Travelling Ionospheric Disturbances Forecasting System

T-FORS

Compilation of Stakeholders' Requirements

Version 1.0

The T-FORS project has received funding from the European Union's Horizon Europe Research and Innovation Actions programme under Grant agreement No 101081835

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Document Information

Milestone Number: Deliverable Title:	5 Compilation of Stakeholders' Requirements
Date of Delivery:	30st June 2023
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Work Package no.:	WP1
Work Package title:	Strategy and capabilities
Work Package leader:	BGD
Dissemination level:	Public
Nature:	Report

Abstract

The deliverable presents an initial compilation of stakeholders' requirements. The contents are collected through contacts with the members of the T-FORS network and through literature review. It provides information regarding the standards adopted by international programmes and service requirements regarding the availability of TID forecasts.

Document history

Version	Date	Edited by	Reason for modification / Remarks
0.1	2023.06.11	Ivan Galkin	First draft
1.0	2023.07.04	Anna Belehaki	Additional information on stakeholders' requirements
IR	2023.07.11	Ivan Galkin	Initial Release (IR) finalized

Disclaimer

Executive Summary

T-FORS project aims at providing new models able to interpret a broad range of observations of the solar corona, the interplanetary medium, the magnetosphere, the ionosphere and the atmosphere, and to issue forecasts and warnings for TIDs several hours ahead [AD-1]. T-FORS expects to develop prototype services based on specifications from the users' community with a comprehensive architectural concept allowing for possible future adjustments to develop a real-time operational service.

This document is the initial review of stakeholders' mandatory and desirable requirements gathered among those affected by TID phenomenon. Some of the contributors represent T-FORS consortium members: GFP for high-frequency (HF) communications, INGV for N-RTK, and ONERA for the OTH radar. The requirements are named, described, and assigned an identification number and priority.

1 Purpose and Scope of the Document

This document presents the initial review of stakeholders' mandatory and desirable requirements gathered among those affected by TID phenomenon. The document is divided into four sections:

Section 1 (the current section) describes the purpose of this document and its organisation.

Section 2 lists the applicable and reference documents and also contains the list of acronyms used in this document.

Section 3 reviews T-FORS usage scenarios as anticipated by stakeholders

Section 4 presents the list of requirements.

2 Applicable and Reference Documents

Applicable Documents

The following Table 1 contains the list of applicable documents.

Table 1. List of applicable documents

AD	Document title
[AD-1]	Grant Agreement number: 101081835 — T-FORS — HORIZON-CL4-2022-SPACE-01
[AD-2]	Milestone 3: Initial T-FORS standards, quality control and best practices
[AD-3]	Deliverable 1.2: State of the art review report on standards and capabilities in TID detection procedures

Reference Documents

The following Table 2 contains the list of references used in this document.

Table 2. List of reference documents

RD	Document title
[RD-1]	Space Situational Awareness - Space Weather System Requirements Document, Prepared by ESA SSA Team Reference SSA-SWE-RS-RD-0001
[RD-2]	Belehaki, A., I. Tsagouri, D. Altadill, et al. (2020) An overview of methodologies for real-time detection, characterisation and tracking of traveling ionospheric disturbances developed in the TechTIDE project, J. Space Weather Space Clim., 10, 42, DOI: https://doi.org/10.1051/swsc/2020043

RD	Document title
[RD-3]	3DIM 2021: 3D ionospheric modelling workshop, University of Birmingham, UK, 29 November 2021, unpublished.
[RD-4]	National Research Council (2010), Precise Geodetic Infrastructure: National Requirements for a Shared Resource. *Washington, DC: The National Academies Press*. https://doi.org/10.17226/12954
[RD-5]	Fung, S. F., Benson, R. F., Galkin, I. A., Green, J. L., Reinisch, B. W., Song, P., & Sonwalkar, V. (2022). Radio-frequency imaging techniques for ionospheric, magnetospheric, and planetary studies. In *Understanding the Space Environment through Global Measurements*, 101-216, Elsevier. https://doi.org/10.1016/B978-0-12-820630-0.00006-4
[RD-6]	Jakowski, N., Mayer, C., Wilken V., & Hoque, M. M. (2008), Ionospheric impact on GNSS signals, In: Física De La Tierra, 20, Ciudad Universitaria de Madrid, https://doi.org/10.5209/REV_FITE.2008.V20.12305

Acronyms

The following Table 3 contains the list of all acronyms used in this document.

