IPS : Ionospheric Prediction Service

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Science and Navigation Programs / Civil Aviation

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Introduction to IPS (Ionosphere Prediction Service)

- "Ionosphere Prediction Service" (IPS) is a project funded by the **European Commission** through the Tender contract No: 434/PP/GRO/RCH/15/8381.
- The objective of IPS is to design and develop a prototypal service platform with the aim to translate the current status and forecast of the ionosphere into tangible results and user-devoted metrics.
- The pillars of this service will be:
  - Characterization of ionospheric effects that influence the GNSS performance and improvement of current solutions to monitor and predict the ionosphere effects.
  - Generate, archive and distribute performance and prediction reports, analysis results, disseminate alert and early-warning messages, sensor data, etc., customized to the relevant User Communities on the basis of the requirements defined for each of them.
  - The implementation of a Front-End Platform to interface the User Communities providing dedicated services and presenting relevant monitoring and forecast data results.

Main Project Steps

1. Collect requirements from the different user communities (aviation, rail, maritime, high precision, etc.) to identify their needs in terms of services based on the evaluation and prediction of ionosphere effects.
2. Analyse the State-Of-The-Art, the past and parallel similar projects and services to better characterize the originality of IPS and harmonise its specifications with the services currently available.
3. Introduce the Service Concept Definition to clarify the main objectives of the IPS and sketch its design concept with reference to its distributed architecture.
4. Developing the Ionospheric Prediction Service (IPS) prototype to be eventually integrated with the European GNSS Service Center (GSC).
5. Testing and Verification of the IPS Prototype (unit/system) to qualify the service and the implemented forecasting capabilities (6 months).
6. IPS corrective maintenance. Delivery of log-registers and User-Manuals.
7. Dissemination activities.

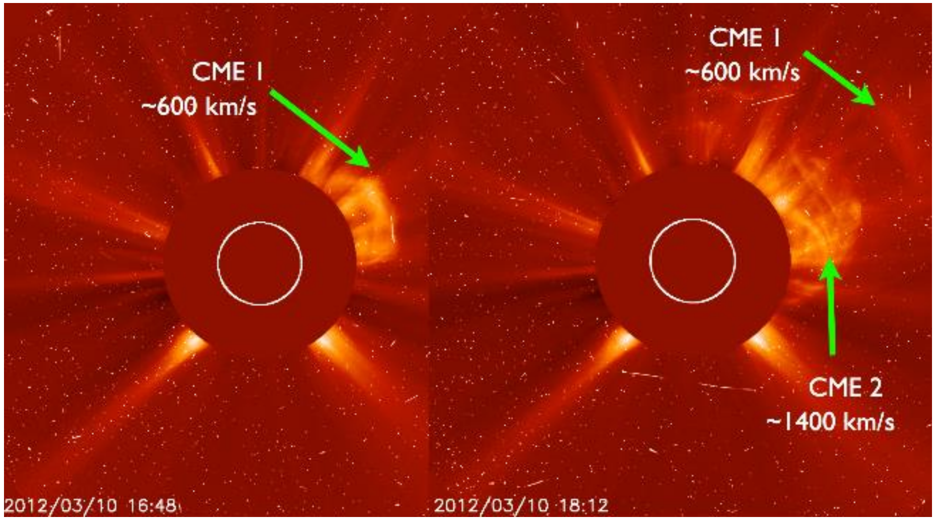
Project Team Members

Team Member	Type	Roles
Telespazio	Industry	Prime Contractor. In charge of IPS design, development and testing activities.
Telespazio VEGA Germany	Industry	Involved in T5 (IPS Service Requirements), support to T6 and T9
NSL (Nottingham Scientific Ltd)	Industry	Involved in T2 (User Req analysis), T6 (warning message generation) and T9 (feedback from aviation UC).
University of Tor Vergata	University	Monitoring and forecast of Flares and Coronal Mass Ejections. Measurements of SEP and GCR.
INGV	Research Institute	Forecast and nowcast of VTEC, spatial and temporal gradients, Proxy Scintillation Indices (PSI), S4, σ_Φ
University of Nottingham	University	Prediction of GNSS tracking errors, loss of signal lock and expected levels of positioning errors. Detection of Travelling Ionospheric Disturbances (TIDs).

University of Tor Vergata

Key Personnell: Prof. Francesco Berrilli, Prof. Roberta Sparvoli, Dr. Dario Del Moro

The Department of Physics – established on May 25th, 1983 at the same time with the foundation of the "Tor Vergata" University – directs the scientific research and the didactics in Physics, in both the experimental and the theoretical fields.



UTOV R&D will focus on:

- Observations and algorithms for **Flare** forecasting and research on magnetic reconnection as trigger of flares and **Coronal Mass Ejections** (CMEs).
- Implementation and validation of nowcasting and long-term forecasting tools for detection and parameter estimation of CMEs released by the Sun.
- Measurements of SEP (**Solar Energetic Particles**), GCR (**Galactic Cosmic Rays**) and related research activities.

INGV

Key Personnel: Dr. Giorgiana De Franceschi, Dr. Lucilla Alfonsi, Dr. Luca Spogli, Dr. Claudio Cesaroni, Dr. Vincenzo Romano

The National Institute of Geophysics and Volcanology is an Italian government institution devoted to studies in geophysics, seismic and volcanic hazards.

The **Upper Atmospheric Physics group** monitors and researches the ionosphere, from polar to low latitudes. The team expertise runs from GNSS receivers installation and configuration, to data treatment and structuring, to data analysis and original modelling tools development.

INGV R&D will focus on:

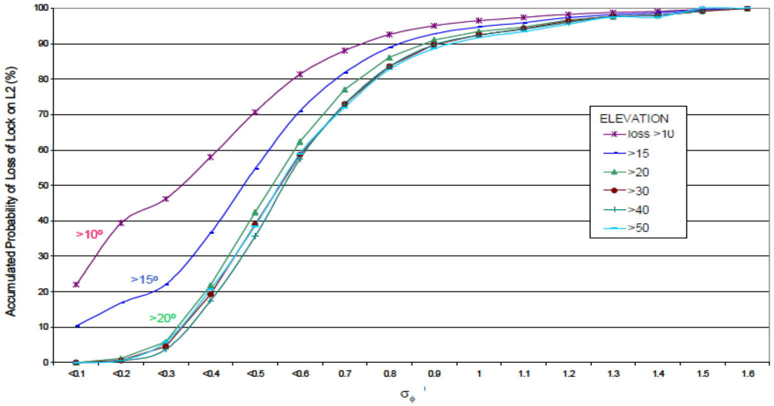
- Study of the morphology and dynamics of the ionospheric plasma to develop **TEC** and **Scintillation** mapping and modelling tools on different temporal and spatial scales.
- Implementation of statistical approaches to develop nowcasting, short term and long term mapping tools on global and/or regional scale.

