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The ionosphere prediction service prototype for GNSS users

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Abstract – The effect of the Earth's ionosphere represents the single largest contribution to the Global Navigation Satellite System (GNSS) error budget and abnormal ionospheric conditions can impose serious degradation on GNSS system functionality, including integrity, accuracy and availability. With the growing reliance on GNSS for many modern life applications, actionable ionospheric forecasts can contribute to the understanding and mitigation of the impact of the ionosphere on our technology based society. In this context, the Ionosphere Prediction Service (IPS) project was set up to design and develop a prototype platform to translate the forecast of the ionospheric effects into a service customized for specific GNSS user communities. To achieve this overarching aim, four different product groups dealing with solar activity, ionospheric activity, GNSS receiver performance and service performance have been developed and integrated into a service chain, which is made available through a web based platform. This paper provides an overview of the IPS project describing its overall architecture, products and web based platform.

Keywords: Global Navigation Satellite System / Space Weather / Solar Flares / Coronal Mass Ejections / Ionosphere / Total Electron Content / Scintillation / GNSS receiver performance / GNSS user positioning

1 Introduction

There is a growing reliance on Global Navigation Satellite Systems (GNSS) for safety critical applications such as civil aviation, marine navigation and land transportation, as well as in many other aspects of social and economic human activity, including environmental monitoring and high accuracy applications in construction, mining, agriculture, surveying and geodesy. Although GNSS systems, such as the Global Positioning System (GPS), GLONASS, Beidou and Galileo underpin a significant part of modern infrastructure, they suffer from a number of known vulnerabilities. One severe vulnerability is the effect of space weather on the GNSS signals, a topic highlighted in the report published by the Royal Academy of Engineering (Cannon, 2013). As defined in this report, "Space Weather is a term which describes variations in the Sun, solar wind, magnetosphere, ionosphere and thermosphere, which can influence the performance and reliability of a variety of space borne and ground based technological systems and can also endanger human health and safety". In this respect, forecasting the ionospheric effects on GNSS signal propagation is an important contribution to space weather prediction.

Two of the principal ionospheric drivers caused by solar activity are solar flares and Coronal Mass Ejections (CMEs). Solar flares are explosive events in the solar corona where significant amounts of energy, up to 10^{25} J, are released on short time scales – less than 20 min – on length scales of the order of 10^7 m. Often such flares happen in correspondence with the launch of CMEs, which carry high energy particles out from the Sun into the interplanetary medium. Only those CMEs which are aimed at the Earth, having an intense magnetic field, and/or high speeds and/or large particle density will create geo-effective radiation and in extreme cases perturbations of the Earth's magnetic field leading to inductive electric fields that can cause

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power transmission network instabilities and transformer burn out (Schrijver & Siscoe, 2010). Solar Energetic Particles (SEPs) are high-energy particles that originate from the Sun in association with solar flares and/or CMEs (Berrilli et al., 2014). They consist of protons, electrons and ions with energy ranging from a few tens of keV to a few GeV. SEPs can cause ionospheric disturbances and can also contribute to the atmospheric radiation environment leading to satellite operational outages and failures (Bailey et al., 2017; Pulkkinen et al., 2017).

During solar geo-effective events, the ionosphere may become highly variable. For GNSS users, an important ionospheric parameter is the integral of the vertical electron density distribution, i.e., Total Electron Content (TEC), which is directly related to the ionospheric refractive index and proportional to the first-order range error in positioning and navigation. Global maps of vertical TEC (VTEC) are of value in quantifying the effect of the ionosphere on L-band signals and to observe the effects of space weather. In addition to large scale TEC variations, small to medium scale (from centimetres to hundreds of metres) irregularities may be generated during the solar events, leading to diffractive effects on GNSS signals, registered as amplitude and phase fluctuations, a phenomenon known as scintillation. The two areas most affected by scintillation are the ionospheric equatorial regions, extending from about 20°N to 20°S geomagnetic latitude, and the high latitude regions extending from geomagnetic latitudes of about 65° to 90° (Basu et al., 2002; Kintner et al., 2007). It is also known that scintillation occurrence significantly correlates with strong TEC variability (Spogli et al., 2013; Cesaroni et al., 2015).

Ionospheric scintillation can degrade the GNSS receiver signal tracking performance. Both amplitude and phase scintillation increase the GNSS receiver tracking error (or "tracking jitter"), which is individual to each satellite-receiver link and propagates into the quality of the estimated position (Aquino et al., 2005). When the tracking jitter exceeds a certain threshold, loss of lock/cycle slips may occur in the receiver (Conker et al. 2003). The receiver tracking jitter shows significant correlation with scintillation levels, both at high and low latitudes (Sreeja et al., 2012; Aquino & Sreeja, 2013; Vadakke Veettil et al., 2018). During moderate to strong scintillation conditions, even high grade receivers (e.g., with an adaptive tracking loop bandwidth) that are able to maintain track, exhibit degraded positioning accuracy.

Practical forecasts of the ionospheric conditions can thus contribute to the understanding and mitigation of the impact of ionospheric related geophysical events on our technology-based society. Actionable ionospheric forecasts depend on better understanding of the Sun and solar-terrestrial interactions as well as measurements of ionospheric related quantities and modelling of the ionospheric related phenomena. In this context, the main aim of the Ionosphere Prediction Service (IPS) project was to translate forecasts of the ionosphere into GNSS user specific metrics through the design and development of an ionospheric prediction service prototype. At the very beginning of the project an extensive user requirements analysis was carried out and it was decided to tailor the products for those markets for which requirements were clear and more mature such as high accuracy and aviation applications of GNSS. The IPS outputs are nowcasting and forecasting products generated by algorithms implemented in so called Remote Processing Facilities (RPFs) and can be divided into three main blocks: solar and space weather monitoring (RPF 1), ionospheric activity monitoring and forecasting (RPF 2) and GNSS receiver and user positioning performance (RPF 3). In addition to these products, a fourth RPF addressed nowcasting and forecasting of the GNSS service performance, targeted at aviation users (RPF 4). The RPFs are integrated into a service chain, whose main layers are the input sensors, the RPFs, the Central Storage and Processing Facility (CSPF) and the web server. This paper presents a general overview of the IPS prototype architecture, the nowcasting and forecasting products developed in the project, as well as the IPS project web portal.