Table 3. List of acronyms

Acronym	Definition
BGD	Borealis Global Designs EOOD
CME	Coronal Mass Ejection
D2D	Digisonde-To-Digisonde
DF	Direction Finding
DLR	German Aerospace Center
ESA	European Space Agency
FI	Foldfizikai es Urtudomanyi Kutatointezet
GFP	Bundespolizei
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HF	High-Frequency
HF-INT	HF Interferometry
IAP-L	Leibniz-Institut fur Atmospharenphysik ev an der Universitat Rostock

Acronym	Definition
IAP-P	Ustav Fyziky Atmosfery av CR, v.v.i.
INGV	Istituto Nazionale di Geofisica e Vulcanologia
IPR	Intellectual Property Rights
IPT-SWeISS	Inter-Programme Team on Space Weather Information, Systems and Services
IR	Initial Release
LSTID	Large Scale TID
LOFAR	Low Frequency Array
ML	Machine Learning
MSTID	Medium Scale TID
MUF	Maximum Usable Frequency
NOA	Ethniko Asteroskopeio Athinon
N-RTK	Network Real-Time Kinematic
OE	Observatorio del Ebro Fundación
ONERA	Office National d'Etudes et de Recherches Aerospatiales
OSCAR	Observing Systems Capability Analysis and Review Tool
OTH	Over The Horizon
OTHR	OTH Radar
PPP	Precision Point Positioning
ROB	Royal Observatory of Belgium
RMI	Institut Royal Meteorologique de Belgique
RTK	Real-Time Kinematic
SAR	Synthesized Aperture Radar
SSA	Space Situational Awareness
TEC	Total Electron Content
TechTIDE	Warning and Mitigation Technologies for Travelling Ionospheric Disturbances Effects
T-FORS	Travelling Ionospheric Disturbances Forecasting System
TID	Travelling Ionospheric Disturbance
WIGOS	WMO Integrated Global Observing System

Acronym	Definition
WIS	WMO Information System
WMO	World Meteorological Organization
WP	Work-package

3 T-FORS Stakeholders and Usage Scenarios

3.1 General Considerations

Although T-FORS ultimately targets the development of an operational, real-time system to issue forecasts and warnings for TID activity several hours ahead [AD-1], it will remain a *functioning prototype* throughout the project's period of performance. The prototype will serve as the recommendation for its transition to operations at the end of the term. This review of the stakeholders' needs therefore avoids specific requirements that define standards of operations such as maximum downtime or issuance of scheduled maintenance alerts, because these *performance* metrics will be managed under the best-practice regulations of the agency where the final design will be eventually hosted. On the other hand, the T-FORS research team encountered strong requirements that go beyond the stated capability of forecasting to a few hours' time horizon; these are included for completeness. Additionally, the intended requirements that describe the spatial extent to which T-FORS forecasting shall apply were extended to include global specification of TID activity to recognize the universally important impact of the space weather on human civilization's everyday practices such as travel by air.

3.2 Background

Traveling ionospheric disturbances (TID) are natural or man-made phenomena of quasi-periodic plasma density undulations [AD-3, Section 2.1]. The adverse effects of TIDs on operational systems that employ radio signals traversing the ionosphere are well established, though not sufficiently understood to predict or mitigate in real-time. The top-level classification of TIDs [AD-3, Section 2.2.3] includes the large-scale LSTID (rapid-moving, large-amplitude perturbations of the wavelength above 600 km) and the medium-scale MSTID (slower-moving, lower-amplitude perturbations of 50-600 km scale). Although both types affect the radio systems in a similar way, LSTIDs are easier to detect and find contra-measures to address (e.g., by establishing a network of reference location nodes to compute and distribute augmentations to the systems). MSTIDs are harder to detect and not feasible to compensate for by the reference network like N-RTK ([augmentation] Network for Real-Time Kinematic positioning service), which would have to be prohibitively dense and expensive. MSTIDs are also hard to forecast because of the staggering variety of different physical mechanisms that are responsible for their generation, none of which easily admit real-time specification and forecast themselves.