University of Nottingham

Key Personnel: Prof. Marcio Aquino, Dr. Sreeja Veettil.

Project will be run at the NGI (Nottingham Geospatial Institute).

About NGI:



- Industry-led research profile
- Pioneered the operation of GPS ionospheric scintillation and TEC monitor receivers in Northern Europe in 2001
- Longstanding research record on GNSS and Galileo

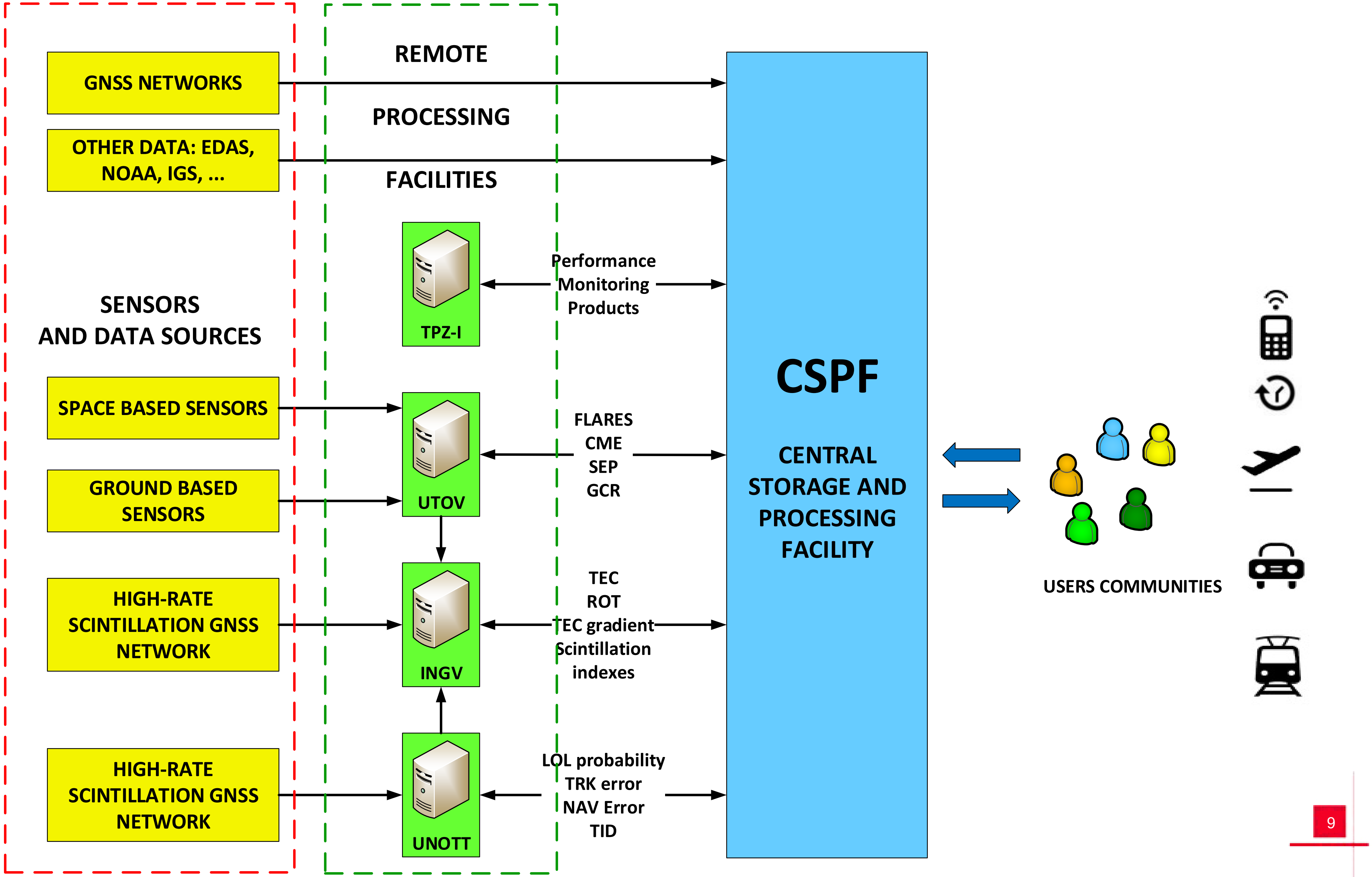
UNOTT R&D will focus on:

- Developing tools for modelling and prediction of **GNSS Tracking Errors**, **Signal Loss-Of-Lock** and expected levels of **Positioning Errors**
- Developing algorithms to detect **Travelling Ionospheric Disturbances** (TIDs) from Global TEC maps (in collaboration with INGV).

Ionosphere Forecast Products

Parameter	Details	Organization	Proposed Service	Input Data
Solar Flares		UTOV	Monitoring + forecasting (24 h)	MOTH instrument, SDO/HMI
SPE	Solar Particle Events	UTOV	Monitoring	PAMELA apparatus
CME	Coronal Mass Ejection	UTOV	Monitoring + forecasting	Satellite-born coronagraph imagers
EUV	Extreme Ultraviolet data	UTOV	Monitoring	NASA TIMED/SEE mission EUV data
GCR	Galactic Cosmic Ray	UTOV	Monitoring	Pamela apparatus
TEC	VTEC, spatial gradient, temporal gradient (ROT)	INGV	Nowcasting (global and regional) Short-term forecasting (30 minutes global and regional) Long-term forecasting (global climatology)	IGS real time service and archived data, high-rate scintillation GNSS network
Scintillation	Proxy Scintillation Indices (PSI), S4, σ_{Φ}	INGV	Nowcasting (global and regional) Long-term forecasting (global climatology)	High-rate scintillation GNSS network data
TID	Travelling ionospheric disturbance	UNOTT + INGV	Regional detection (near real time)	High-rate scintillation GNSS network data
Effect on Receiver Performance	GNSS receiver tracking errors, user positioning errors, probability of loss of lock of GNSS satellite signals	UNOTT	Now-casting, short-term and long-term predictions as per availability of the INGV proposed service	IGS data, ISMR high-rate scintillation data

IPS Functional Architecture



Remote Processing Facility (RPF)

- The **RPFs** use the data acquired from the sensors to generate the scientific results related to the ionosphere and solar activity and the effects on the receiver signal acquisition and navigation functions.
- Such results will be available in the form of plots, images, tables, binary data files, operational reports, etc..
- Final products and input data transmission from the local RPFs to the Central Storage might take place through two different modes:
  - FTP: the RPFs have to be equipped with a ftp server for temporarily data storage. The CSPF (ftp client) periodically asks to the RPFs to download (locally) stored data according to a acquisition plan that can be customized by the system manager.
  - WEB SERVICE: the RPF sends to the CSPF the available products together with their meta-data through an agreed protocol as soon as new products have been generated and are available.

