# GNSS PERFORMANCE ASSESSMENT AND DATA RECORDING GUIDELINES IN AVIATION

BEYOND

Building EGNSS capacitY On EU & Neighbouring multimodal Domains

ICG#11 (Sochi)

8th of November 2016

European Global Navigation Satellite Systems Agency

HORIZON 2020

The project leading to this application has received funding from the European GNSS Agency under the European Union's Horizon 2020 research and innovation programme under grant agreement N°641607

# H2020 Project


**Horizon 2020** is the **European Union financial instrument** implementing the Innovation Union, a Europe 2020 flagship initiative aimed at securing Europe's global competitiveness.

This program offers opportunities for the development of applications to use with EGNOS and Galileo which is crucial to meet the overall objectives of the Galileo programme and to foster the uptake of E-GNSS (European Global Navigational Satellite programs, including EGNOS and Galileo).

The BEYOND project is part of the European H2020 framework of projects funded by the European Commission (EC), managed by the European GNSS Agency (GSA) and led by the European Satellites Service Provider (ESSP), the EGNOS Service Provider.

# BEYOND Objectives

1. **Promoting the use of EGNSS** and growing the interest towards EGNSS outside EU and thus possibly stimulating investments in relation to EGNSS;

2. Prepare target countries towards and optimal adoption of EGNSS, and thus contributing to the **growing of know-how, capacity and knowledge in relation to EGNSS outside EU;**

3. Support **networking** and liaisons between **EU and non-EU players** and communities consequently creating the basis for cooperation and the **establishment of relationships possibly evolving into business opportunities.**


**GALILEO-4-2014:** *"EGNSS awareness raising, capacity building and/or promotion activities, inside or outside of the European Union"*

# Geographical scope & Partners

Project coordinated by ESSP (EGNOS Service Provider)
Started on March 2015, expected to finish on July 2017.

***Fifteen*** countries and strong of ***nineteen*** partners including:

- Industry,
- Academia,
- Air Navigation Service Providers,
- Research institutes,
- Civil Aviation and Transport Authorities.

# Telespazio

TELESPAZIO
a LEONARDO and THALES company

Telespazio, a joint venture between Leonardo (67%) and Thales (33%), is one of the world's leading players in satellite services.

The company, headquartered in Rome (Italy), employs approximately 2500 people. It relies on an international network of space centres and teleports and operates worldwide through many subsidiaries.

Telespazio is a multinational company with a consolidated presence in Europe and an important presence also in Brazil, Argentina and USA.