In recognition of the expected varying uncertainty in the forecast depending on its time horizon, we accept the following terminology:

- **TID warning**: forecast of an upcoming disturbance with a 2 or more hours advance, based on (1) monitoring of the helio- and geospace activity and intelligent-system models of the corresponding global response of the ionosphere or (2) statistical expectations of the MSTID occurrence;

- **TID alert:** forecast of an upcoming or ongoing disturbance with less than the 2-hour horizon, based on objective TID event sensor detections and a short-term forecast of its direction of travel; and
- **TID report:** backcast of the observed disturbance for an improved re-analysis of the retrospective end-user data using thus updated specification of the ionosphere.

An example of TID report relevance to end users would be the HF geolocation sensor with an acceptable delay of the accurate TID description provided by T-FORS that allows the sensor to improve the accuracy of its geolocation.

3.3 Stakeholders by Domain of Interest

Several important agencies and end-user organizations have indicated their strong interest in qualifying and quantifying adverse effects from the anomalous TID activity in the ionosphere. Historically, the European Space Agency (ESA) has been considering TID effect mitigation as a clear customer requirement (marked "essential") for the Space Weather segment of the Space Situational Programme (SSA) [RD-1]; a dedicated network of services has been established to address the problem [RD-2]; however, the requirement for a TID forecasting service is not fulfilled.

According to the ESA SSA Space Weather service requirements, several general standardized functionalities, which apply to a TID prediction service, must be met:

- Analysis reports shall identify the models, input parameters, tools and data used to generate the content
- The system shall support the automatic and manual generation of analysis reports for a given event and/or period of interest
- The user shall be able to select the content of an analysis report from the service elements available (graphical and numerical outputs shall be supported)
- Known limitations arising from data and/or model availability shall be identified and listed
- Uncertainties in model and data output shall be listed where available.
- For the data sources that provide calculated values (whether indices, derived parameters, extrapolations of basic parameters or any result from a calculation process), the system shall provide accurate description of the model and parameters used for their generation as well as which exact information is provided by each parameter and its domain of applicability.
- The system shall estimate the accuracy and confidence of the provided services and make it available to the users.
- Uncertainties in the data and model outputs shall be quantified in the form of quality metrics.
- The service shall warn the user when the accuracy and confidence of the delivered products are degraded.

Recently, the World Meteorological Organization (WMO) assembled an Inter-Programme Team on Space Weather Information, Systems and Services (IPT-SWeISS) to coordinate space weather activities within the WMO Programmes, to maintain linkage with the constituent and partner organizations, and to provide guidance to WMO Members. Some of the main tasks of IPT-SWeISS among others are:

- Standardization and enhancement of Space Weather data exchange and delivery through the WMO Information System (WIS);
- Coordinating the development of SPW best practices for end-products and services, including, for example, quality assurance guidelines and emergency warning procedures, in collaboration with aviation and other major application sectors;
- Oversee the development and review of the Observing Systems Capability Analysis and Review Tool (OSCAR) so that it meets the needs of WMO Integrated Global Observing System (WIGOS) concerning user space weather observing system capabilities.

Furthermore, T-FORS must consider the Advisories adopted by the ICAO to address impacts on aviation of GNSS systems, HF communication, and radiation levels at flight altitudes. Specifications for the Advisory Messages are produced on the basis of expert interpretation of products, which include ionospheric products, such as Total Electron Content mapping (for GNSS users) and Post-Storm Depression of (foF2 and Maximum Usable Frequency ratios) at global and European levels.

T-FORS is planning to follow the WMO/IPT-SWeISS and ESA SWE standardization for the data quality and the ICAO standards for the alerts. Alerts will be issued as advisory when the TID parameters cross two thresholds: Moderate (MOD) and Severe (SEV). These thresholds will be specified in the on ground demonstrations, although some important work has been done in the previous TechTIDE project where activity thresholds were defined based on comparison of performance degradation data with disturbances in specific ionospheric characteristics due to TIDs [RD-2]. This is background knowledge and will be used for the definition of alerts' thresholds. The T-FORS alerts will provide some standard information (time stamp, service provider, advisory numbering, etc.), the intensity of the expected TID characteristics, the spatial extent and duration of the disturbance. ICAO will be reviewed and followed for designing the alerts to have the maximum possible compatibility and reliability. This plan for standardization and quality assurance will efficiently support Research and Innovation projects of users who are concerned about the TID effects in their operations.