Central Storage and Processing Facilities (CSPF)

The **CSPF** includes its two main components: IPS-FE and LPF.

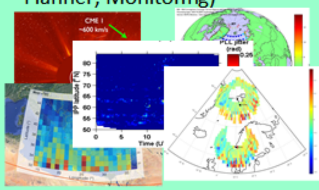
1. About the **IPS Front-End** (IPS-FE):
   - Implemented using COTS Content Management Systems tools and custom business logic SW.
   - Web-Portal designed and configured to present the products arranged according to the interests of the User-Communities.
   - Automatic data acquisition and archiving functions.
   - User profiling and Product Access rights customization. Administrators will be able to define new products types, plan their periodic and automatic acquisition, and publish them in the web portal.
2. The **LPF** has a complementary role in completing analysis and reporting functions not available from the RPFs.

Roles of the CSPF (Central Storage & Processing Facility)

CENTRAL STORAGE AND PROCESSING FACILITY

IPSFE (IPS FRONT-END)

AGW (Application Gateway)
- FTP server
- IPS and related products descriptions (static web pages)
- Users and profiles management
- Product search, download and upload
- System Configuration (Product catalogue manager, Acquisition Planner, Monitoring)



WND (Warning and NAGU Distribution)
- Configuration of early warnings distribution
- Distribution of early warnings and NAGU

DB (DataBase and Data Storage)
- RDBMS to store products metadata
- File System storage

RDBMS

FS

PRM (Product Manager)
- Automatic product acquisition (FTP), processing and archiving functions
- Supports product upload (via http)

RTM (Real-Time Module)
- Acquisition of GNSS real time data via NTRIP
- Clock synchronization

LPF (Local Processing Facility)

WNG (Warning and NAGU Generation)
- Calculus of the warning messages and NAGUs, customized for the different user communities
- Generation and formatting of warning message content.
- Generation of periodic reports (spreadsheet files, PDF documents, tables, etc.)

UPI (Users Performance Indicators)
- Translate scientific data and reports generated by the RPFs to Key Performance Indicators relevant and meaningful to the User Communities identified
- Implement data filtering functions to generate products relevant to a specific region, site and temporal interval according to the defined user requirements.

APS (Additional Post-Processing Analysis Services)
- Retro-validation of generated products through comparison between nowcast and available predicted data
- GNSS Performances Prediction based on prediction products and models provided by the Research Institutes.
- Analysis on the archived scientific data, generating further analysis: statistics, plots, diagrams, etc.
- Perform Quality Analysis of the single frequency ionospheric compensation (Klobuchar, Nequick) with respect to generated reference VTEC maps for mass market users.
- Perform statistical correlation analysis between solar activity products, ionospheric disturbances and GNSS user performances

Sensor Data

Output Products

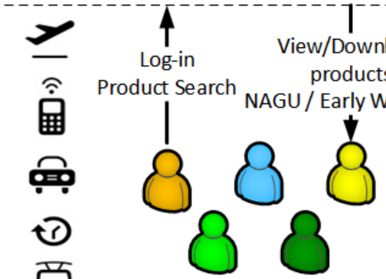
Input Products

SENSORS

REMOTE PROCESSING FACILITIES

Log-in
Product Search

View/Download products
NAGU / Early Warnings



USERS COMMUNITIES

GNSS Application Domains

Aviation

Emerging

High Accuracy

Mass Market

Critical Infrastructures

Space
- Precise Orbit Determination
- Satellite RT Navigation
- Satellite Formation Flying

Surveying
- Land Surveying
- Mapping and GIS
- Aerial Surveying

Location Based Services
- Tourism
- Games
- Carpooling and Transport on Demand
- Fleet Management
- Traffic law enforcement
- Surveillance of Parolees

Civil
- Aviation
- Financial
- Power Grids
- Road / Rail
- Maritime
- Industry

Scientific
- Timing
- Earth Sciences
- Space-time Metrology
- Fundamental Physics

Military
- Military Navigation
- Target Acquisition

Autonomous
- Autonomous Driving
- Train Control and Signalling
- Unmanned Aerial Vehicles
- Remotely Piloted Aircraft Systems

Impact of Ionosphere on GNSS-based Aviation (1)

- Aviation operations, including navigation, surveillance and timing, are relying more and more on GNSS services.
- GNSS is already widely used for the **En-Route** part of the flight and is being further developed for the (Precision) **Approach and Landing** operations. The surveillance domain follows the same trend (ADS-B).
- GNSS is already used as a time reference for some radar and multilateration synchronization and an increasing number of networks will rely on GNSS time
- When GNSS satellite signals are being transmitted from the GNSS satellites to the GNSS receivers, the signals are affected by the upper region of Earth's atmosphere (Ionosphere).
- The dispersive nature of the ionosphere induces various effects on the GNSS signal (Group delay, carrier phase advance, shift Doppler and phase or amplitude scintillation).
- In particular, GNSS satellite signals experience a delay which is proportional to the total number of free electrons along the propagation path between satellite and receiver.

Impact of Ionosphere on GNSS-based Aviation (2)

- In order to obtain the full potential of GNSS for aviation purposes it is important to be aware of the ionospheric effects on GNSS satellite signals, especially during enhanced ionospheric activity.
- SBAS systems like EGNOS use a dense network of reference receivers to real-time update a thin-shell ionospheric model valid at regional level.
- GNSS based aviation operation can be heavily affected by ionospheric effects.
  - Unexpected position and timing errors can occur at user level.
  - Under extreme conditions the GNSS receiver can lose satellite reception and the position can no longer be computed.
  - As a side effect, GNSS based surveillance applications could become unavailable.
  - SBAS or GBAS augmented services, used for approach and landing, are more demanding in terms of accuracy and integrity than the en route/TMA GNSS based navigation. Such services are more sensitive to space weather events, and their unavailability would be more frequent.

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Other Effects of Ionosphere on Aviation

- Degradation of radio/satellite communication:
  - During solar events, some disturbance may happen on the HF and satellite communication, which can have side effects on CPDLC, ADS-C, AOC etc.
  - Line of sight VHF communication may not be impacted.
- On board system failure due to radiation:
  - During a radiation storm, when striking a sensitive node, radiation may induce shortcuts, change of state or burnout in on-board electronic devices. This phenomenon is called “Single Event Effect”.
  - Its impact may vary a lot from unnoticeable to a complete failure of the system.
  - This kind of failure may become more frequent in the future because modern electronic equipment is more vulnerable to radiation due to the smaller size of their devices.
- Radiation doses:
  - During radiation storms, unusually high levels of ionizing radiation may lead to an excessive radiation dose for air travellers and crew.
  - The dose received by passengers and crew is higher at higher altitudes and latitudes.