2 Existing parallel services/activities

There are a number of existing parallel services and international projects/activities related to space weather monitoring and forecasting. An extensive state of the art review along with a user requirement analysis was performed at the beginning of the IPS project to identify as a starting point the technology gaps related to the GNSS users of such services. The most important characteristics of some of the main existing parallel services and initiatives are summarized in Table 1, which highlights the differences with the IPS concept to derive the added value of the IPS itself. The last column in Table 1 compares the considered service and IPS with a justification of the most important difference between the two.

It is clear from Table 1 that there are no other similar initiatives among the analysed services that can entirely cover the IPS objectives. Some of the services can offer limited synthetised information useful for some end users. However, sometimes the products reflect the nowcasted conditions and not the forecast of the specific performance parameter. Moreover, the products are generic, not customizable and not designed for specific GNSS end user classes. IPS is designed to be a service that provides forecasting of key performance indices that will assist GNSS users in different categories of applications (high accuracy and aviation).

3 IPS architecture

The IPS architecture is based on the following three main elements, namely:

(a) Sensors: This element collects and gathers all the necessary raw data for the generation of the IPS products. Sensors are external to the IPS processing facilities and are described under each RPF in the next section. IPS does not own the different infrastructures that provide the raw data and this could constitute a liability issue in order to provide a continuous service.
(b) RPFs: This element runs all the algorithms and generates the different nowcasting and forecasting products starting from the collected raw data or from the intermediate products generated by other RPFs. They interact with the sensors to collect the needed input data and with the CSPF to save the generated nowcasting and forecasting products, to retrieve and process data from other RPFs or trigger one or more processes implemented in the

Table 1. Most important characteristics of some of the main existing parallel services/initiatives to IPS and their relation with IPS objectives.

Services/Initiatives	Lifetime of the activity/service	Main available products	Relation with IPS prototype
Solar Monitor's Flare Prediction System Probabilities hosted by the Solar Physics Group, Trinity College Dublin and the Dublin Institute for Advanced Studies	Currently active	• Statistical flaring probability for NOAA solar Active Regions (ARs) • A list of ARs with flaring probabilities (NOAA Number, McIntosh Class, probabilities for C-class, M-class and X-class flares) • A list of events not associated with currently named NOAA regions and notes	Similarly to IPS, flare prediction for different flare classes (C, M, X) is provided. No information about the impact of flares on the ionosphere or GNSS is provided
National Weather Service Space Weather Prediction Center hosted by National Oceanic and Atmospheric Administration (NOAA)	Currently active	• Geophysical alert • 3-Day forecast of solar wind condition and CME alert • Forecast of solar and geophysical activity	Some products from this service (e.g., Kp forecasting) are used in IPS as input data
Space Weather Operations Centre hosted by the United Kingdom Met Office	Currently active	• Open information such as: space weather forecast headline, analysis of space weather activity over past 24 h, and four-day space weather forecast summary • Specific forecasts for authorities and organizations who prepare for and respond to risks such as space weather The service is not open and can be requested by sending an email to the Met office	Information about past and forecasted space weather events are given as text, so this service is considered as not overlapping with IPS
Flare Likelihood And Region Eruption foreCASTing (FLARECAST) prediction system hosted by the Academy of Athens, Greece	H2020 project concluded in December 2017	Solar-flare prediction based on about 20 machine learning algorithms considering different solar flare predicting parameters	Research project not providing real-time service
SpaceWx Alert Monitor (SAM) hosted by Space Environment Technologies (SET) company	Currently active	Alert monitor to predict the arrival time of CMEs and the solar wind velocity at Earth	It is based on NOAA data, but the webpage does not include algorithms for product generation User interaction is not possible
Solar Influences Data Analysis Center (SIDC) hosted by Royal Observatory of Belgium (ROB)	Currently active	• Real time alerts of halo CMEs, X-ray flare detection • 3-day-forecast of solar and geomagnetic activity • PRESTO messages notifying the detection of a CME and some information about possible associated flares, plasma ejection onset time and velocity	Similarly to IPS, this service provides products mainly related to solar event monitoring and real time alerts to the user. No information about the impact of such events on the ionosphere or GNSS is provided. Some products from this service (e.g., CME detection) are used in IPS as input data
Space Weather Information Center (SWIC) hosted by Japan National Institute of Information and Communications Technology (NICT)	Currently active	• Solar wind and CME monitoring • Alerts to provide real time information about the status of the solar wind at L1 lagrangian point and CME • Magnetosphere status and forecasting • Ionosphere status and forecasting at a regional level over Japan by using GNSS and ionosonde data	This service is similar to IPS, but it covers only regional ionospheric monitoring and forecasting. No information on the GNSS receiver performance is provided. It is possible to receive alerts, but the thresholds are not customizable. Detrended (60 min time window) TEC maps are provided to identify Travelling Ionospheric Disturbances (TIDs) in quasi real-time, while IPS is able to provide TIDs detection only on a daily basis
Regional Warning Center of China (RWC-China) hosted by Chinese Academy of Sciences (NAOC)	Currently unavailable	• Current space weather • Flare and geomagnetic activity 48-hour forecast • 72-hour forecast of F10.7 cm radio flux and proton event probability	