A top-level review of various radio systems considering ionospheric weather forecast an essential part of their operation is summarized in Table 4 [RD-3], together with the list of academic research applications that have been vital to the Horizon Europe programme. Table 4 uses three categories of forecast: 3 days, 3 hours, and 3 minutes to represent typical scenarios of system operations. The requirements were assembled by participants of the ESA-sponsored 2021 3DIM workshop for 3D Ionospheric Modelling for an in-depth review of available ionospheric forecast capabilities.

Table 4. Ionospheric weather forecast requirements sorted by domain and application

Domain	Application	Forecast requirements		
		3 Days	3 hrs	3min
HF Systems (radars and Comms)	Coordinate registration	No	No	Yes
	Frequency Management	Yes	Yes	No
	Aviation (and MUF)	Yes	Yes	Yes
	Search and rescue	No	Yes	Yes
	Altimeter error	No	No	Yes
	Geolocation	No	No	Yes
GNSS	Vehicle positioning/automation (Industrial, Agriculture)	Conditional	Yes	Yes
	Aviation (landing)	No	-	Yes
	Aviation (Flight corridors)			Yes
	System integrity	Climatology	-	Yes
	Timing (financial, cellular, synchronization, vehicular)	Climatology	-	Yes
	Autonomous shipping (HF & GNSS)	No	No	Yes
	Mining, drilling, sea drilling	Yes	Yes	Yes
Science	SAR – Earth Observations	Yes - Planning	No	Yes
	LOFAR	Yes - Planning	No	Yes
	Atmosphere – Ionosphere – Thermosphere – Magnetosphere coupling	Reanalysis	No	No
	Ray tracing	No	No	Yes
	Space climate	Reanalysis	No	No
	Space weather	Reanalysis	No	No

Forecasting TID is an essential part of the activities listed in Table 4, as further detailed below.

3.3.1 Geodetic Applications with PPP Requirements

Figure 1 illustrates the significance of interest in accomplishing precise point positioning (PPP) to 1 mm - 10 m accuracy in various branches of human activity [RD-4]. The vertical axis of the chart presents the positioning precision/accuracy requirement for the applications, while the horizontal axis is the latency requirement ranging from immediate (in seconds) to historical (in decades). All applications with a latency requirement above hours do not require a weather forecast service; all applications with an accuracy requirement above 10 m are not strongly affected by TID activity. The affected PPP applications experience unacceptable and, more importantly, undetectable TID-induced deterioration of positioning accuracy and precision.