Determination of Vertical TEC Maps (1)

Pre-Processing of OBS/NAV
- Data quality analysis
- Selection of network valid stations

TEC Analysis
- P_{L4} / Φ_{L4} calculus
- Cycle-Slips detection
- Carrier-phase TEC smoothing
- Biased (ST-1) or compensated (ST-2) TEC calculus

GNSS Receivers IFB Estimation
Network stations IFB estimation

<u>Solution developed by Telespazio in the frame of SENECA project:</u>

- Modelling and estimation of ionospheric propagation delays and variance maps computed over a grid of IGPs (VTEC maps).
- Produce alternative SBAS messages in EMS format, generated by modifying EGNOS messages introducing this ionospheric model.

GNSS Derived TEC Maps
Interpolation of ionospheric measurements over a grid (Planar Fit, Kriging, etc.)

IONEX
Ionospheric map in IONEX format

SBAS/EMS msg
EGNOS messages in EMS format modified with PNAV iono model

Graphics
Vertical delay maps, historical iono activity

Determination of Vertical TEC Maps (2)

GNSS Receiver Inter-Frequency Bias (IFB) Determination

- Biased TEC measurements are processed in order to separate receiver H/W biases (IFB, inter-frequency biases) from the ionospheric delay, multipath delay and thermal noise by appropriate modelling of their process dynamics.
- The estimation algorithm is based on the following assumptions:
  - Slant TEC ($STEC$) and vertical TEC are related by the obliquity factor $F(\theta)$.
  - Satellites and receivers biases are assumed to be constant on daily basis.
  - The deterministic component of the VTEC at the ionospheric pierce point (IPP) can be described by an analytical model which is function of IPP lat/lon.
- Estimation of IFBs and TEC model coefficients at IPPs is carried out by properly designed recursive estimation algorithms (Discrete Kalman Filter).

$$STEC = K \cdot F(\theta) \cdot \mathbf{E}(\boldsymbol{\lambda}_{IPP}, \boldsymbol{\varphi}_{IPP}) + \boldsymbol{DCB} + \boldsymbol{IFB} + \varepsilon$$

Satellite Differential Code Bias computed by CODE (University of Bern)

$$\mathbf{E}(\boldsymbol{\lambda}_{IPP}, \boldsymbol{\varphi}_{IPP}) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{m_{max}} \boldsymbol{E}_{nm} \cdot (\lambda_{IPP} - \lambda_0)^n \cdot (\varphi_{IPP} - \varphi_0)^m$$

- Local model based on bi-dimensional Taylor series expansions
- Global model based on spherical harmonic expansions

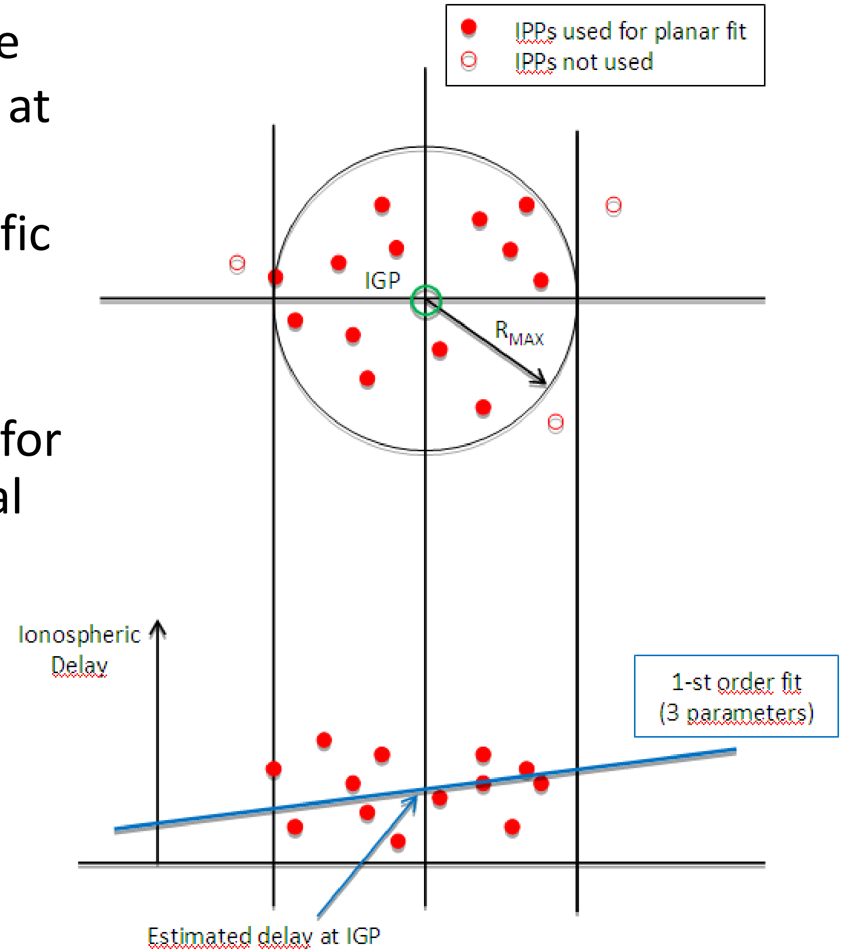
Problem unknowns estimated by the DKF

Determination of Vertical TEC Maps (3)