(Continued on next page)

Table 1. (Continued)

Services/Initiatives	Lifetime of the activity/service	Main available products	Relation with IPS prototype
South Africa National Space Agency (SANSA) regional Space Weather service	Currently active	• Space weather bulletin • Daily forecast of solar and geomagnetic conditions • 3-day prediction of solar and geomagnetic conditions	This service provides nowcasting and forecasting (3 days) information about solar, geomagnetic and ionospheric condition as "level" of activity. No information on the GNSS receiver performance is provided. User interaction and definition of thresholds is not possible
SWACI – Space Weather Application Centre Ionosphere hosted by German Aerospace Center (DLR)	Currently active and under development for forecasting and prediction	• TEC maps (global-Europe) in real time and 1-hour forecast • Plot of scintillation activity and proxy (ROTI) in near real time • Estimation of 3D electron density in near real time	It offers tools to develop services for GNSS users, but it does not provide information to be easily incorporated into user applications
European Space Agency (ESA) Space Situational Awareness (SSA) Programme/Ionospheric Weather Expert Service Centre (ESC) hosted by ESA	Currently active and under development for forecasting and prediction	The I-ESC provides, implements and supports the ionospheric and upper atmosphere weather products and capabilities of the ESA SSA SWE network	The I-ESC provides "federated products" from different partners, i.e., not a service that can be compared directly to IPS
MONITOR – Ionospheric Monitoring Experimentation Plan & Instrument Development hosted by ESA	Currently active and under development. Not clear if forecasting and prediction will be developed	Several products are planned and not yet available: scintillation indices, TEC maps, EGNOS TEC maps, Rate of TEC, perturbation parameters, reports	This service cannot be directly compared to IPS since it does not provide forecasting products. Also, it does not provide end users with final products to be directly integrated into their GNSS based applications
SWPC – Space Weather Prediction Center hosted by NOAA	Currently active	TEC maps (global, continental USA)	It offers tools to develop services for GNSS users, but it does not provide users information to be easily incorporated into their applications. The products are mainly for the American sector
SWS Space Weather Services – Australia hosted by Commonwealth of Australia, Bureau of Meteorology	Currently active and under development for forecasting and prediction	• Daily solar, geomagnetic and Australian region ionospheric forecast • Solar and geomagnetic conditions • TEC regional and global maps	It offers tools to develop services for GNSS users, and provides users with limited information that can be incorporated into some of their applications
AOSWA – Asian Oceanian Space Weather Alliance hosted by National Institute of Information and Communications Technology, Japan	Currently active	• Regional TEC and scintillation maps and plots • Regional prediction of probability of positioning error and loss of lock	It offers tools to develop services for GNSS users, and provides users with limited information that can be incorporated into some of their applications. There are no products focused on specific GNSS end user classes
International GNSS Service (IGS)	Currently active	Both final and rapid products are freely available via FTP	The products provided by IGS are not in real-time and only at global level
SeSolstorm hosted by Norwegian Mapping Authority (NMA)	Currently active	TEC, ROTI and spatial gradient maps	Products in the form of maps are open to the public. However, there is no mention regarding the data access/availability
Low-Latitude Ionospheric Sensor Network (LISN) hosted by Instituto Geofisico del Peru	Currently active. Not clear if forecasting and prediction will be developed	• Near real time regional TEC and scintillation maps	It offers tools to develop services for GNSS users, and provides users with limited information that can be incorporated into some of their applications. There are no products focused on specific GNSS end user classes

(Continued on next page)

Table 1. (Continued)

Services/Initiatives	Lifetime of the activity/service	Main available products	Relation with IPS prototype
		• Some of the data is not freely available and its use requires the creation of an authorized account. The images of processed data are available with no restrictions	
International Space Environment Service (ISES)	Currently active, but not an operational service. ISES serves as a forum to share data, to exchange and compare forecasts, to discuss user needs, and to identify the highest priorities for improving services.	• Forecasts, warnings, and alerts of solar, magnetospheric, and ionospheric conditions • Space environment data customer-focused event analyses • Long-range predictions of the solar cycle	No overlap with the IPS products
TomoSCand hosted by Finnish Meteorological Institute (FMI)/University of Oulu	Currently active	From the TomoScand webpage it is possible to visualize a 3D ionospheric reconstruction coming from an inversion of the data acquired and automatically generated using general default parameters. The 3D electron density is provided in post processing with a latency that seems to be about 2 months	No overlap with the IPS products
Pan-European Consortium for Aviation Space weather User Services (PECASUS)	Currently active	Advisories to International Civil Aviation Organization (ICAO) on space weather impacts on aviation GNSS systems, HF communication and radiation levels at flight altitudes. Advisories are in accordance with the ICAO's specification.	Advisories and products are available only to ICAO, so this service could partially overlap with IPS only for aviation users

CSPF. The IPS prototype has four RPFs that are distinguished according to the category of the generated products. RPF 1 is dedicated to the monitoring and prediction of solar events like solar flares, CMEs and SEPs. RPF 2 is dedicated to monitoring and predicting the ionospheric activity, such as TEC variation and scintillation. RPF 3 is dedicated to GNSS user receiver performance, in particular the high accuracy users. RPF 4 is dedicated to the performance of GNSS systems at service level particularly for the aviation users. Both RPF 3 and RPF 4 take as input also the ionospheric estimation provided by RPF 2. An overview of the main products generated by each of the RPFs is provided in the next section.

(c) CSPF: This element implements all the functionalities related to the storage and distribution of the generated IPS products and the interaction with GNSS user community through the web portal.

