.

Additionally, the XML schemas, which may be of interest to advanced users, are also available in this category after authentication.

The first official prototype was released in May 2023 with the functionalities detailed in this document. Recently the second protototype was released. This second prototype provides full user management capabilities and the implementation of further Data Collection execution methods. Additionally, most Data Collections are accessible via one or more interaction methods (see section 4.2). During the final year of the project the implementation of advanced services (workflow capabilities and machine learning algorithms) will be investigated and implemented as appropriate.

4.1. Registration and management

Registration of new PITHIA-NRF metadata is accomplished by submitting XML documents to the eSC portal, where all documents are validated against the governing requirements of the PITHIA-NRF *Schema*, PITHIA-NRF *Ontology*, and XML *Syntax*.

To access the hidden features (Data Collection and Catalogue **registration, management and deletion** functionalities) of the eSC user **login** is required. The additional functionalities available to authorised users are shown at the bottom of Fig. 19.

The Data Registration group of functionalities focuses mainly on how Organisations and their Members can register metadata. Any member of an organisation validated by the eSC staff has the authority to register, update and delete metadata under the Register & Manage Metadata option. They can register Data Collections, Catalogues and Workflows, modify earlier registrations or delete unnecessary ones. Additionally, the Metadata Registration Guide is a document that explains the structure of the Metadata and how Organisations should create and register them in compliance with the PITHIA-NRF schema. Finally, the Metadata Models option presents all the schemas that each registration item is validated against before it can be registered.

When a member of a validated organisation selects the Register & Manage Metadata option, the eSC offers three options:

- Data Collection-related Metadata, where one can manage registrations according to the twelve-steps registration process.
- Catalogue-related Metadata, where one can manage registration in the three Catalogue categories.
- Workflows, where one can manage the execution of interconnected data collections, usually via a single API.

Data Collection – related metadata are registered following the sequence of twelve steps as shown in Fig. 20. All PITHIA-NRF data resources are registered with the e-Science Centre using the International Standards Organisation guidelines for Observations and Measurements (ISO 19156:2011). PITHIA-NRF leverages metadata designs for space physics data registration developed by the ESPAS consortium (Belehaki et al., 2016) in 2012–2015. During the active period of the PITHIA-NRF project, the governing ISO standards prescribe using XML as the physical format. While PITHIA-NRF data registrations are done using XML as the metadata format, some additional capabilities are offered with the addition of the interactive wizard.

To facilitate the registration process, document templates are provided for each step. Each template is pre-structured according to the PITHIA-NRF metadata model. Editing replaces the example content with resource-specific information. Such a template-based approach facilitates the registration process, with less likelihood of errors. However, to make the process fully robust, the eSC always goes through a set of comprehensive checks of every uploaded document. First, it checks the XML syntax for formal errors. Second, it assures that all XML documents are compliant with the defined XML schemas and the PITHIA-NRF ontology. Finally, it guarantees that all other XML documents that are referred to from the currently uploaded one do exist. In case of errors eSC notifies the user pointing to the origin of the problem. With this rigorous process, errors (except semantic errors that refer to the scientific content or logic) can be eliminated.

Data resource registration is organised using the concept of the Metadata Model and of the Domain Ontology:

- Metadata Model: ISO-controlled organisation of the metadata components and their relationships in a generic, science-neutral manner;
- Domain Ontology: a vocabulary of physical concepts pertaining to a particular domain of science; usually structured and provided with wider-narrower relationships.