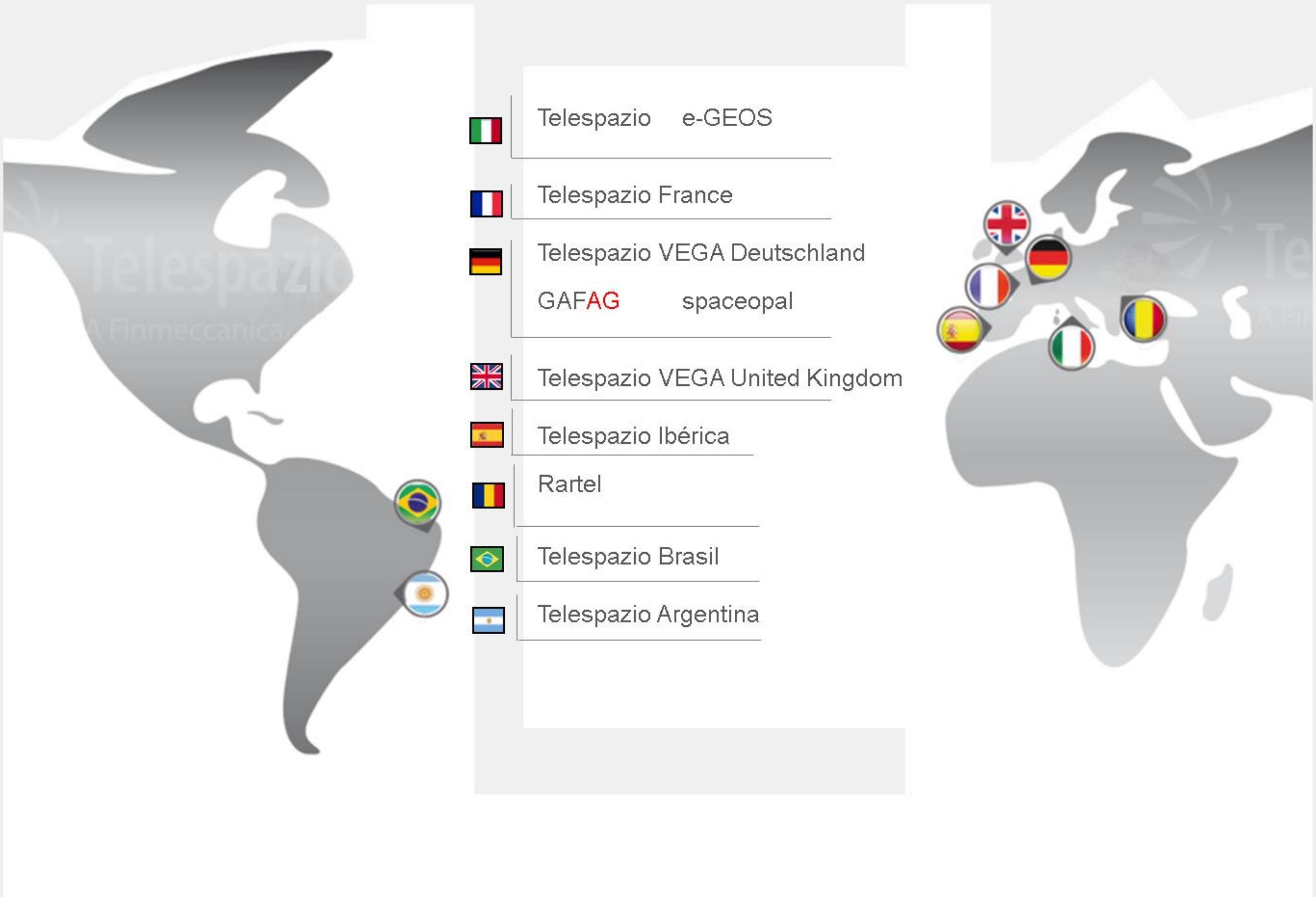
Telespazio has a consolidated experience in satellite navigation and in EU projects dealing with E-GNSS.

In the BEYOND Project Telespazio is the WP leader for:

- WP3000 'Capacity building in Mediterranean countries'
- sWP2400 'GNSS commercialization tour for East-EU'.

# Telespazio

## International Presence



# ENAV

enav

**ENAV is the Italian Air Navigation Service Provider, playing a key role in the evolution process of the Aviation sector at national and international level**