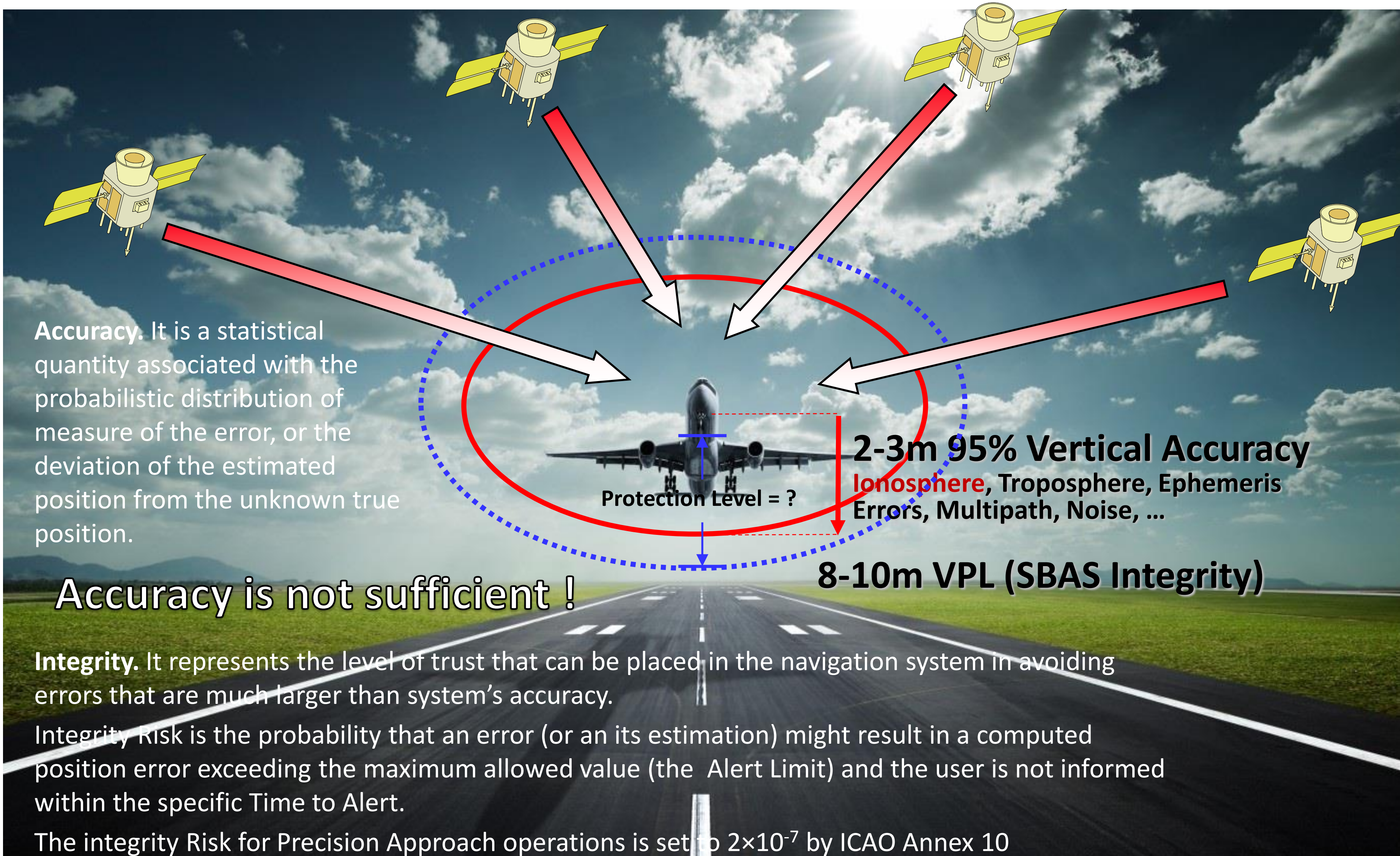
- Starting from the calibrated TEC values, the ionospheric vertical delay is reconstructed at the nodes (IGP) of an interpolation grid placed above the earth's surface at a specific altitude (single layer model).
- The implemented algorithm allows configuring the calculus of the VTEC maps for differently shaped and spaced geographical areas. Maps are then provided in standard IONEX format and as jpeg images.
- A planar fit algorithm is used to generate iono correction information
- The vertical iono delay around an IGP thus takes the form:

$$\hat{I}_{V,IGP}(\Delta\lambda, \Delta\varphi) = \hat{a}_o + \hat{a}_1 \cdot \Delta\lambda + \hat{a}_2 \cdot \Delta\varphi$$

- $\Delta\lambda$ and $\Delta\varphi$ are the relative longitude and latitude from location of the IGP



The Need for Accuracy and Integrity in Aviation



Accuracy. It is a statistical quantity associated with the probabilistic distribution of measure of the error, or the deviation of the estimated position from the unknown true position.

Accuracy is not sufficient !

Integrity. It represents the level of trust that can be placed in the navigation system in avoiding errors that are much larger than system's accuracy.

Integrity Risk is the probability that an error (or an its estimation) might result in a computed position error exceeding the maximum allowed value (the Alert Limit) and the user is not informed within the specific Time to Alert.

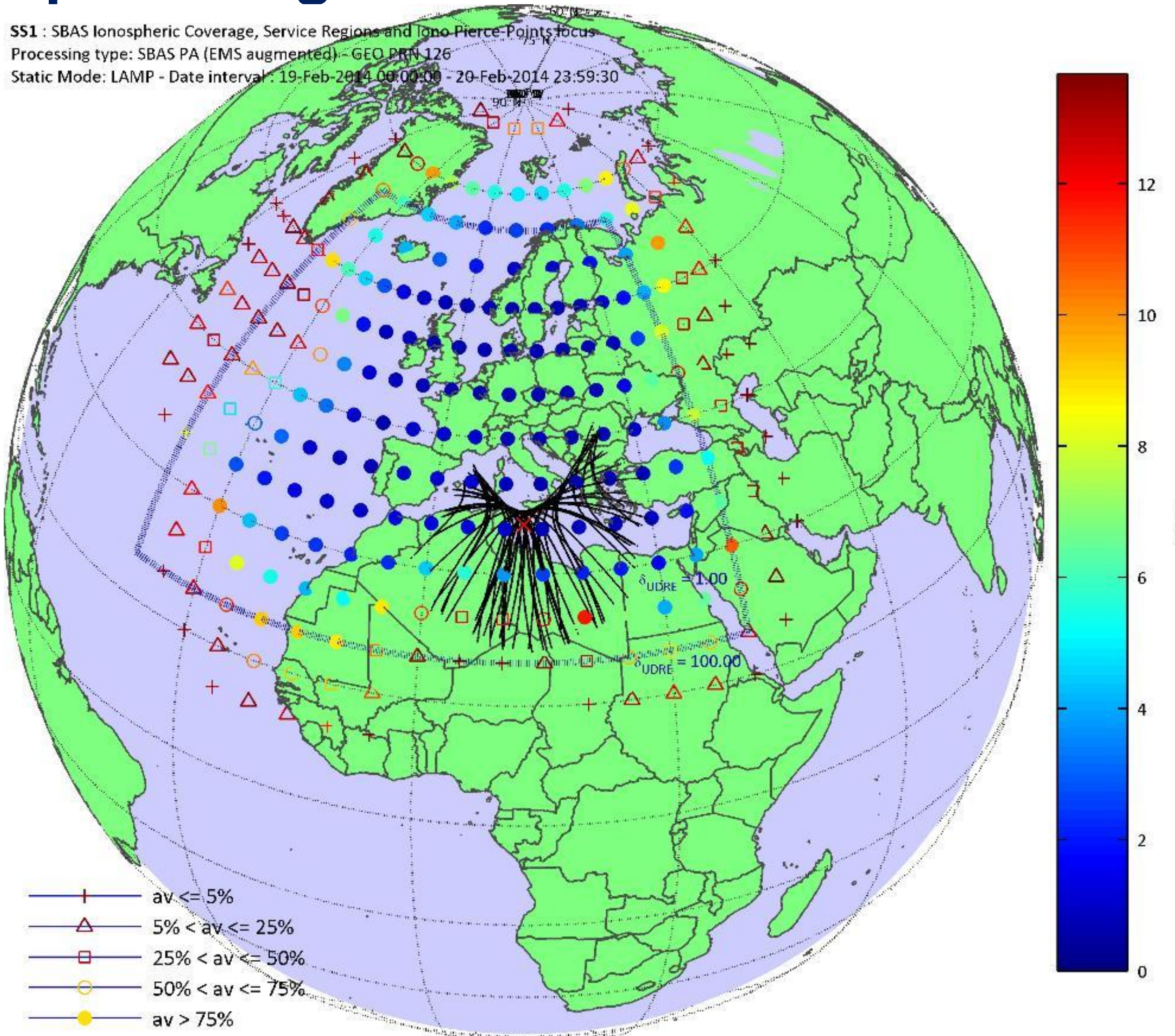
The integrity Risk for Precision Approach operations is set to $2{\times}10^{-7}$ by ICAO Annex 10