4 Remote Processing Facilities (RPFs)

A high-level description of products generated by each of the four RPFs along with the sensors required to generate them is given in this section. Details of the algorithms and their validation are included in companion papers published in the meantime (Napoletano et al., 2018; Vadakke Veettil et al., 2018; Del Moro et al., 2019).

4.1 Solar and Space Weather Monitoring (RPF 1)

Some manifestations of solar activity are known to significantly affect the ionosphere (Piersanti et al., 2017). The list of RPF 1 products is given in Table 2, together with their casting type (i.e., nowcasting and long-term forecasting) and corresponding refresh time.

The diagram summarizing the algorithms, which generate the RPF 1 products related to flares, CMEs, and SEPs, is shown in Figure 1. The figure also describes the various data sources used as input to the algorithms. The black arrows in the figure indicate that the output of CME nowcasting and forecasting algorithms are used as input to the SEP forecasting algorithm. The nowcasting and forecasting products providing information about detected or forecasted flares, CMEs, and SEPs properties are presented in the form of tables or figures.

The three databases (FlareWatch, CMEWatch and SEP-Watch) necessary to run the RPF 1 algorithms are fed by several data sources. In particular, for flares detection and characterization, the real-time Geostationary Operational Environmental

Table 2. List of the RPF 1 products along with the casting type and the refresh time.

Parameter(s)	Type of casting	Refresh rate
Flare	Nowcasting	6 h
Flare	Long-term forecasting	1–6 h
CMEs	Nowcasting	1 h
CMEs	Long-term forecasting	6 h
SEPs	Nowcasting	15 min
SEPs	Long-term forecasting	1 h

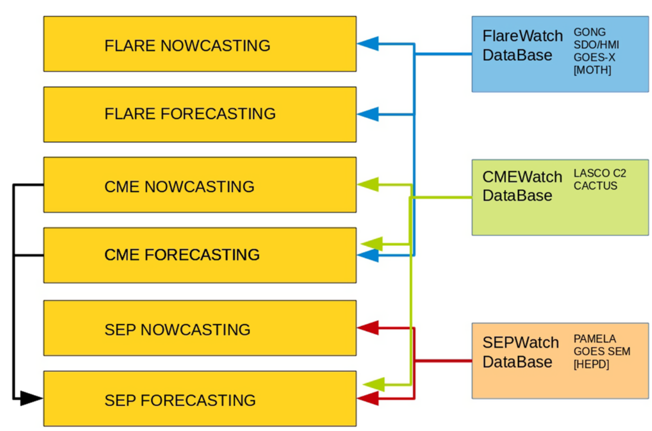

Fig. 1. Block diagram summarizing the developed RPF 1 products and their input data.

Satellites (GOES) X-ray flux from the SWPC archive, real-time Hα full-disk images retrieved from the Global Oscillation Network Group (GONG), the full disk images from Atmospheric Imaging Assembly (AIA, Lemen et al., 2012) instrument on board the Solar Dynamic Observatory satellite (SDO, Pesnell et al., 2011) are used. The flare probability forecast for the next 24 h is computed by an algorithm based on Schrijver (2007) using as data sources the real-time SDO/Helioseismic and Magnetic Imager (HMI, Scherrer et al., 2012) full-disk magnetograms and SDO/AIA full disk images retrieved from the Joint Science Operation Center (JSOC) data archive, with a possible future use of the data from Magneto-Optical filters at Two Heights (MOTH, Jefferies et al., 2006) as a backup for the SDO data.

For CMEs detection and characterization, the data sources are the Large Angle and Spectrometric COronagraph (LASCO) images on the Solar and Heliospheric Observatory (SOHO, Brueckner et al., 1995), near real-time Computer Aided CME Tracking (CACTUS) automated catalogue (Robbrecht & Berghmans, 2004) and the GOES X-ray flux from the SWPC archive. The probabilistic model for the computation of interplanetary CMEs (ICMEs) travel times presented in Napoletano et al. (2018) and implemented in Del Moro et al. (2019) is used to forecast the time of arrival and velocity at 1AU (with associated uncertainties) of Earthbound CMEs, using the CME nowcast characterization as input.

For SEP fluxes, the data source was PAMELA (Adriani et al., 2002), but since its discontinuation in 2017, the source has been updated to GOES SEM flux from the SWPC archive, with a possible use of High-Energy Particle Detector (HEPD, Alfonsi et al., 2017) on board the CSES/limadou satellite, as backup. The forecast of the SEP flux peaks associated with Earthbound CMEs, is computed by applying the model in Papaioannou et al. (2016), using both CME nowcast characterization and the CME forecast as inputs.

4.2 Ionosphere activity monitoring and forecasting (RPF 2)

The research activity on the ionosphere focuses on parameters that are recognized to be of interest for the GNSS service end-users. Namely, they are the TEC (in TECu), the Ionospheric Range Error on L1 frequency (IRE, in m), the TEC gradient (in TECu/km) and the amplitude and phase scintillation indices (in dimensionless and radians respectively) or proxy scintillation indices (PSI in TECu/min, respectively). Table 3 lists the RPF 2 products together with their casting type (i.e., nowcasting, short-term and long-term forecasting), refresh time, coverage and the spatial resolution for which they are provided in the form of maps, plots, or tables.

The algorithms to generate the RPF 2 products are based on different approaches and use as input data from available external sources, as depicted in Figure 2. Note that data within Box 1, Box 2 and Box 4 of Figure 2 are common to several algorithms and outputs from some algorithms are used as input to other algorithms (shown by black arrows). Data is accessible via File Transfer Protocol (FTP) or, when possible, NTRIP (Networked Transport of RTCM via Internet Protocol) streaming in order to minimize the latency of such products.