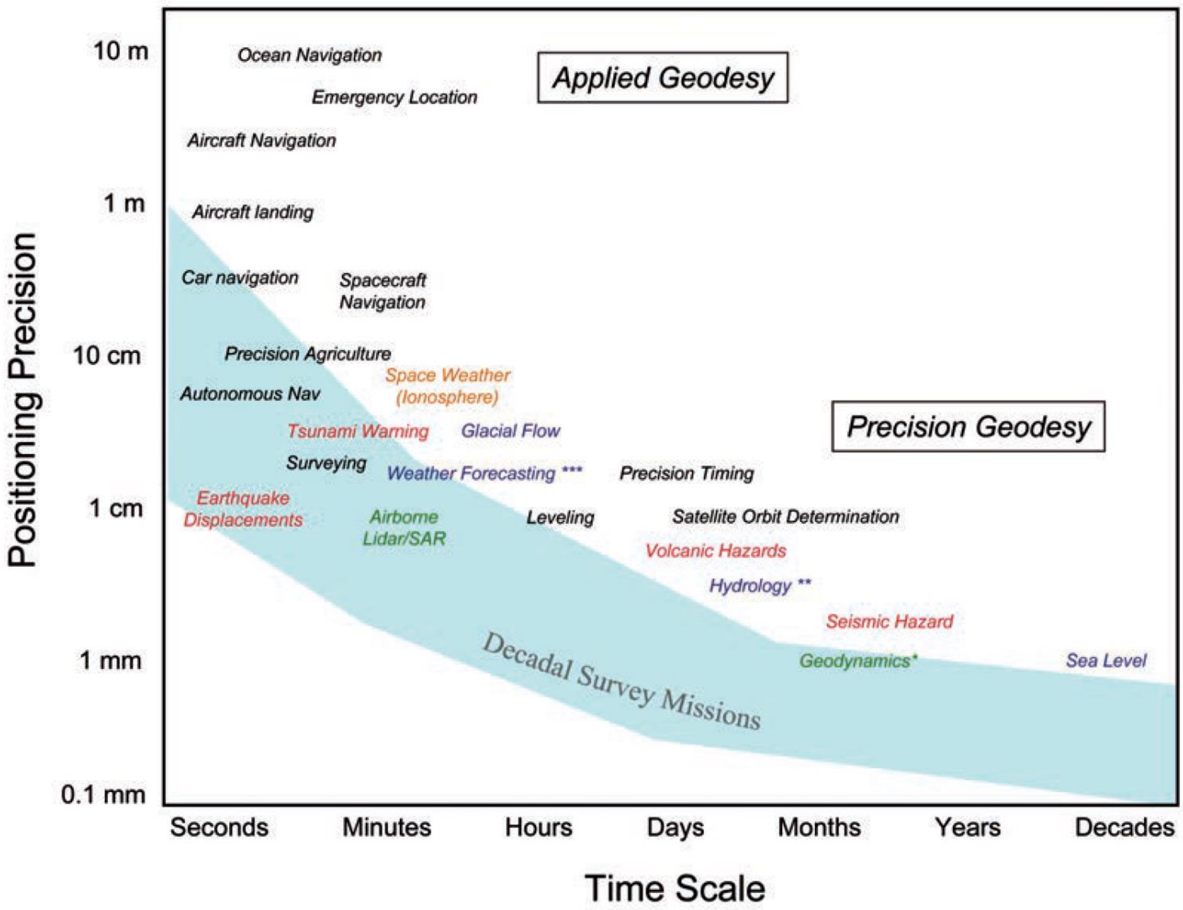

Figure 1. A plot of the precision of current geodetic applications that rely on PPP capability as a function of the required time interval.

The most demanding applications at the shortest time intervals include GNSS/GPS seismology and tsunami warning systems. At the longest time intervals, the most demanding applications include sea level change and geodynamics. (after [RD-3])

* *Plate motion, plate deformation, mountain building, mass transport, ice-sheet changes (using loading motion and gravity changes observed from space).*

** *Vertical surface motion from GNSS/GPS and InSAR for groundwater management; water redistribution is monitored from space based on gravity measurements).*

*** *Water vapor and other meteorological information from GNSS/GPS ground stations and radio occultations in space.*

Dubbed "silent accuracy killers" [RD-5], both large- and medium-scale TIDs can inflict up to several meter errors on RTK (real-time kinetic), Network-RTK (NRTK), and PPP. Unlike the loss of lock or scintillation events that can be plausibly identified by the receiver circuitry autonomously, it is practically impossible to sense the positioning error caused by TIDs without an external alert from the navigation spacecraft to the rover so that it can trigger its autonomous measures to compensate for the overpassing disturbance or to pause its operations due to the positioning uncertainty.

The RTK/NRTK services were introduced for GNSS with the intended purpose to provide necessary data to mitigate the ionospheric effects from the plasma disturbance variety. Given the many-hundred km scale of the LSTID phenomenon, such RTK mitigation measures are quite practical using a sparse wide-area network of stationary reference stations to determine and disseminate corrections to rovers and other precise navigation users. However, the same approach faces formidable challenges in its implementation to mitigate the impact of MSTIDs, because it is harder to meet the requirement that corrections apply universally across the area between reference sites.

The smaller wavelength of the MSTIDs translates to a required ~100 km baseline of the reference station on the grid, rendering its implementation impractical because of associated costs per station. A simple linear interpolation of the corrections determined across a sparser-coverage RTK service area was proven unsatisfactory [RD-4] as overpassing TIDs violate the "same ionosphere as the reference" condition and thus broadcasted correction message to the rovers may simply be wrong. Figure 2 illustrates two common scenarios of this violation due to plasma irregularities of medium (the left panel) and small (the right panel) scales.