## International Membership

EUROCONTROL

canso
civil air navigation services organisation

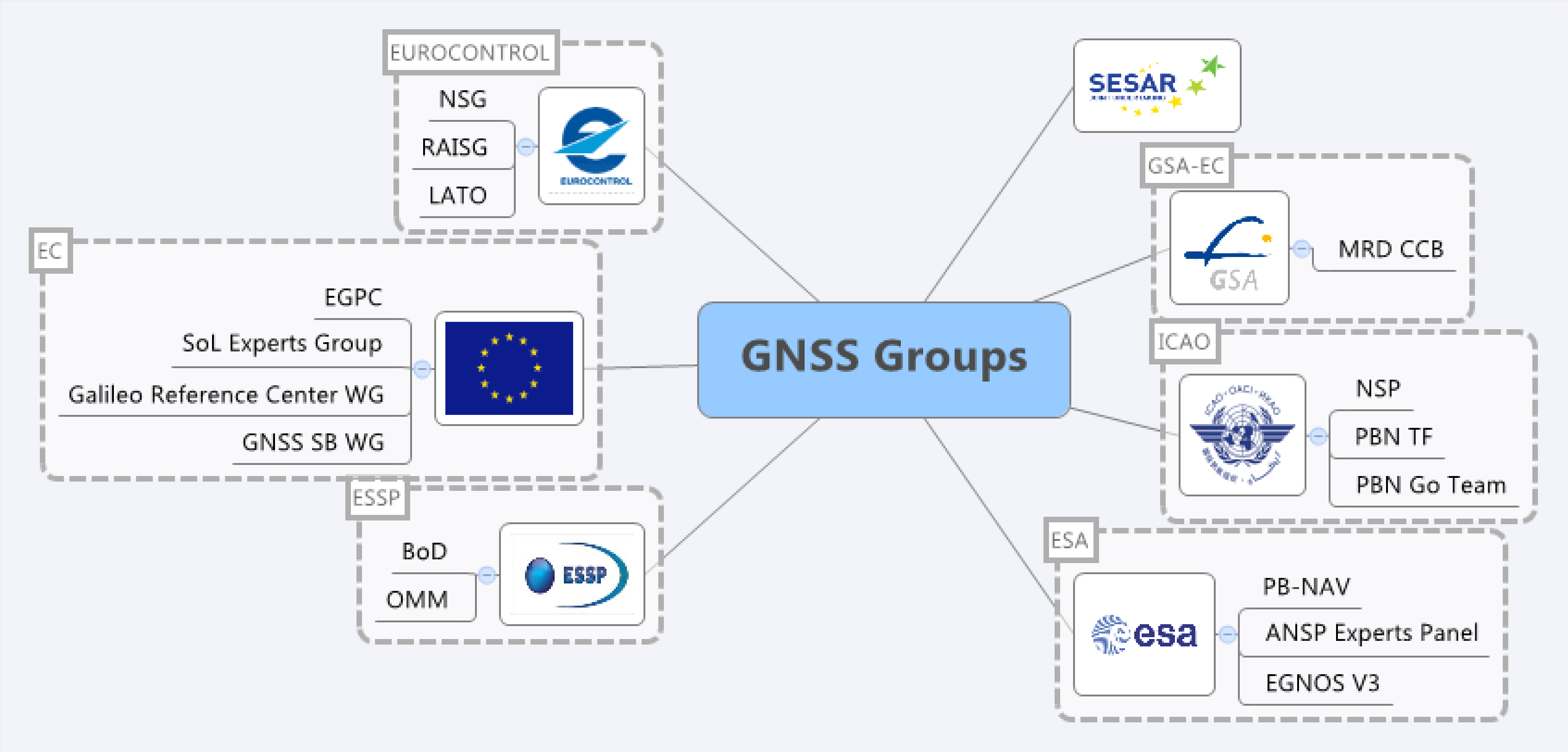
SESAR
JOINT UNDERTAKING

SESAR
DEPLOYMENT MANAGER

## Key operational numbers

| | |
|---|---|
| Flights handled in one year | **Roughly 1.8 mln** |
| Peak of flights managed in one day | **6.113** |
| Control Towers (TWRs) | **43** |
| Area Control Centers (ACCs) | **4** |
| Total sq km of airspace managed | **751.728** |
| Air/ground contacts per year | **31 mln** |
| ENAV Group Employees | **4.265** |
| Hours of training imparted | **Roughly 200.000** |