Figure 3 shows the relationship between input data types and the corresponding data repositories accessed by the algorithms. The worldwide facilities providing RINEX, DCBs (Differential Code Biases) and geomagnetic/solar products are well known, widely accepted and used. Table 4 shows the geographic coordinates of the Ionospheric Scintillation Monitoring Receivers (ISMRs) used for the nowcasting of scintillation indices over Europe, along with the institution in charge to manage the station, the latitudinal sector and the receiver type.

4.3 GNSS receiver and user positioning performance (RPF 3)

The main focus of the RPF 3 products is to provide meaningful information to GNSS end-users, through algorithms developed for nowcasting and forecasting receiver tracking errors, probability of loss of lock and user positioning errors by exploiting the ionospheric scintillation related products generated by the RPF 2. An additional RPF 3 product focuses on the detection and estimation of the main characteristics of Medium Scale Traveling Ionospheric Disturbances (MSTIDs) based on TEC maps over Italy generated by RPF 2. The RPF 3 model algorithms were developed to deliver the products listed in Table 5, together with their casting type, refresh time, coverage and the spatial resolution for which they are provided in the form of maps, plots, and tables.

The input data required to run the RPF 3 model algorithms are the outputs from the RPF 2 as depicted in Figure 4. The input for the RPF 3 regional nowcasted products are the regional scintillation indices nowcasted by RPF 2, whereas the input for the global nowcasted and long term forecasted products are

Table 3. List of the RPF 2 products related to the ionospheric TEC and scintillation along with the casting type, the refresh time, the coverage and the spatial resolution.

Parameter(s)	Type of casting	Refresh rate (min)	Coverage	Spatial Resolution (lat × long)
TEC, IRE, TEC_grad (N-S, E-W)	Nowcasting	10	Italy	0.1° × 0.1°
TEC, IRE, TEC_grad (N-S, E-W)	Nowcasting	15	Europe	0.5° × 0.5°
TEC, IRE, TEC_grad (N-S, E-W)	Nowcasting	15	Global	2.5° × 5°
TEC, IRE	Short-term (30 min)	10	Italy	0.1° × 0.1°
TEC, IRE	Short-term (30 min)	15	Europe	0.5° × 0.5°
TEC, IRE	Short-term (30 min)	15	Global	2.5° × 5°
TEC, IRE	Long-term (24 h)	120	Global	2.5° × 5°
Scintillation indices (S4, σ_φ)	Nowcasting	15	Europe	Values at the ionospheric pierce point (IPP)
Proxy scintillation indices (PSI)	Nowcasting	15	Global	2.5° × 5°
Proxy scintillation indices (PSI)	Long-term (24 h)	180	Global	2.5° × 5°

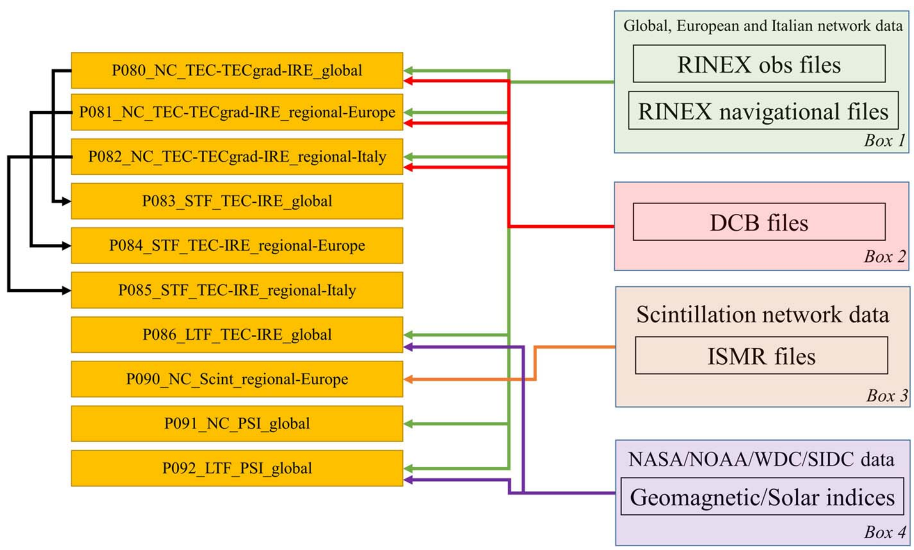

Fig. 2. Block diagram summarizing the RPF 2 products and their input data.

the nowcasted global PSI and the global long-term forecasted PSI, respectively. The input data to detect and estimate the main characteristics of MSTIDs are the daily IONEX files generated from the 10 min nowcasted TEC maps over Italy by RPF 2.

Data collected by ISMR networks operational at the high and low latitudes during the years of 2012–2015 were exploited to develop statistical models to estimate the tracking errors, user positioning errors and probability of loss of lock. The technique of generalised linear modelling (McCullagh & Nelder, 1983) was applied to develop statistical models to estimate the Phase Locked Loop (PLL) tracking errors on the GPS L1 frequency as a function of the scintillation levels. The details of the tracking error model development and validation are presented in Vadakke Veettil et al. (2018). The technique of non-linear regression was applied to develop the models to estimate the probability of loss of lock and the 3D user positioning errors as a function of scintillation levels. The detailed description of the development and validation of the probability of loss of lock and user positioning error models is presented in a manuscript under review in the *Journal of Navigation*. The algorithm related to detection of TIDs is able to provide information on the presence of MSTIDs and their main characteristics, namely