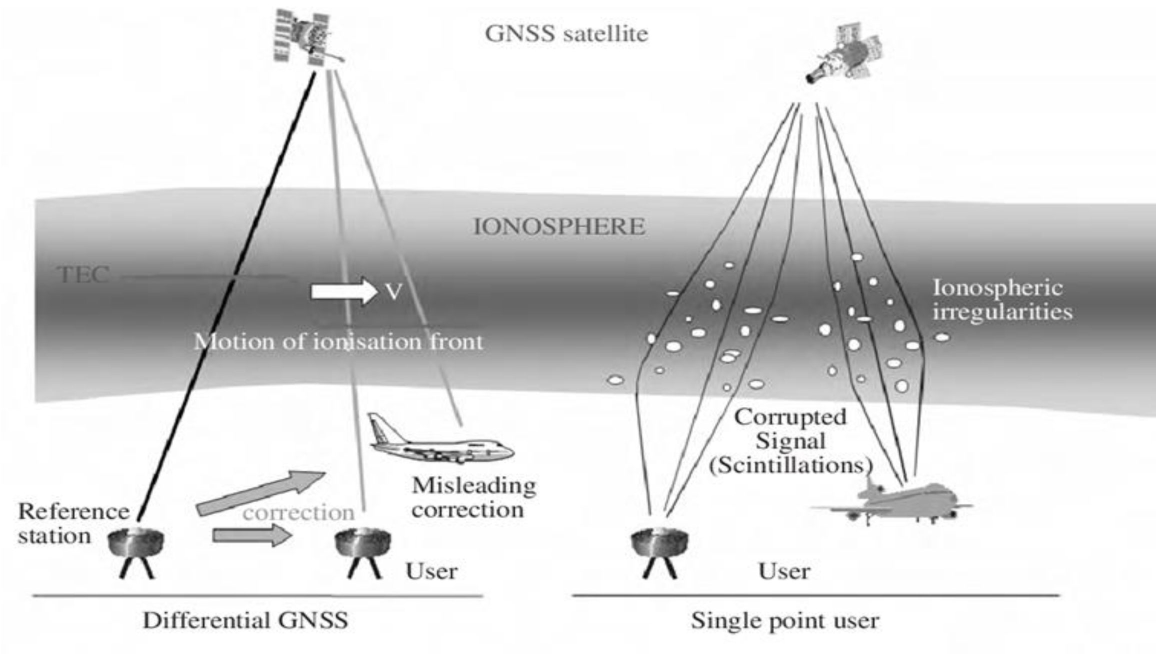

Figure 2. Common scenarios of the RTK augmentation services in which determined correction at the reference station does not apply to the ionospheric conditions at the rover location. (after [RD-6])

3.3.2 Ionospheric backscatter sounding

Ionospheric backscatter sounding by frequency/elevation scanning is a powerful tool for determining the characteristics of the ionosphere and performing geophysical studies. An example of backscatter ionograms recorded by NOSTRADAMUS skywave OTH radar, is given in Figure 3. The TIDs forecasting will make it possible to analyze the effects on the soundings and the impacts on the various inversion techniques. In return, the determination of TID parameters can be compared to forecasts. TIDs forecasting must be able to provide information such as: intensity of the phenomenon, duration, time of start and end, geographic extent, and probability of occurrence.

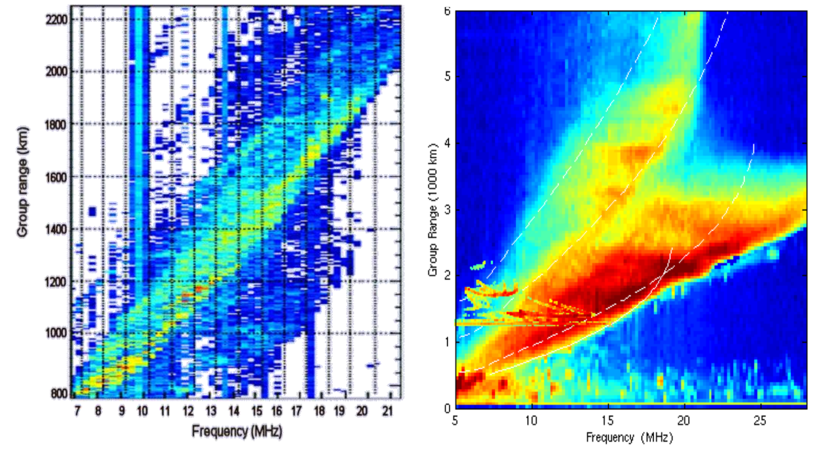

Figure 3. Example of backscatter ionograms by frequency/elevation scanning (raw data)