ABAS vs SBAS (Pros & Cons)

	ABAS	SBAS
Basic Information	ABAS (Aircraft-based Augmentation System) enhances GNSS performance with information available on-board the aircraft The most common ABAS technique is called Receiver Autonomous Integrity Monitoring (RAIM).	A Satellite-based Augmentation System (SBAS) is a civil aviation safety-critical system that supports regional augmentation through the use of GEO satellites which broadcast the augmentation information. SBAS augments primary GNSS constellations by providing GEO ranging, integrity and correction information to increase position accuracy.
Coverage	(+) Global, depending on satellite geometry (at least 6 satellites in view are required)	(-) Regional, where available (e.g. Europe and Northern Africa covered by EGNOS, US by WAAS) (+) It covers very large areas of airspace not served by other navigation aids
Accuracy	(-) RAIM doesn't increase receiver accuracy	(+) SBAS provides an Augmentation source to achieve much higher positioning accuracy than RAIM.
Performance	(-) Not usable for Vertical Guidance approaches (down to RNP-0.1) (-) Single failure detection only (+) (In theory) it is able to also detect and reject errors at user level (like multipath)	(+) SBAS provides Horizontal and Vertical guidance. (+) SBAS provides NRT Integrity Information and Satellite Status (+) EGNOS is currently certified for Precision Approaches from E/R through to LPV-200 category over the most of ECAC area.
Reliance on external infrastructures	(+) Its operation doesn't depend on ground infrastructures or any external source of information. (+) Simpler avionics implementation	(-) It depends on available ground infrastructures and a link with the SBAS GEOs. (-) A more complex (and expensive) GNSS Avionic Receiver is needed.

SBAS / EGNOS Ionospheric Augmentation

- The ionospheric coverage of EGNOS extends over Europe, northern Africa and the Atlantic Ocean.
- The rectangular boundary delimits the EGNOS integrity service region.
- Full disk shows the grid points with higher data availability on daily basis where the EGNOS service is more stable and reliable.



Effect of Ionosphere on GNSS Systems Performances (1)

Telespazio will design the IPS component to monitor and predict GNSS systems performance figures (accuracy, integrity, availability and continuity)

- "Nowcast analysis":
  - Compute receiver absolute positon based on the on measurements acquired by the reference station GNSS receiver
  - Compute receiver position error and related statistics based on the knowledge of accurate antenna position
  - Derive statistics on non-ionospheric error sources locally affecting the RS to fed predictive models to be used for forecast analysis.
- "Forecast analysis":
  - Use of TEC and ionospheric scintillation predictive models available in IPS
  - Usage of predictive models of non-ionospheric error sources generated during the "Nowcast Analysis".
  - Receiver position error and integrity forecast, calculus of related statistics based on the above models. Forecast horizon presumably lower than 1h.
  - Retrovalidation functions to assess forecasting quality.

Effect of Ionosphere on GNSS Systems Performances (2)

GNSS Raw Data (observables, navigation data, SBAS messages)

ABAS/SBAS Avionics GNSS Processor

Position, Position Error and Time

Position and integrity nowcasting

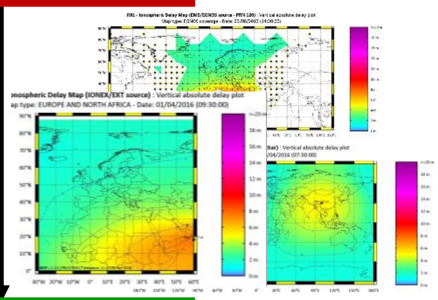
Performance Analysis

Performance Reports (ABAS/SBAS)

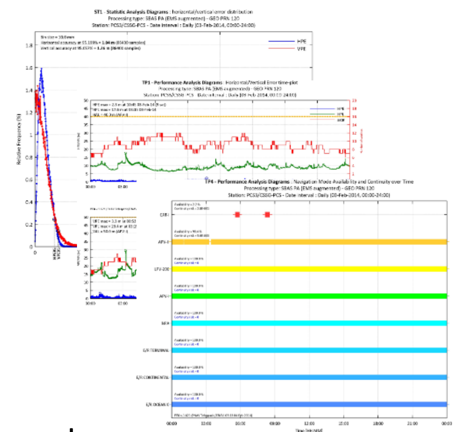
URE samples

Forecast Models for Non-Ionospheric Errors

Augmentation ionospheric models (Klobuchar, NeQuick, SBAS-TS, …)



Non-Iono errors forecast models (clocks, tropo, ephemeris, etc.)



IPS TEC and Scintillation Forecast Products

Iono Augmentation Models vs Forecast Products (Error Maps)