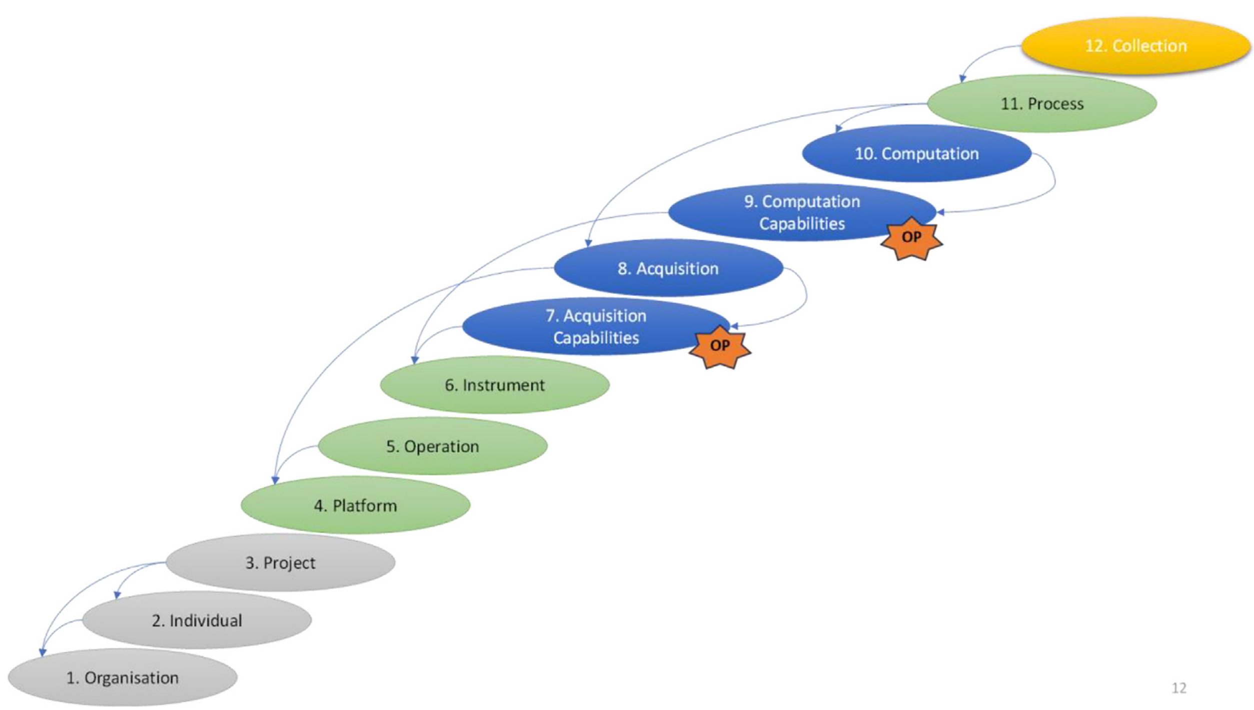

Fig. 20. Twelve steps of PITHIA-NRF data resource registration. Different colours are used to indicate the complexity of the definitions; blue ovals are harder to define. OP is *Observed Property* information commonly used for content-aware searches. The arrows denote dependencies (references) between steps.

The PITHIA-NRF Space Physics Ontology for content-aware data collection registration with the PITHIA-NRF e-Science Centre is detailed in a guide available in the e-Science Centre by Galkin (2023).

Catalogues are listings of events or investigations assembled to aid users in locating data of interest. Each Catalogue entry has distinct begin and end times and an optional DOI to the Data Subset in a permanent storage. Catalogues are not part of the standard Data Collection registration. The catalogues are managed separately, based on the Data Collections in PITHIA-NRF eScience Centre. Only data registered in the eSC can be included in a catalogue. There are three types of components of each Catalogue:

1 Top-level Catalogue Category (e.g., Catalog_VolcanoEruption)
  a. The Catalogue Category is ontology-controlled

2 Individual entries of the Catalogue describing each specific event or investigation (e.g. HungaTonga_2022-01–15)
  b. Each entry has a description and PhenomenonTime
  c. Each entry is linked to the Catalogue Category document

3 *Data Su*bset items (e.g. Manually Scaled Ionograms)
  a. Each Data Subset refers to a Data Collection
  b. Each Data Subset includes < resultTime > to define intervals of time that the subset spans
  c. Optionally, the data provider may specify a DOI for the persistent storage of the Data Subset – DOI generation is directly supported by the eSC, but it can also be generated externally

4.2. Data collection interaction methods

One of the most important roles of the eSC is the provision of methods to enable interaction with models and observational data (Data Collections, DC). Such interactions enable scientists to execute a model on-demand, or retrieve, visualise and manipulate data from a dataset or an underlying database. As this is the ultimate aim of the eSC, it is important that the system caters for multiple options and requirements.

In general, the implementation of each interaction method should be simple for the resource provider and as automated as possible. Four different interaction methods are supported in the eSC. Each Data Collection (DC) provider can decide which method they implement. It is essential to provide at least one interaction method, otherwise users cannot access the DC. For further flexibility, implementing multiple interaction methods is also supported.

The currently planned interaction methods in the eSC are summarised below. The first two of these methods have already been implemented and integrated into the eSC. The last two methods are currently under investigation and prototyping.

1. Get a link once the Data Collection is found

This method is fully implemented and a natural part of the Data Collection registration process. In this method, the Data Collection provider registers a link to the Data Collection in the "linkage" field of the DC's XML registration file. When a user finds a DC as a result of search or browse, the eSC displays this link based on the XML registration document. Once clicking on the link, the user is redirected to an external site/repository managed by the PITHIA-NRF partners in order to access and interact with the DC.

The major advantage of this method is its simplicity. The provider does not have to do anything extra on top of the actual registration, and the DC, being maintained at the data provider organisation, is always up-to-date. However, the method also comes with shortcomings. As the link takes the user outside the eSC, all functionalities are reduced to the capabilities of the provider's services. While this method allows users to find and discover Data Collections from the single entry point of the eSC, it does not provide further integration beyond this.

2. Execute Model within the e-Science Centre via API

In this method the provider has to implement (if not already available) an API (ideally, following the OpenAPI standard https://www.openapis.org/) to execute a model or query/retrieve a dataset. Next, a machine readable YAML or JSON specification of this API needs to be created (or preferrably, generated automatically). Finally, this API specification needs to be registered in the eSC by simply providing a link to it. Using this specification, the e-Science Centre automatically generates a graphical user interface to interact with the Data Collection. This method is also fully implemented in the eSC.