3.3.3 Civil air traffic control

Civilian airplanes may have to leave the surveillance zones of conventional aerial surveillance radars for various reasons (normal transcontinental airline, hijacking, breakdown ...). The experimental Skywave OTH radar NOSTRADAMUS operated by ONERA has the capacity to cover areas at long range, at very low altitude. The case of flight MH370 is emblematic of what skywave OTH radar could have provided in terms of monitoring this flight (Figure 4).

Figure 4. Search areas of flight MH370

TID forecasting can improve the coverage capacities of OTH radar: increase in the coverage ratio, anticipation of propagation channel modifications, increase of radar availability, etc. For this application, the multi-level forecasts of T-FORS and the relevant alerts in compliance to the standardized format recommended by ICAO should enhance the capabilities of the service.

3.3.4 Space objects fallout

The increase in the number of rocket launches and satellite orbiting, naturally increases the risk of uncontrolled fallout of large space debris (first rocket stage, uncontrolled satellite). Predicting fallout zones is made difficult by a lack of knowledge of the characteristics of local atmospheric drag. To remedy this, we must be able to track the object as long as possible. But the coverage of space surveillance radars is limited by the radio horizon. Skywave OTH radar should make it possible to increase the area covered and the quality of the trajectory (Figure 5). This can be useful for alerting populations and for determining the areas to be evacuated.

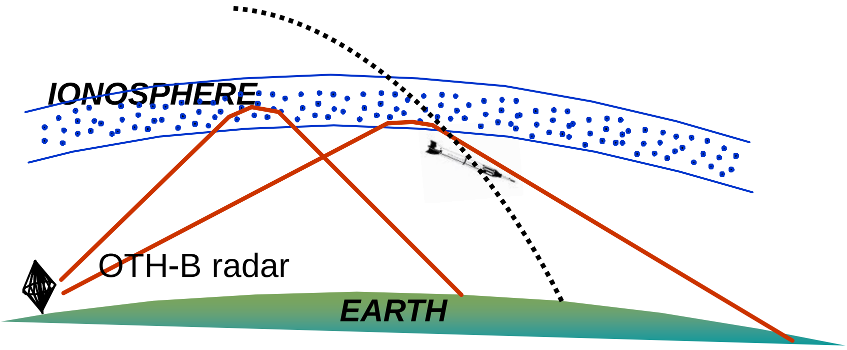

Figure 5. Space objects fallout detection principle

3.3.5 HF direction finding

HF operators need to perform a qualitative and quantitative assessment of the probability and intensity of the influence of TIDs on deviation of elevation and azimuth values of HF direction finding systems. T-FORS should aim to simple alert messages in a standardized format with the occurrence of TIDs and the associated effects. Technical aspects such as limitations or damage in the equipment used (e.g., antennas) or other ionospheric influencing factors can be adequately taken into account, but a method to reliably predict TIDs is currently lacking. The information on TIDs is important for both retrospective and prospective analysis of communication conditions. For retrospective analysis, the prediction services provide an additional source of information to understand the reason for poor reception quality afterwards. For planning purposes, the TID prediction information helps to predict and determine the current and future communication channel characteristics. So far, there is no reliable method to incorporate the existing knowledge of TIDs, and therefore operations are currently carried out with suboptimal data.