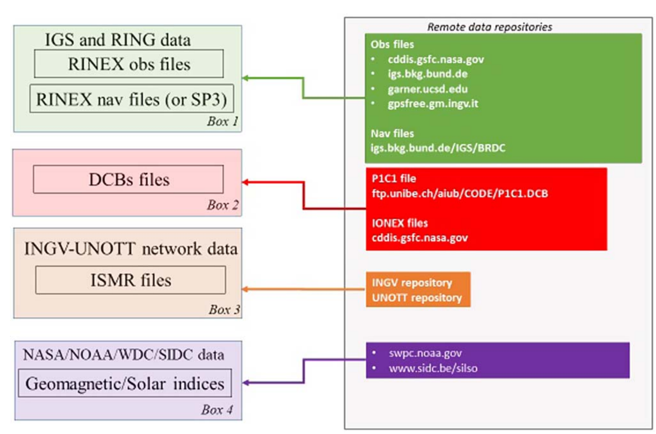

Fig. 3. Block diagram summarizing the data repositories necessary to run the RPF 2 algorithms. In addition to the world wide recognized repositories, note the RING geodetic network (http://ring.gm.ingv.it/), constituted by about 180 dual frequency receivers over Italy managed by Istituto Nazionale di Geofisica e Vulcanolgia (INGV, Italy) and the ISMRs (sampling at 50 Hz) operational at Northern Europe managed by INGV and University of Nottingham (UNOTT, United Kingdom) (Table 4).

Table 4. List of ISMRs (sampling at 50 Hz) operational in Northern Europe.

ID	Station/Institution	Lat (°N)	Long (°E)	Sector	Receiver type
NYA0	Ny-Alesund (Dirgibile Italia)/INGV	78.92	11.93	High latitude	GSV4004/PolaRxS
NYA0	Ny-Alesund (Kartveerk)/INGV	78.92	11.93	High latitude	GSV4004
LYB0	Longyearbyen/INGV	78.17	15.99	High latitude	GSV4004
TRON	Trondheim/UNOTT	63.41	10.41	High latitude	GSV4004
NOTT	Nottingham/UNOTT	52.95	−1.19	Mid latitude	PolaRxS
CYPR	Cyprus/UNOTT	35.18	33.38	Mid latitude	PolaRxS
LAM0	Lampedusa/INGV	35.52	12.62	Mid latitude	GSV4004

Table 5. List of the generated RPF 3 products along with the casting type, the refresh time, the coverage and the spatial resolution.

Parameter	Type of casting	Refresh rate (min)	Coverage	Spatial resolution (lat × long)
Tracking error	Nowcasting	15	Europe	Values at the IPP
Tracking error	Nowcasting	15	Global	2.5° × 5°
Tracking error	Long-term forecasting	180	Global	2.5° × 5°
User positioning error	Nowcasting	15	Europe	Values at the station
User positioning error	Nowcasting	15	Global	2.5° × 5°
User positioning error	Long-term forecasting	180	Global	2.5° × 5°
Probability of loss of lock	Nowcasting	15	Europe	Values at the IPP
Probability of loss of lock	Nowcasting	15	Global	2.5° × 5°
Probability of loss of lock	Long-term forecasting	180	Global	2.5° × 5°
Travelling Ionospheric Disturbances (TIDs)	Batch processing	1440	Italy	0.1° × 0.1°

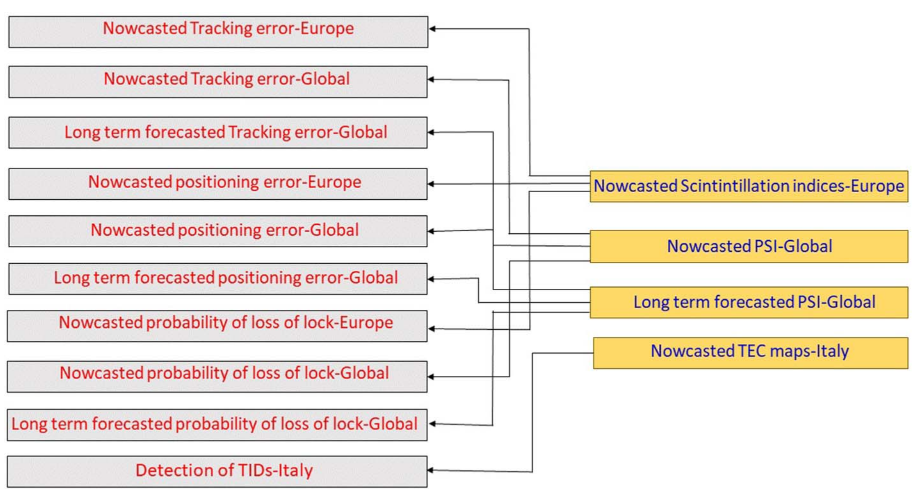

Fig. 4. Scheme reporting the input data types for the RPF-3 algorithms.

time period, horizontal drift velocity and horizontal wavelength. Details of this algorithm are presented in Alfonsi et al. (2018).