This method provides much closer integration with the eSC than the first one. When a user interacts with the Data Collection, this happens from inside the eSC. The look and feel is the same for every application and as such it is easier for the users to get accustomed to it. On the negative side, the task of DC providers is significantly bigger. They need to assure that the Data Collection is accessible via a suitable API and they have to provide a formal specification of it (although, there are several software tools that automate this process). This may require significant development effort on the producer side, especially in case of legacy Data Collections.

3. Dynamically deploy Data Collection (Model) in the Cloud

This method is not implemented yet and only a preliminary specification and a proof of concept exist regarding its realisation (Pierantoni, Kiss & Bolotov et al., 2022). The core of the idea is to take a containerised version of the Data Collection and deploy it dynamically on-demand in cloud computing resources (Kiss, Kacsuk &

Kovacs et al., 2019). This scenario would require the Data Collection provider to containerise the application and then upload it to a suitable container repository (e.g. DockerHub[3]). After this, the provider also needs to describe the Data Collection with a YAML[4]-based description file (Pierantoni, Kiss & Terstyanszky et al. 2020). When a user selects the DC, it gets deployed in the cloud and a copy of it is executed specifically for the user. Once it is not required anymore (e.g. execution terminates or the user decides to delete the service), it gets destroyed. The method is specifically suitable for models that can be deployed as a set of microservices and then executed.

The advantage of the method is its flexible execution in the cloud. Using cloud resources and only utilising these when necessary is scalable and cost effective. On the negative side, this approach requires the most expertise and effort from the provider.

By interfacing the e-Science Centre and the dynamic deployer module with EGI, we can ensure deployability into 30 national/regional OpenStack clouds which are federated in the EGI Cloud Compute service. This network can give PITHIA-NRF and its users the possibility to select the national cloud resources for each user, lowering/eliminating the need for cross-national compute consumption.

4. Download and install Data Collection on local computer

This method also has not been implemented yet while it requires only a minor effort. The idea is to package and make the Data Collection (typically a model) available for download and installation by the provider. The download happens through the eSC. Once users find the model via browse or search, they can download and install it in the local environment.

The advantage of this method is its simplicity for all parties. However, on the negative side, it is only suitable for small models that are executable on the user's local machine.

In the next section a more detailed description of the second method is provided. As described it has already been implemented and provides a higher level of integration as compared to the first method.

4.3. Registration of scientific models via API

The objective behind this interaction method is to provide Scientific Users with a Graphical User Interface (GUI) that offers homogeneous access to all Data Collections that have implemented an API. Most Data Collections have their custom GUI, which Scientific Users must learn before interacting with the Data Collection. There are also Data Collections without a GUI for access. These may come with a Command Line Interface (CLI), which Scientific Users must get access to and learn how to use. When an organisation registers a Data Collection by also providing an API, it provides the Scientific Users two benefits. When a Scientific User uses the API as an interaction method:

- The eSC dynamically generates a GUI specifically dedicated to that Data Collection. For all Data Collections, the look and feel will be similar in the eSC, the only difference between the various Data Collections being that they will offer different options for available actions.
- The eSC will not redirect the user to any external source but will handle the communication with the Data Collection itself, and the Scientific User will stay in the eSC.

Additionally, for those Data Collections that do not offer a GUI and are available only through CLIs, it is much simpler for the providers to create an API than to build a GUI, as they relieve themselves from creating and maintaining the custom views of the GUI.

The tool that the eSC uses to produce the automatically generated GUI is Swagger UI.[5] The source code of Swagger UI has been customised and integrated into the eSC in a dedicated Django Application that reads the API specification, creates the interface, and handles the communication with the Data Collection's API. Fig. 21 below presents the two steps Scientific Users have to take to interact with an API. On the left hand side, the Scientific Users must select one of the search or browse options of the eSC and find the Data Collection they want to interact with. Suppose the Data Collection offers an API (right-hand side of Fig. 21), Scientific Users can click the link – Open API Interface in new tab – and the eSC will dynamically generate an interface. Following this, the Scientific Users can perform any of the available actions and conduct their scientific research by communicating with the Data Collection's API.

Several models are registered in the eSC using API as an interaction method. A list is provided below.

- The Drag Temperature Model 2020 is a semi-empirical thermosphere model (DTM2020; Bruinsma and Boniface, 2021).
- BSPM (Belgian SWIFF Plasmasphere Model) is a 3D-Kinetic semiempirical model of the plasmasphere developed by the Solar Wind Division of the Royal Belgian Institute for Space Aeronomy (Pierrard and Stegen, 2008; Pierrard and Voiculescu, 2011; Botek et al., 2021; Pierrard et al., 2021 for the last version).
- The hmF2_qModel (Altadill et al., 2013) calculates and predicts the ionospheric electron density peak height of the F2 region, hmF2, under quiet conditions.

[3] DockerHub – https://hub.docker.com/.
[4] YAML – https://yaml.org/.
[5] Swagger UI – https://swagger.io/tools/swagger-ui/.