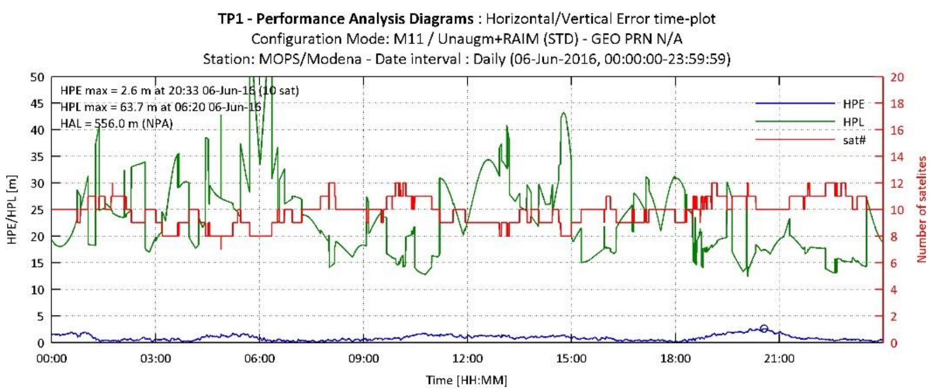
Iono error short-term forecast models

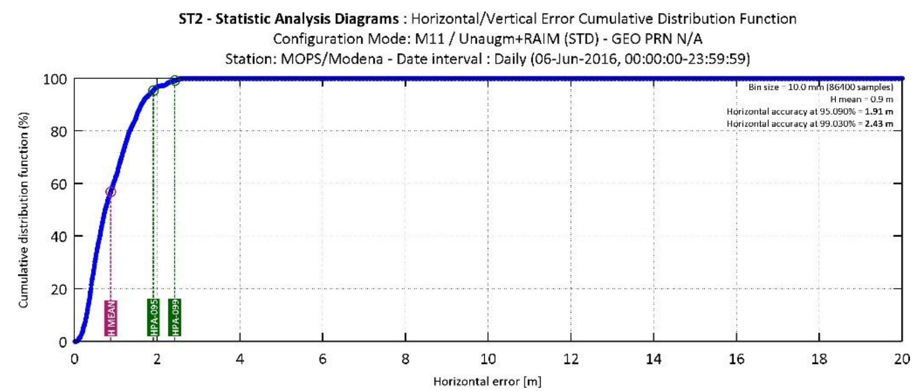
Position and Integrity Error Forecast

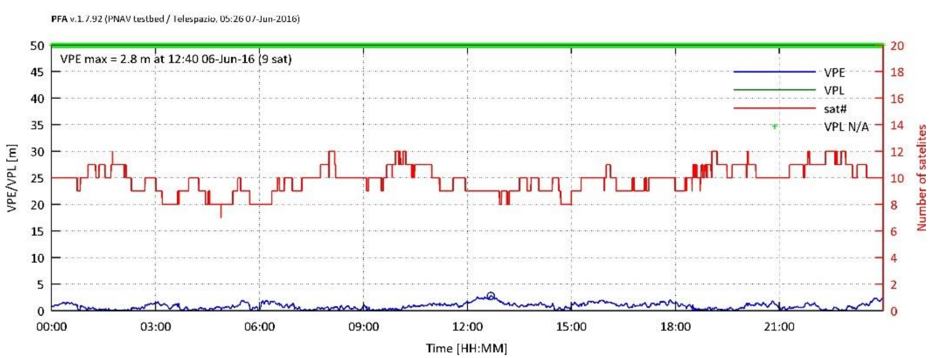
Position and integrity prediction (short-term and very short term forecast)

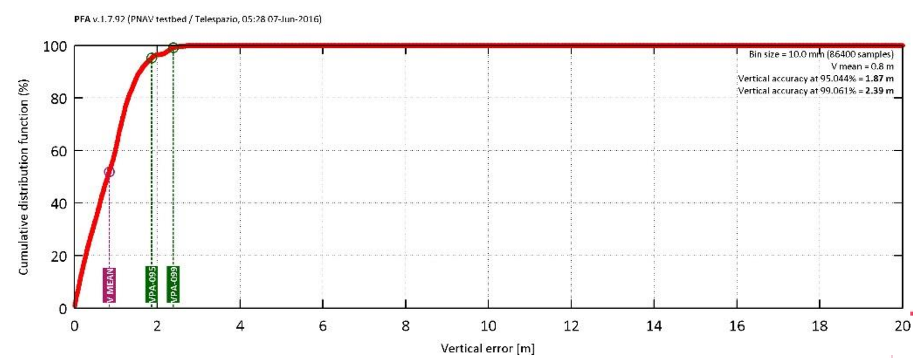
ABAS Performances Forecasting

- Error and Integrity analysis for the relevant reference stations **(GPS L1 + RAIM mode)**;
- Only Horizontal Integrity is available (RAIM allows only En-Route or TMA operations, no approach and landing !)
- RAIM gives higher Horizontal Protection Levels (from 15m to 50m and above)
- More degraded accuracy than SBAS solution (95% H/V accuracies around 2m)