# ENAV role in GNSS



# PBN concept

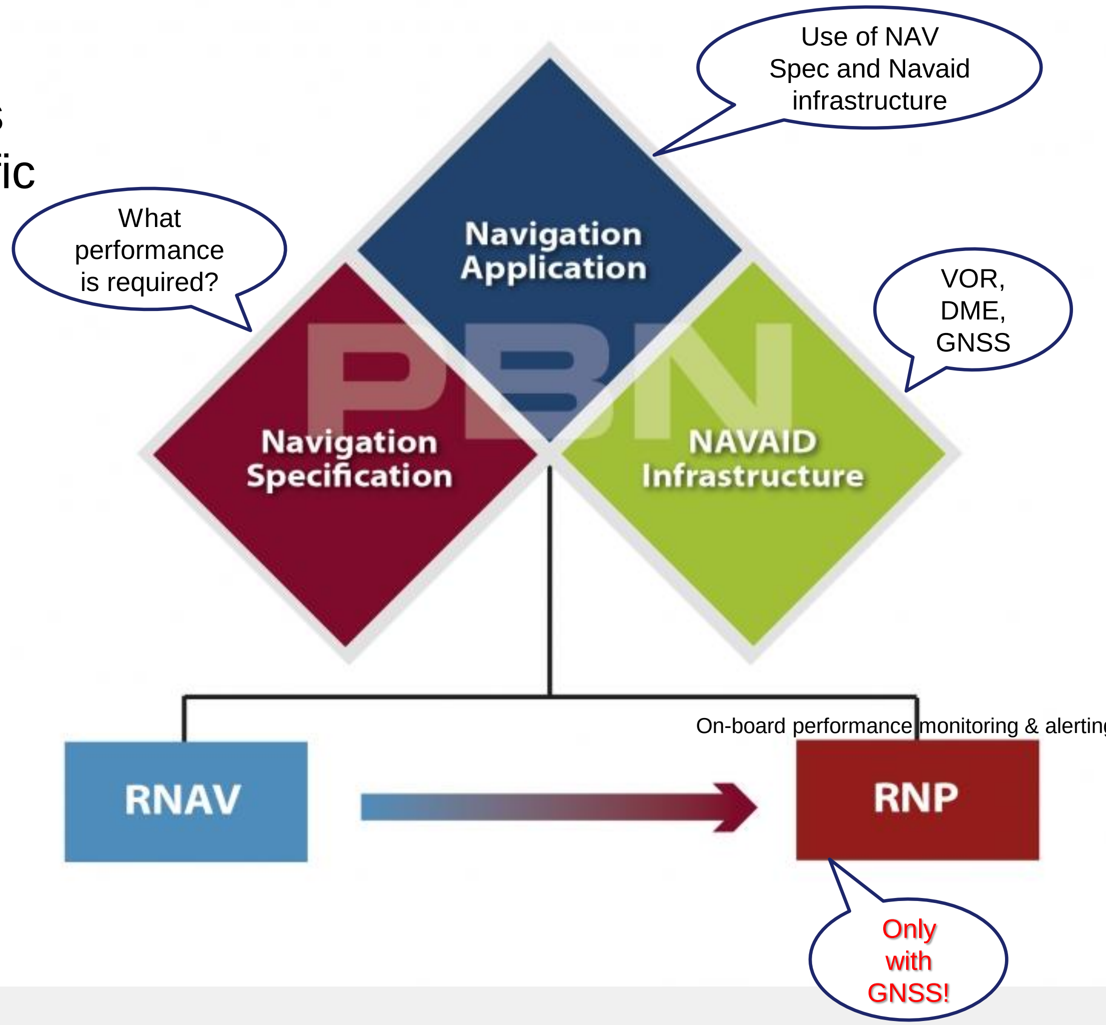
Globally applicable

Navigation based on specified system performance requirements for aircraft operating on an air traffic route, instrument approach procedure, or in a designated airspace.