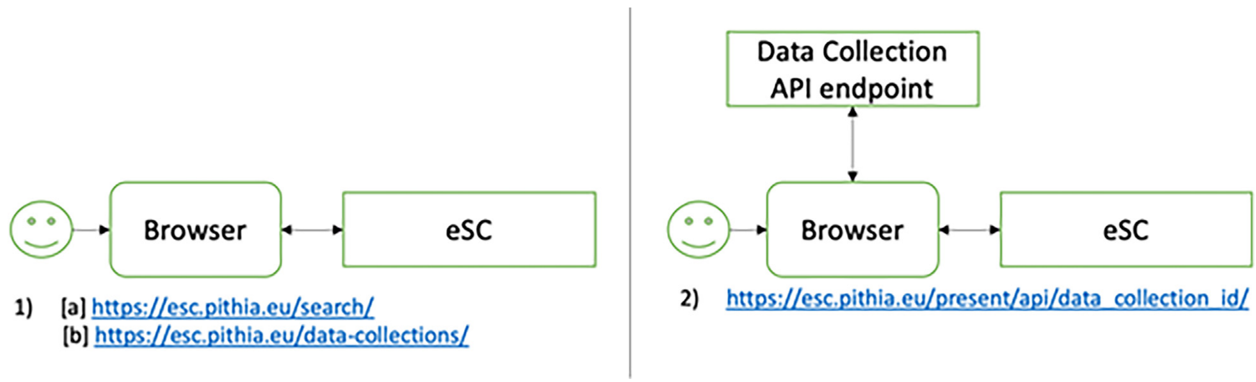

Fig. 21. Interacting with Data Collections through an API.

- The B0B1_qModel (Altadill et al. 2009) calculates and predicts the thickness B0 (km) and shape B1 (dimensionless) parameters of the F layer under quiet conditions on the basis of climatological models.
- The Equatorial Plasma Bubbles (EPB) detection tool (Blanch et al. 2018) is a method to identify plasma depletions associated with EPBs and its main observables (duration, depth of the depletion and the total disturbance) with data gathered from receivers of Global Navigation Satellite System (GNSS).
- The Solar Wind driven autoregression model for Ionospheric short-term Forecast (SWIF) calculates ionospheric forecasts up to several hours ahead, for the European region (Tsagouri, Koutroumbas and Belehaki, 2009).

5. Data quality

Scientific model development and data analysis require the availability of quality controlled data to ensure the accuracy and reliability of the results. Within the context of PITHIA-NRF, one crucial yet insufficiently discussed area involves establishing standards for data quality control and management among the participating RI facilities. To address this problem, we specify higher-level data products, in alignment with the guidelines proposed by relevant organisations such as the Research Data Alliance, ESFRI, and EOSC. This entails an extensive review of domain-specific methodologies, along with the examination of current practices in PITHIA-NRF RIs concerning quality control tools and curation processes. Our primary objective is to construct a reference framework that outlines key aspects of data quality, and offers guidelines to PITHIA-NRF data providers for assessing and publishing research data. A notable contribution from our initiative is the establishment of a Data Quality Flag, signifying the scientific quality of research data. This effort proves challenging, not only for PITHIA-NRF but also for many other European Research Infrastructures.

PITHIA-NRF nodes generate clean data from the raw data collections and utilise standardised processes for higher-level data products. All datasets that will be registered in the e-Science Centre need to be validated for their quality. Each data provider will be responsible for the quality assurance of the datasets.

The quality of digital research data is determined by:

- Their intrinsic scientific quality;
- The quality of metadata that describe the research data;
- The quality of data resources.

Although the data providers are responsible for assessing the quality of their own datasets, the eSC provides recommendations on how to assess the quality. These are summarised in the sections below.

5.1. Scientific data quality

Scientific quality is defined using the data quality flag (DQF). It describes measures taken to *clean* and *validate* the data, as well as characterise the residual data noise. Based on this qualifier the user may extract conclusions regarding data quality. Commonly, Data Level 1 refers to observed properties of the instrument probing signal while Data Level 2 corresponds to the derived geophysical properties of the Feature of Interest. The full list of all DQF definitions adopted in PITHIA-NRF is provided in Table 2.

DQF gradations are not mutually exclusive; Data Collection, Acquisition, Computation, and Catalog Subset documents may assign multiple data quality flags for the same data product. For example,

- Volcano Eruption Catalogue: a Subset of the ionogram-derived measurements is registered in the Catalogue that was VERIFIED-CLEAN by manual editing of ionograms and VALIDATED against other measurements of the same study. Data in this catalogue are used by Verhulst et al. (2022).
- Space Weather Monitoring: assimilative data models that assess the quality of their input data may require data products that are CLEAN and EVALUATED in order to use them in a Kalman-filter assimilation procedure.

Table 2
Definitions of data quality flags.