3.3.6 Research Infrastructures

T-FORS can offer data, methodologies and algorithms for the forecast of TIDs to support the integrated development and operation of Research Infrastructures. This complete set of assets, and especially the codes that forecast TID will be delivered for the first time, and are expected to provide significant advances beyond the state of the art. The following projects are going to see immediate benefit:

- PITHIA Network of Research Facilities, a Horizon 2020 Research Infrastructure project (2020 – 2024). The registration of T-FORS datasets and model codes in the e-science center of PITHIA-NRF is expected to enhance considerably the possibilities offered by the PITHIA nodes for the implementation of innovative projects by the users.
- PECASUS (ICAO): PECASUS can significantly benefit from the development of the T-FORS prototype service through the provision of warnings and alerts for TIDs in a format compatible with ICAO standards.
- ESA Space Weather Network: Enhanced support to the ESA Space Weather Network with new services that forecast TIDs. To satisfy ESA's requirements T-FORS has to provide the forecasts in ASCII and graphical mode and describe the metadata with the SPASE schema. The products must be provided in JSON (JavaScript Object Notation) format and in addition to the real-time availability, an archive must be kept.
- LOFAR and ALMA: The radio astronomical community requires forecasts for TIDs to plan their observations and to interpret their quality. Simple forecast advisory messages and alerts will support the efficiency of these operations.

4 Stakeholder Requirements

Table 5 provides the initial assessment of the stakeholder requirements, to be refined as T-FORS proceeds interacting with the users.

Table 5. T-FORS Requirements of Mandatory (M) and Desirable (D) priority.

Req ID	Requirement Statement	Priority	Users
1000 Series: General Scope of Services			
1010	T-FORS shall establish an operational system for issuing TID-in-progress alerts	M	All
1020	T-FORS shall establish an operational system for issuing upcoming TID possibility warnings	M	NRTK, EGNOS
1030	T-FORS shall establish an operational system for producing retrospective TID occurrence reports	M	All

1040	T-FORS shall accept geographic information to issue location-specific reports, alerts, and warnings	M	All
1050	T-FORS shall report timing information on elevated TID activity	M	All
1051	T-FORS shall report onset time of elevated TID activity	M	All
1052	T-FORS shall report stop time of elevated TID activity	M	All
1053	T-FORS shall report severity level of TID activity at the specified temporal resolution	M	All
1060	T-FORS shall report spatial information of elevated TID activity	M	All
1061	T-FORS shall report severity level of TID activity at the specified spatial resolution	M	All
1062	T-FORS shall accept geographic location parameters to issue location-specific timelines of reports, alerts, and warnings	M	All
1063	T-FORS shall accept geographic area parameters to issue area-specific 2D maps of reports, alerts, and warnings	M	All
1070	T-FORS shall report percent certainty metrics of reported TID activity at the specified temporal and spatial resolution	M	All
1080	T-FORS shall use 4-level severity level: 0 (minor), 1 (elevated), 2 (strong), 3 (severe) at each define spatial and temporal resolution step	M	All
1100	T-FORS shall report LSTID and MSTID activity separately	M	All
1200	T-FORS shall issue geospace activity metrics in support of the TID alert and warning evaluations	M	All
2000 Series: Nowcast and Backcast Operation			
2010	T-FORS shall complete the operational nowcast computation within 15 minutes of the latest sensor measurement	M	All
2020	T-FORS shall complete computation of the updated backcast within 2 hours of the current time	D	GFP

2021	T-FORS shall complete computation of the updated backcast within 1 hour of the current time	M	ONERA
2030	T-FORS shall report the TID-in-progress Nowcast and Backcast with 5-min time resolution	M	All
3000 Series: LSTID Forecast			
3010	T-FORS shall issue a 3-day operational forecast of upcoming LSTID activity at a 1-hour cadence	D	NRTK, EGNOS
3011	T-FORS shall issue the 3-day forecasts with 1-hour resolution	D	NRTK, EGNOS
3020	T-FORS shall issue a 12-hour operational forecast of upcoming LSTID activity at a 30-min cadence	M	NRTK, EGNOS
3021	T-FORS shall issue the 12-hour forecasts with a 30-min resolution	M	All
3030	T-FORS shall issue a 2-hour operational forecast of upcoming LSTID activity at a 15-min cadence	M	NRTK, EGNOS
3031	T-FORS shall issue the 2-hour operational forecasts with a 15-min resolution	M	All
4000 Series: MSTID Forecast			
4010	T-FORS shall issue a 12-hour operational prediction of possible upcoming MS-TID activity	M	All
4041	T-FORS shall issue the 12-hour predictions with a 1-hour resolution	M	All