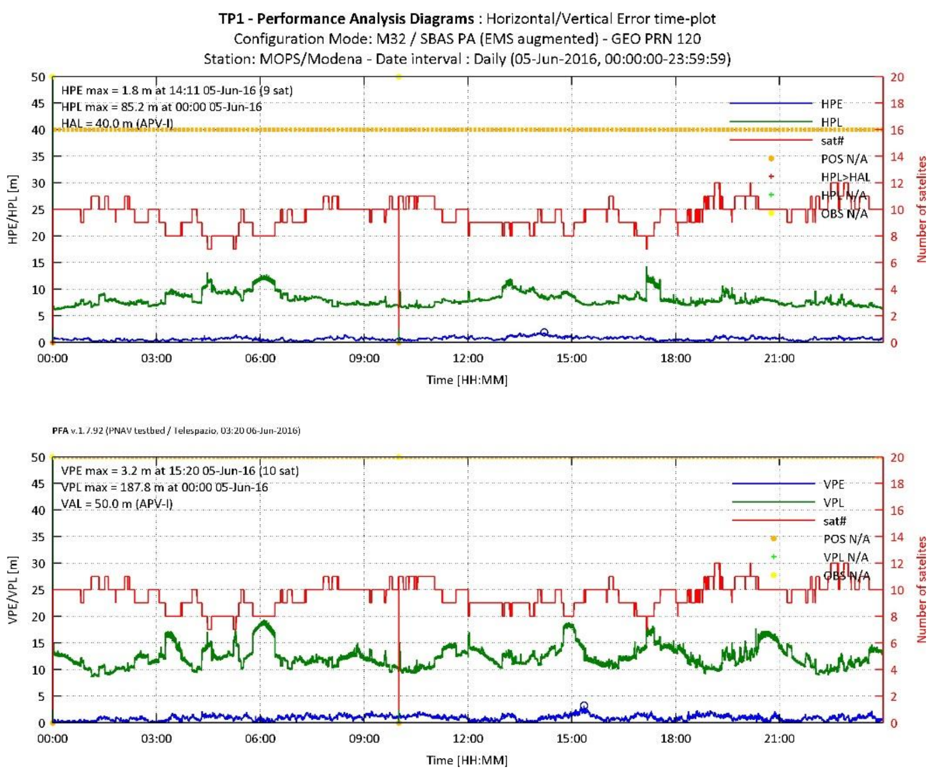


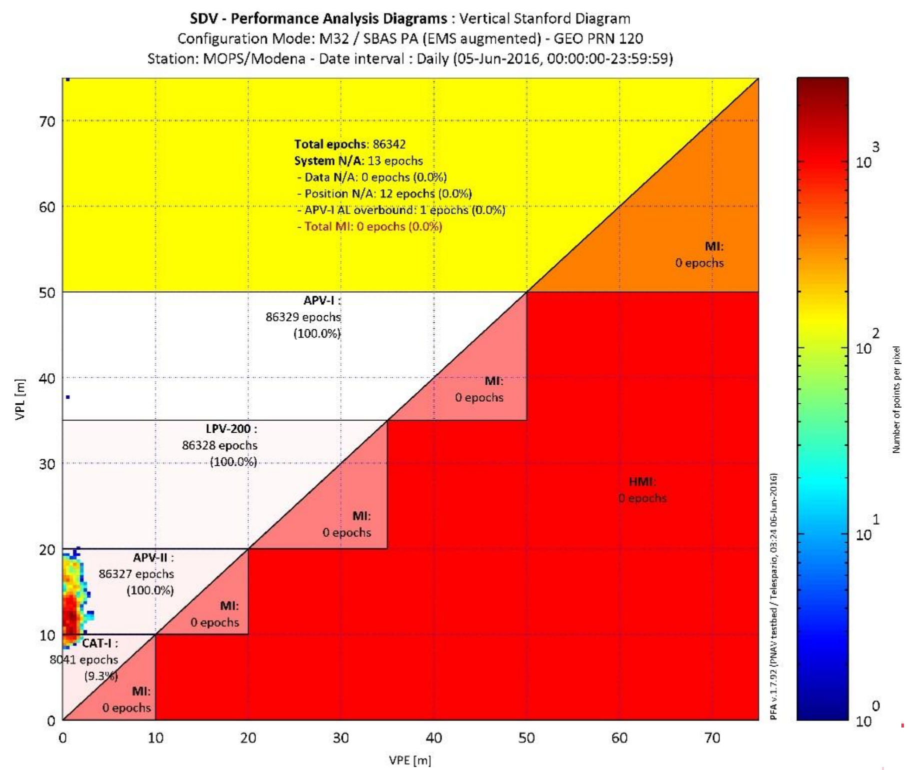




SBAS Performances Forecasting

- Error and Integrity analysis for relevant reference stations **(GPS L1 + SBAS mode)**;
- Both Horizontal and Vertical Integrity are available (From En-Route down to LPV-200 minima precision approaches)
- Lower Protection Levels (HPL around)
- Better accuracy than ABAS solution (HPA95 around 1m, VPA95 around 1.5m)





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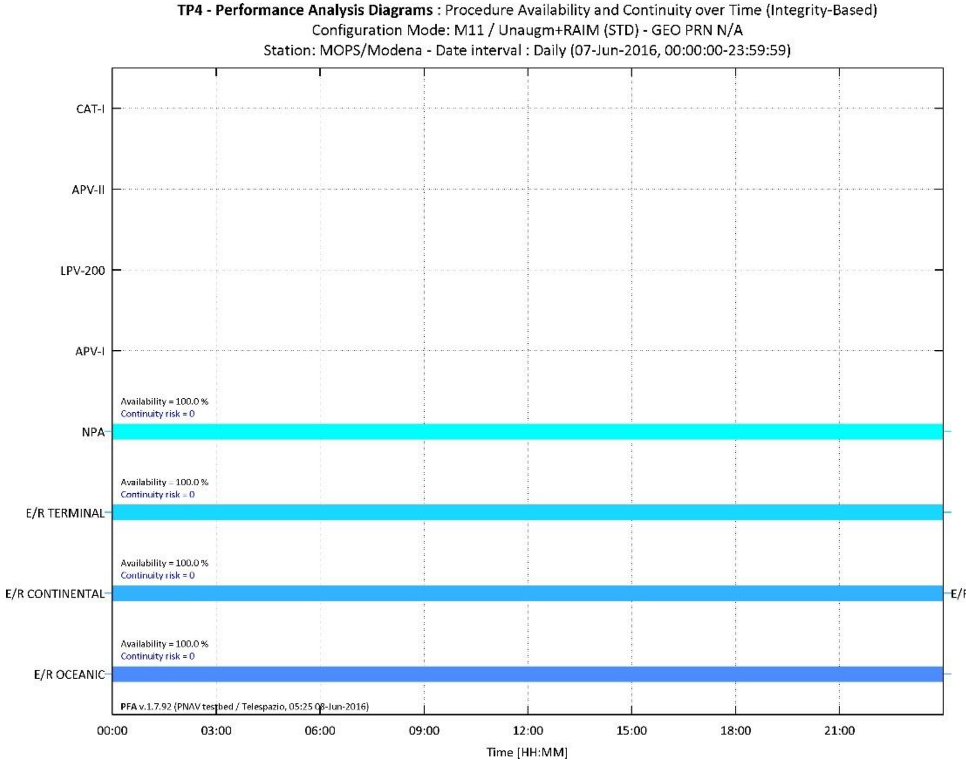
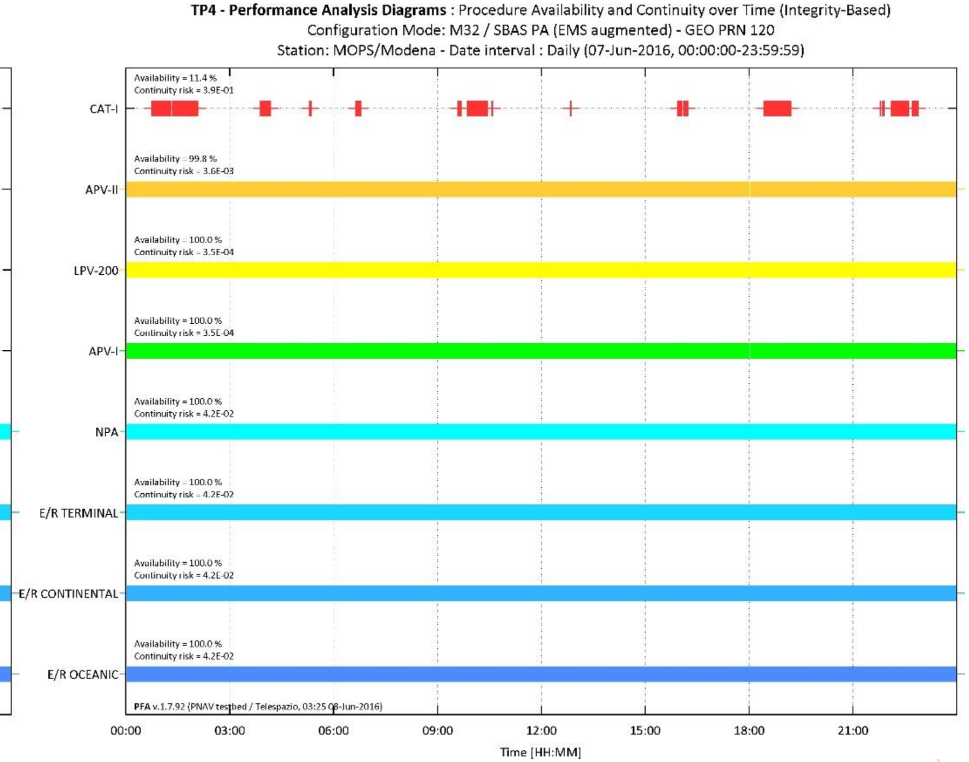
Prediction of Approach Procedure Availability

- Forecast analysis will extend to other specific performance figures defined to assess the quality of the GNSS (precision) navigation services over a defined time interval: Availability and Continuity.
- Such function will involve En-Route and Approach operations.



ABAS



SBAS

THANK **YOU** FOR YOUR ATTENTION

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