DQF	Name	Description
0	RAW	Raw output of Acquisition or model Calculation with no regard to its quality
1	CLEAN	Automatic data conditioning is applied
2	EVALUATED	Provided with confidence and uncertainty metrics
3	VERIFIED-CLEAN	Post-processed manually to ensure removal of data noise
4	VALIDATED	Validated against independent measurements or models

- Manually Edited Ionograms: although manual editing ensures that ionogram scaling is correct (VERIFIED-CLEAN), the profile inversion Computation may use an ensemble of software algorithms to evaluate the uncertainty of true height values (EVALUATED).

5.2. Quality of metadata

Descriptive metadata (DM) describe resources and services with the help of useful key-value pairs and in so far classify them according to a number of specified semantic dimensions. DM also add information that is not part of the resource or service such as documenting its creation and modification contexts, its internal encoding and formatting principles, its availability and accessibility. DM should also include provenance information to allow people to trace back how the resource was created.

Where metadata are used in dynamically changing research environments, flexibility is one of the most important requirements: (1) New elements are defined and need to be added; (2) researchers are using different selections of the defined elements to prevent overhead and (3) researchers want to borrow elements from different sets to re-use already existing definitions.

High quality metadata are needed for long-term preservation of observation data generated by the PITHIA-NRF facilities. Based on e-IRG ESFRI Quality Data Management recommendations, a reference check-list is provided below that can be used by PITHIA-NRF data providers to examine the metadata quality:

MQ1: Usage. There is a distinction between descriptive, structural and administrative metadata. These must be provided in accordance with the applicable guidelines of the data repository.

- Descriptive metadata are data required to be able to find research data and that add transparency to their meaning (definition and value) and importance. Examples of descriptive metadata are the data elements of the Dublin Core Element Set,[6] with fields such as Creator, Type, and Date.
- Structural metadata indicate how different components of a set of associated data interrelate. These metadata are needed to be able to process the research data. When data are coded, the codebook will be a component of the structural metadata.
- Administrative metadata are required to enable permanent access to the research data. This concerns the description of intellectual property, terms of use and access, and so-called preservation metadata needed for sustainable archiving of the research data.

MQ2: Scope. PITHIA-NRF data providers shall agree on a set of specific elements to semantically describe their data, models and other services and resources. The creation of the PITHIA-NRF ontology is an important contribution to reaching this objective.

MQ3: Provenance. DM should include or refer to provenance information to support long-term preservation and further processing.

MQ4: Persistence. Metadata descriptions need to be persistent, to be identified by persistent identifiers and also to refer to the resources and services they represent by using persistent identifiers.

MQ5: Aggregations. Descriptive metadata have an enormous potential to describe various forms of groupings and can give them an identity, i.e. making them citable.

MQ6: Standardisation. Descriptive metadata need to be based on well-defined element semantics and a schema-based format to cater for presentations for humans and machine operations. Where fixed schema solutions are given up, elements need to be re-used which are registered in open registries.

MQ7: Interoperability. Descriptive metadata need to be open and offered for harvesting via widely accepted mechanisms to cater for interdisciplinary usage.

MQ8: Quality. Researchers need to be urged to produce high quality metadata descriptions.

MQ9: Earliness. Researchers should be motivated to create metadata immediately and tool developers should add those descriptors that can be created automatically.

MQ10: Availability. It is a MUST for all resource and service providers to create and provide quality metadata descriptions.

5.3. Quality of data resources

Quality of data resources concerns quality of data generation, quality of data repository and quality of data usage.

Quality of Data Generation: When generating research data, PITHIA-NRF data providers should adopt specific data format and documentation recommendations.

DGQ1. Data format. The bits that form a digital research object are organised according to the rules for a particular data format. Preferred formats are formats designated by a data repository for which it guarantees that they can be converted into data formats that will remain

[6] https://www.dublincore.org/.

readable and usable. The preferred formats should be *de facto* standards employed by PITHIA-NRF communities.

DGQ2. Documentation. Providing metadata describing any kind of research resources (data, models, services) is an urgent requirement for PITHIA-NRF data providers. RDA Recommendation[7] provides guidelines for documenting data by describing the why, who, what, when, where, and how of the data.

Quality of Data Repository: The data repository is responsible for access and preservation of digital research data on the long term. PITHIA-NRF data providers should consider two factors that determine the quality of the data repository:

DRQ1. Organisation and processes. Organisations that play a role in digital archiving and are establishing a Trusted Digital Repository (TDR) possess at least a sound financial, organisational and legal basis on the long term. Depending on the task assigned to an organisation, a TDR may support research and cooperation projects between the host and other organisations in the realm of data archiving and data infrastructure. The outcomes of such research are shared, both nationally and internationally. In addition, these organisations will also share physical infrastructures, software and other knowledge among each other, where possible.

DRQ2. Technical Infrastructure. The technical infrastructure constitutes the foundation of a Trusted Digital Repository. The OAIS reference model,[8] an ISO standard, is the de facto standard for using digital archiving terminology and defining the functions that a data repository fulfils.[9]

Quality of Data Usage: The quality of the use of research data is determined by the degree to which the data can be used without limitation for scientific research by the various target groups, while complying with certain rules of conduct. The open and free use of research data takes place within the legal frameworks and the policy guidelines as determined by the relevant (national) authorities.