4.4 GNSS service performance (RPF 4)

The RPF 4 is devoted to implement batch, nowcast and forecast performance analysis of GNSS aviation services. Two main products are available. The first allows the evaluation of short-term and long-term past performances of Aircraft-Based Augmentation System (ABAS) and Satellite-Based Augmentation System (SBAS) in terms of integrity, accuracy, availability and continuity for En-Route and Approach/Landing operations, depending on the required application, compliant with accepted and referred aviation standards (RTCA, 2006, 2009; ICAO, 2012). This solution is based on the batch processing of observations collected from a network of GNSS reference stations located worldwide and, when possible, in strategic locations, like airports. Such data is retrieved from identified GNSS data providers like IGS and EUREF. In detail, this product implements the following functions:

- Position calculation:
  - Un-augmented GPS L1 PVT (without integrity);
  - Un-augmented GPS L1 ABAS PVT solution, integrating RAIM-FDE capabilities;

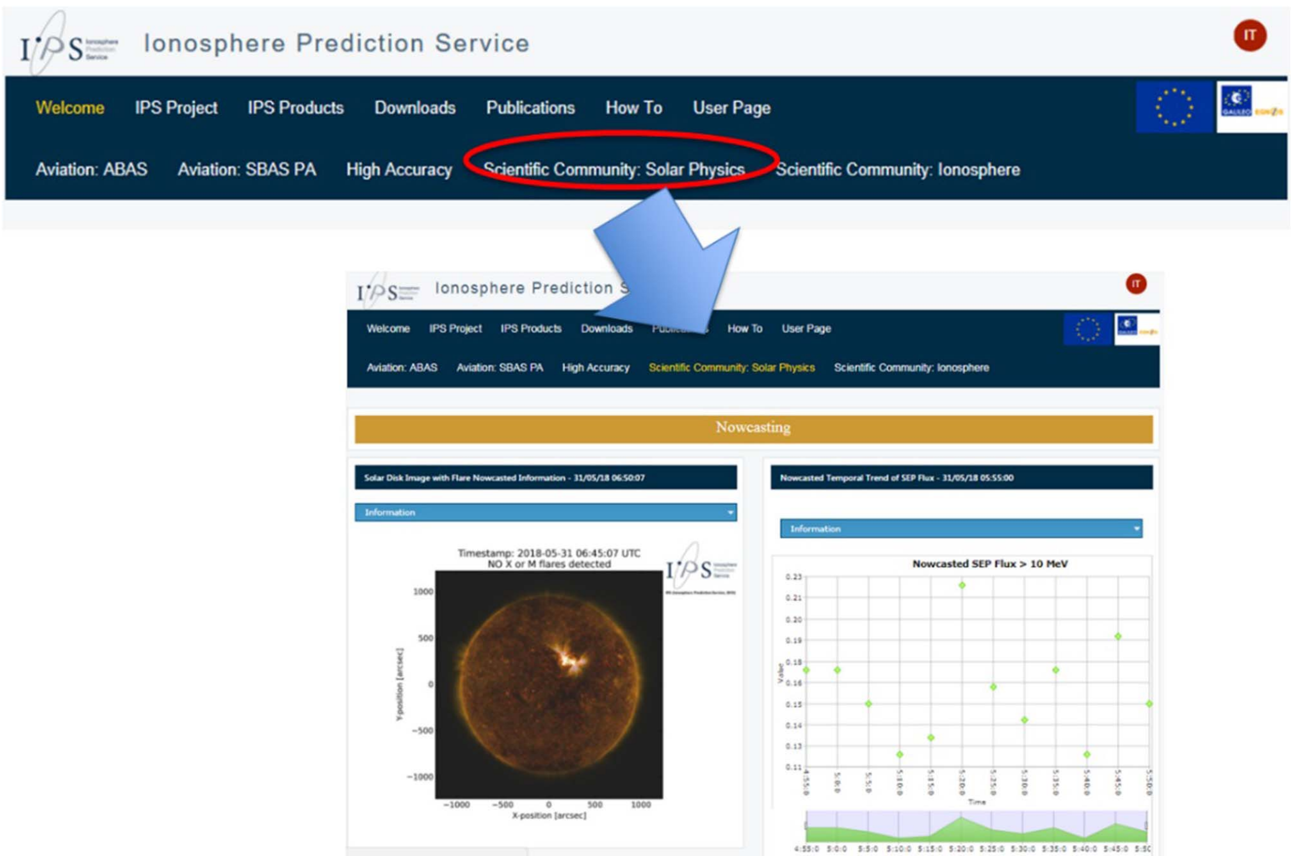

Fig. 5. An example of user community page.

- GPS L1 SBAS augmented PVT, emulating the processing of a SBAS-capable airborne receiver compliant with RTCA (2006), implementing both Localizer Performance (LP) and Localizer Performance with Vertical Guidance (LPV) navigation modes

- Performance analysis reports:
  - Position error and integrity analysis in both time and statistics domains;
  - xDOP (satellite geometry) analysis;
  - Availability and continuity plot for different aircraft operations;
  - Constellation status analysis;
  - Horizontal and Vertical integrity diagrams for both ABAS and SBAS solutions;
  - RAIM-FDE performance diagrams;

The second product uses standard GNSS observation data, forecast models and the forecasted ionospheric indicators generated by the RPF 2 to produce GNSS systems nowcast and forecast performance maps at specific locations, regions or volumes at global level. The effective coverage of this product depends on the type of analysis, the requested computation burden and actual model and data availability. In detail, this product implements the following functions:

- Evaluation of EGNOS performances in terms of service availability and continuity over the coverage area for several operations, from En-Route to LP/LPV Precision Approaches;
- The forecast analysis of the expected receiver position error and protection levels (e.g., HPL/VPL) for the ABAS avionic solution; these data will be available in the form of maps extended to the service coverage area.

5 CSPF and the web server

The core of the IPS architecture is the CSPF element that allows the exchange of the internal products among the RPFs and the web server. A central database is implemented as a backend element, where products are stored to be retrieved, if necessary, by users through the web server.

The IPS web portal is one of the most distinguishing components of the system and also represents the principal interface between the users and the service itself. It has been designed to give an immediate access to the several IPS generated products to every user, allowing a high level of interaction and customization. The users must register in order to access the whole IPS service. Non-registered users can only access the principal web page, the project description and the project publications, as well as the definition and characteristics of the several available products. The registration to IPS is free and can be requested by filling the registration form available on the project website: https://www.ips.telespazio.com.