6. Data management policies

The PITHIA-NRF Data Management strives to reach maximal compliance with fully open access and FAIR data principles. Data management adheres to the following common policies concerning registration of and open access to data collections, catalogues, and workflows.

PRI 1. Support European Commission Open Research data policies, and endeavour to bring the PITHIA-NRF community to a higher level of Openness and FAIRness.

PRI 2. Adopt EOSC relevant standards, including AAI, PID and data management.

PRI 3. Respect PITHIA-NRF data providers' own development objectives and status, and define policies based on community requirements.

PRI 4. Ensure consensus through open discussions at each stage of the policy development.

Below we provide details on how PITHIA-NRF approaches the challenge of aligning the eSC concept with this data management policy.

6.1. Open data

The eSC functionalities allow its users to register their metadata and make them publicly accessible. In this sense the access to the eSC registration and user-support functionalities (i.e. the ontology and registration guides) is open. However, PITHIA-NRF policies need to balance openness and protection of scientific information, commercialisation and Intellectual Property Rights (IPR), privacy concerns, security as well as data management and preservation questions. This is in accordance with the EC approach described as "as open as possible, as closed as necessary". PITHIA-NRF facility nodes are free to specify embargo periods for their data. If data cannot be open, registration of the metadata about the data is encouraged. This will help increase findability and discoverability. It must provide instructions of what users have to do to request access.

6.2. FAIR data

The FAIR principles (Findable, Accessible, Interoperable, Reusable) were originally published by Wilkinson et al. (2016). The FAIR Data Maturity Model Working Group subsequently assessed and evaluated the FAIRness levels and proposed a FAIR Data Maturity Model (FAIR Data Maturity Model Working Group, 2020). The model specifies FAIRness core assessment criteria and provides guidelines for evaluating datasets in terms of FAIRness. It is adopted by EOSC projects and other activities coordinated by EOSC, e.g., EGI-ACE (Sipos et al., 2022) and EOSC Synergy.[10]

Based on the FAIR Data Maturity Model and a template provided by Bahim et al. (2020) in their Table 1 a FAIR assessment and evaluation of the Data Collections to be included in the eSC was conducted. The complete set of indicators (7 Findable, 12 Accessible, 12 Interoperable, and 16 Reusable) was considered for the assessment task. For each indicator one of the priority levels, Essential, Important and Useful, was specified (see Table 2 of Bahim et al., 2020, for Priority Level definitions).

The assessment conducted within the PITHIA-NRF project revealed that most Data Collections are not yet fully compliant with the FAIR principles. Problems were identified and actions were proposed to remedy the prob-

[7] https://dataoneorg.github.io/Education/bp_step/describe/.
[8] https://www.oais.info/.
[9] https://en.wikipedia.org/wiki/Open_Archival_Information_System.
[10] https://www.eosc-synergy.eu/.

lems. Specific tasks were given to Data Collection providers to render their Data Collections compatible with the eSC registration requirements and the PITHIA-NRF Ontology. The results of the assessment suggest that the interaction via API with the Data Collections registered in the eSC will drastically improve their FAIRness compliance.

7. Conclusion and outlook

PITHIA-NRF "Plasmasphere Ionosphere Thermosphere Integrated Research Environment and Access services: a Network of Research Facilities" is a European Commission (EC) Research Infrastructure project funded by the Horizon 2020 Programme. The PITHIA-NRF project runs from 2021 to 2025. PITHIA-NRF aims at building a European distributed network that integrates observing facilities, data processing tools and scientific models dedicated to ionosphere, thermosphere and plasmasphere research. For the first time, PITHIA-NRF integrates, on a European scale, key national and regional research infrastructures such as EISCAT, LOFAR, Ionosondes and Digisondes, GNSS receivers, Doppler sounding systems, riometers, and VLF receivers. The integration ensures optimal use and joint development of the participating facilities. PITHIA-NRF is designed to provide formalised access to experimental facilities, FAIR data, standardised data products and training and innovation services. PITHIA-NRF promotes research advances in the field of upper atmosphere and near-Earth space, through the integration of data collections from ground-based and space-born observing instruments and of results from key prediction models that can be accessed by scientific users for joint exploitation with the data collected from the research infrastructures of the network. PITHIA-NRF paves the way for new observing technologies, and for the standardisation of software and high-level data products tuned to meet the requirements of technologies concerned, linking best-in-class R&D facilities to provide seamless multi-technology services.

By the end of the EC funded period (in 2025), PITHIA-NRF is expected to deliver a unique European Infrastructure that produces services to the international community of upper atmosphere researchers and stakeholders, including early-career researchers and software and instrument development professionals. The following main services are deployed:

- Standardisation of data registration, discovery and access, based on the domain-specific ontology and standard-based metadata.
- Standardisation of scientific models' registration, and delivery of data products for research, development and innovation
- Standardisation of policies for the optimised operation of experimental facilities.
- Subsidised *trans*-national access to research facilities for academics and SMEs ensuring a continuous cooperation and interaction with data providers and scientists.
- E-Science tools to support R&D projects, while ensuring compliance with FAIR criteria.
- Innovative solutions for software development, high-level data product definition and the development and deployment of new experimental facilities.

The development of these services is supported by the TransNational Access (TNA) programme, which is conducted in the framework of open calls for projects, and by the Innovation Framework which organises discussions with expert stakeholders on their needs and experience from using the PITHIA-NRF services. TNA projects implemented in PITHIA-NRF nodes demonstrated research advances in the following areas:

- Multi-instrument data analysis, with data obtained directly from the observing instruments in the nodes and from the eSC; these projects were focused on the 3D propagation of gravity waves (solar and lower atmosphere driven), and on the identification of ionospheric irregularities and the effects to geodetic applications. Most of these projects used resources provided by multiple nodes.
- Development and validation of scientific models; these projects are focused on the ionospheric electron density modelling using LOFAR and GNSS data. Nowcasting and forecasting of TEC is attempted at regional and global scales with empirical and artificial intelligence techniques. Models for ionospheric irregularities (MSTIDs and scintillations) are developed and validated with ground-based data. Most of the projects that drop in this category were implemented in a single node, but several data collections required for the models' validation were accessed through the eSC from global databases.
- Ionosphere – interplanetary medium imaging methods; these projects are based on the analysis of observations collected during special campaigns. The analysis of EISCAT data confirmed that the polarisation of auroral emissions can be used as a new space weather diagnostic tool, although the origin of polarization is still puzzling. The joint analysis of LOFAR and solar flare data demonstrated an intriguing correlation found between less bright events and the ionospheric response. For the needs of another TNA project, LOFAR data were used as a diagnostic for interplanetary scintillations. Using also all-sky imaging of LOAFR it was possible the determine the ionospheric state and a future goal is to determine a metric.
- Calibration of new instruments; these projects were also designed to be implemented in specific nodes because of their nature. The instruments considered are: the VHF radar in Haringhata, India; a spaced GNSS receiver net-

work in Svalbard, Norway; a new scintillation receiver in Lisbon, Portugal, and GNSS receivers in the Caribbean.

The combined effect of all these activities should provide the possibility for PITHIA-NRF to:

- Become an internationally-renowned infrastructure for Research and Development leading to excellent research advances in the upper atmosphere and near-Earth space domains;
- Provide simple and open access to data fully compatible with the FAIR principles and to advanced multidisciplinary services;
- Develop novel business practices, project management services and new technologies that together accelerate end-to-end software standardisation and instrument development and calibration.

PITHIA-NRF has the potential for enormous impact on structuring the scientific community, producing innovation, providing societal benefits, and influencing future governance and funding decisions. However, the main achievement that drives all impacts is the expected scientific advances. The major advantage of an integrated research environment is the sharing of data, services, facilities and equipment with all stakeholders, thereby avoiding unnecessary duplication of effort. Using this background knowledge and the support of PITHIA-NRF experts, excellent and innovative scientific results are expected to be generated by users and especially by the young generation of researchers and engineers, considering the first TNA results summarized in section 2.3. For the operations domain, an important benefit is the possibility provided by the PITHIA-NRF ontology to characterize data products with quality flags. This could serve the requirements of the Space Safety and Security Programme of the European Space Agency and of the European Union Space Programme. The production of data with controllable quality is a step beyond the FAIR data and this is achieved only when the scientific data quality, the quality of metadata and the quality of the resources is specified by the data owner. This is a very complex procedure that requires cleaning, curation, transformation and integration among other workflows and it is planned to be achieved by the PITHIA-NRF community in a follow up project. Such development together with the availability of tools to retrieve massively archived data would extremely support future AI/ML modelling developments where the use of clean data and the availability of archived data is instrumental for the reliability of the models' performance and the retraining process. The establishment of an AI/ML modelling framework is the next major goal for the PITHIA-NRF community to address the critical requirement for real-time forecasts with specified accuracy regarding ionospheric disturbances and irregularities, atmospheric drag effects and the plasmasphere dynamics depending on geomagnetic activity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Acronyms

The following table contains the list of acronyms used in this document.

Table A1

List of acronyms.