For the registered users, the IPS web portal, shown in Figure 5, provides several products tailored for different GNSS user communities; therefore it is structured with several pages in which a selection of the products are made available by the system administrator to match the specific requirements of the particular user community (solar physics, ionosphere, aviation ABAS and SBAS PA (precision approach), high accuracy).

The IPS products are available to the final user in the form of widgets, for example:

- Map Image widgets: Global and regional products can be displayed in the form of .jpeg images in the web portal;
- Google map widgets: Global and regional products can also be displayed in the form of Google map widgets where the user can move around and zoom in and out;
- Plot widgets: Some products in the form of time vectors can be displayed as plots where the user can select and zoom a time interval;
- Table widgets: Some products producing large output data can be displayed as tables widgets;
- Gauge widgets: Some products consisting of scalar values can be represented by gauges. Gauge widgets are used also to represent active alarm monitoring.

The registered user can also access a personal page, where the user can select the products of interest and display them by using widgets. Here the user can freely customize their personal page by adding one of the available web components (e.g., image viewers, plots, maps, gauges, tables, etc.) to monitor specific performance figures of own interest. As an example, the user can add a viewer to monitor the trend of a performance figure of one of the IPS GNSS stations close to a desired location or monitor the behaviour of ionospheric TEC focusing on a specific location or an area of interest. Currently IPS is able to generate and make available to the users more than 160 different performance products related to the ionospheric status and its effects on GNSS.

It is also possible to define a custom alert from the personal page. The alerting function has the objective to provide a tool for the user to easily monitor the behaviour of specific physical parameters against a user-defined threshold or intervals. When the parameter exceeds the interval of validity, for example, in the event of a forecast for an upcoming ionospheric threat that would need to be notified to the user community, a message or notification is sent to the registered user (via electronic mail).

Additionally, the IPS web portal provides a download function where the user can access the past IPS products corresponding to the specific user community in a specified time window. The user can choose to download the raw IPS product in an internal data format (whose specifications are included in the public downloadable publications archive).

An important feature that is included in the user community pages (also accessible in the personal page and in the download sections of the portal) is the retro-validation function. The "Forecast Retro-Validation" is a periodic report with output of the comparison between the forecast analysis and the corresponding actual value computed at the same time and for the same physical quantity. This function allows to assess how good the forecast algorithms actually perform in predicting the future behaviour of the monitored quantities.

Another relevant IPS function is the Statistical analysis. This function allows the user to continuously calculate statistical parameters on the basic IPS products (like moments, Probability Distribution Function, Cumulative Distribution Function, etc.) to be displayed on the web portal personal page through one of the several widgets available or in form of a table.

The IPS prototype is currently hosted at Telespazio and a parallel activity is ongoing to transfer it to the Joint Research Centre (JRC), Ispra to further test the platform, and to assess whether and how a dedicated prediction service for Galileo users can be implemented as part of the service facilities of the Galileo infrastructure.

6 Conclusions

An overview on the IPS architecture, the newly developed state of the art nowcasting and forecasting products and the whole integrated service chain are presented. The solar and space weather monitoring products (RPF 1) focus on flares, CMEs and SEPs, which can affect the Earth's ionosphere. The focus of the space weather-ionospheric products (RPF 2) is on TEC, IRE on L1, TEC gradients and scintillation on different temporal and spatial scales. The GNSS receiver and user performance products (RPF 3) focus on providing meaningful information to GNSS high accuracy users, through receiver tracking errors, probability of loss of lock and positioning errors. The focus of the GNSS service performance products (RPF 4) is specifically on civil aviation services. The state of the art analysis revealed that there are similar initiatives worldwide, with different objectives, methodologies and products. However, some of the described initiatives seem not active or not fully operational, whereas others are not focused on service provision to final GNSS users. The IPS is a prototype capable of providing in real-time products to assist GNSS users and service providers anticipating potential degradation of GNSS performance. Overall, the IPS products monitor and forecast the solar and ionospheric activity and its well-known effects on GNSS signals and on the final performances of GNSS user applications; a whole class of products translates the observation of the space weather phenomena and perturbations into nowcast and forecast of GNSS performance figures at user level over regional and global scale. Details on the CSPF that manages the output of the chain of RPF's and the web portal that is the final user interface are also presented. The IPS is freely accessible, upon registration, through its web portal https://ips.gsc-europa.eu from July 2018 and the prototype is currently being operated, during which feedback from users are being collected.

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GROUP (2016), RETE INTEGRATA NAZIONALE GPS, DOI:10.13127/RING) providing data over Italy are managed by INGV Earthquake department. Data from stations in Brazil are part of the CIGALA/CALIBRA network. Monitoring stations from this network were deployed in the context of the Projects CIGALA and CALIBRA, both funded by the EC in the framework of the FP7-GALILEO-2009-GSA and FP7–GALILEO–2011–GSA–1a, respectively, and FAPESP Project Number 06/04008-2. SDO images Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams. SDO is a mission for NASA's Living With a Star (LWS) program. The source of HMI data is the SDO HMI and AIA Joint Science Operations Center (JSOC). SOHO data supplied courtesy of SOHO/LASCO consortia. SOHO is a project of international cooperation between ESA and NASA. This work utilizes intensity data obtained by the Global Oscillation Network Group (GONG) project, managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. GOES 5-min X-rays, proton and electron data from the NOAA Space Weather Prediction Center. This work uses data from the CACTus CME catalog, generated and maintained by the SIDC at the Royal Observatory of Belgium. The authors wish to thank Roberta Forte for her helpful contribution to the IPS project. The editor thanks two anonymous referees for their assistance in evaluating this paper.

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