Acronym	Definition
AAI	Authentication and Authorization Infrastructure Architecture
AI/ML	Artificial Intelligence / Machine Learning
AoLP	Angle of Linear Polarisation
API	Application Programming Interface
ASPIS	Autonomous Service for Prediction of Ionospheric Scintillations
ASTRON	Netherlands Institute for Radio Astronomy
BSPM	Belgian SWIFF Plasmasphere Model
CBK/PAS	Centrum Badań Kosmicznych PAN
CCMC	Community Coordinated Modeling Center
CDSS	Continuous Doppler Sounding System
CHAM	CHAllenging Mini-Satellite Payload
CIR	Corotating Interaction Region
CLI	Command Line Interface
CME	Coronal Mass Ejection
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
D2D	Digisonde-to-Digisonde
DC	Data Collection
DEMETER	DEMonstrating the Emerging Technology for Measuring the Earth's Radiation
DGQ	Quality of Data Generation
DLR-SO	German Aerospace Center – Institute for Solar-Terrestrial Physics
DM	Descriptive Metadata
DOI	Digital Object Identifier
DoLP	Degree of Linear Polarisation
DQF	Data Quality Flag
DRQ	Quality of Data Repository
DSND	Automated data analysis procedure DSND for dynasonde measurements
DTM2020	Drag Temperature Model 2020
DTU	Technical University of Denmark
EC	European Commission
EGI	EGI Foundation
EGI-ACE	EGI – Advanced Computing for EOSC
EIA	Equatorial Ionisation Anomaly
e-IRG	e-Infrastructure Reflection Group
EISCAT	European Incoherent Scatter Scientific Association
EO	Earth Observation
EOSC	European Open Science Cloud
EPB	Equatorial Plasma Bubbles
ESA	European Space Agency
eSC	e-Science Centre

Table A1 (*continued*)

Acronym	Definition
ESFRI	European Strategy Forum on Research Infrastructures
ESPAS	Near-Earth Space Data Infrastructure for e-Science
EUV	Extreme UltraViolet
FAIR	Findability, Accessibility, Interoperability, and Reusability
GNSS	Global Navigation Satellite System
GIRO	Global Ionospheric Radio Observatory
GFZ	The Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences
GOCE	Gravity field and Ocean Circulation Explorer
GRACE	Gravity Recovery and Climate Experiment
GUI	Graphical User Interface
HF	High-Frequency (3–30 MHz)
HF VI	High Frequencies Variability Index
IAP	Institute of Atmospheric Physics of the Czech Academy of Science
IGRF	International Geomagnetic Reference Field
IGS	International GNSS Service
IMF	Interplanetary Magnetic Field
INGV	Istituto Nazionale di Geofisica e Vulcanologia
IONEX	IONosphere map EXchange
IPIM	IRAP Plasmasphere-Ionosphere Model
IPP	Ionospheric Pierce Point
IRI	International Reference Ionosphere
ISO	International Standards Organization
ISR	Incoherent Scatter Radar
ITP	Ionosphere, Thermosphere, and Plasmasphere
JSON	JavaScript Object Notation
KAIRA	Kilpisjärvi Atmospheric Imaging Receiver Array
LEO	Low Earth Orbit
LOFAR	LOw Frequency ARray
LSTID	Large Scale Travelling Ionospheric Disturbances
MSTID	Medium Scale Travelling Ionospheric Disturbance
NASA	National Aeronautics and Space Administration
NeQuick	Quick-run ionospheric electron density model
NOA	National Observatory of Athens
NPSM	Nucleon-Pair Shell Model
NRTK	Network Real Time Kinematic
O&M	Observations and Measurements
OE	Observatorio del Ebro Fundación
PID	Persistent Identifier

Table A1 (*continued*)

Acronym	Definition
PITHIA-NRF	Plasmasphere Ionosphere Thermosphere Integrated Research Environment and Access services – a Network of Research Facilities
PLIP	Polar Lights Imaging Polarimeter
PPP	Precise Point Positioning
R&D	Research and Development
RAEGE-Az	Rede Atlântica de Estações Geodinâmicas e Espaciais – Azores Association
RDA	Research Data Alliance
RDF	Resource Description Framework
RELEC	Relativistic ELECtrons
RI	Research Infrastructure
RINEX	Receiver Independent Exchange
ROB	Royal Observatory of Belgium
ROT	Rate Of Chance of TEC
SAR	Synthetic-Aperture Radars
SGO	Sodankylä Geophysical Observatory
SH	Spherical Harmonic
SMEs	Small and Medium-sized Enterprises
SSA	Space Situational Awareness
sTEC	slant Total Electron Content
STIM	Storm Time Ionospheric Model
SWIF	Solar Wind driven autoregression model for Ionospheric short-term Forecast
TDR	Trusted Digital Repository
TEC	Total Electron Content
TIDs	Travelling Ionospheric Disturbances
TNA	TransNational Access
TSAR	Time Series AutoRegressive
TSWC	Tucuman Space Weather Center
UHF	Ultra High Frequency (300–3000 MHz)
UI	User Interface
UPC	Universitat Politècnica de Catalunya
UPC-IonSAT	UPC – Ionospheric determination and navigation based on Satellite And Terrestrial systems
URSI	Union Radio-Scientific Internationale / International Union of Radio Science
UT	University of Twente, The Netherlands
UT3-IRAP	University Toulouse III-Paul Sabatier – Institut de Recherche en Astrophysique et Planétologie
UTC	Universal Time
UV	UltraViolet
VHF	Very High Frequency (30–300 MHz)
VLF	Very Low Frequency (3–30 kHz)
vTEC	vertical Total Electron Content
W3C	World Wide Web Consortium
WIONAS	Wave-like structures in the IONosphere between Athens and Sopron
XML	Extensible Markup Language
YAML	YAML Ain't Markup Language

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