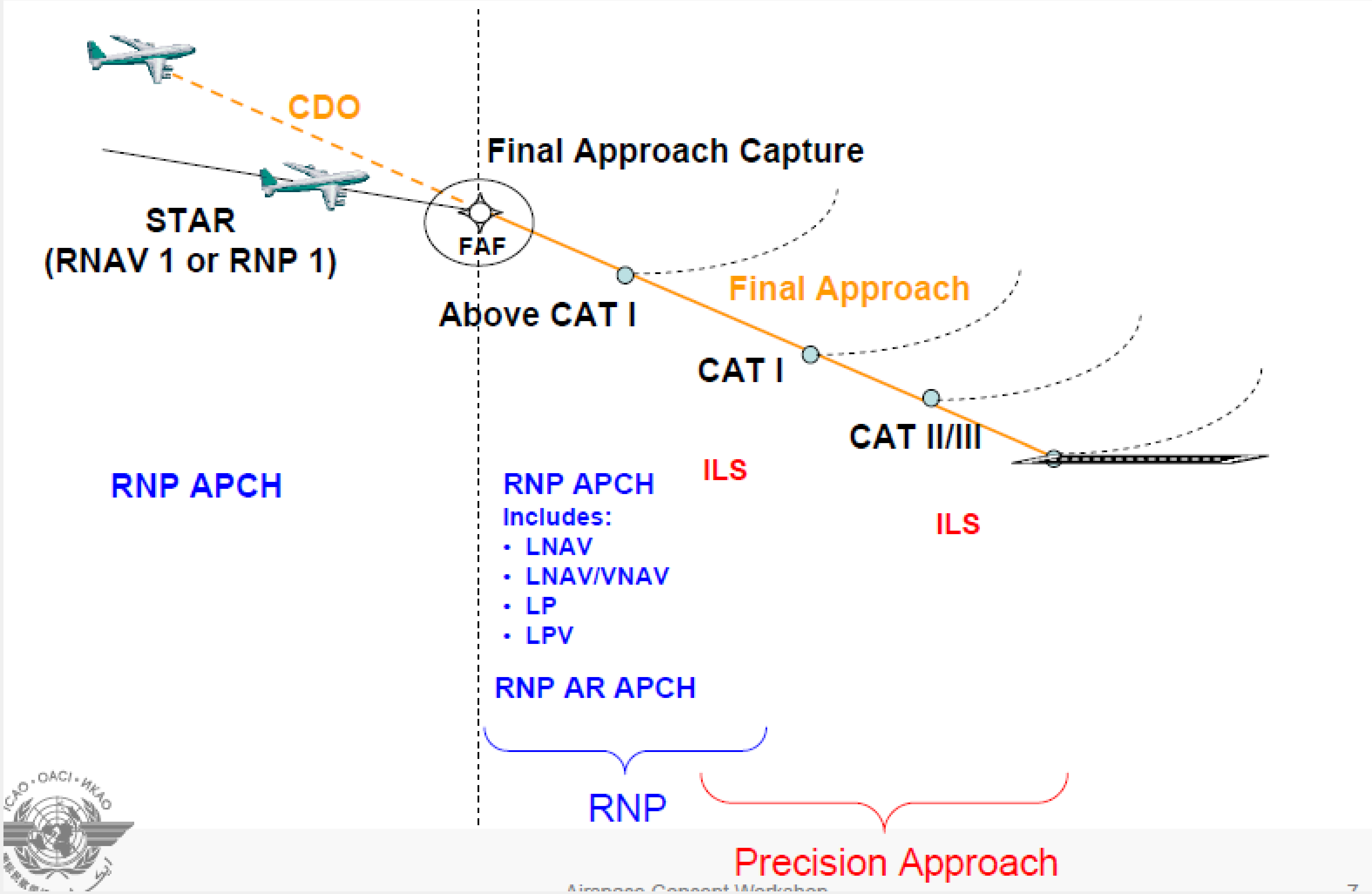
Benefits:

- Flight efficiency
- Avoid proliferation of stds
- Closer routes
- VOR/NDB decomissioning
- GNSS for low traffic volumes airspaces

“Total system approach”



# PBN applications



# Problem statement

- GNSS is a key enabler for PBN
- 12th ICAO Air Navigation Conference recommended that for future use of multiple GNSS constellation, States publish information specifying the GNSS elements (GPS, GLONASS, Beidou, Galileo) that are approved for use in their airspace
- "…State shall ensure that the services are in accordance with ICAO standards"

# State concerns

- *Why* GNSS Monitoring?
- *What* performance parameters need to be monitored for GPS and for the others constellations? and why?
- *How* to measure these parameters? Which density of stations is needed? What computation methodology? Which tools? How often performance reports are needed?
- *Who* should measure the parameters? States/NSAs, ANSPs, the core constellations service providers? International/regional organization?
- *What* to do if degradations/anomalies are measured?

# ICAO NSP Activities

- At ICAO NSP#14 (November 2013) a working paper presented by Italy identified the need for further guidance on GNSS monitoring, including details on the objectives, acceptable methodology, policy for the retention of data, reporting and notification process in case of anomaly.

- The GNSS Monitoring Drafting Group prepared guidance material on GNSS core constellation performance assessment and legal recording.
  - Annex 10 proposal of amendment
  - ICAO Doc 9849 GNSS Manual update

- Participants:

| | |
|---|---|
| USA | ICCAIA |
| UK | France |
| Eurocontrol | Germany |
| EC | Japan |
| Canada | Australia |
| Netherlands | Spain |
| Italy | Russian Federation |

# GNSS Monitoring Concept

**GNSS Monitoring**

- GNSS Performance assessment
- GNSS Data recording
- GNSS Operational status monitoring

# Definitions

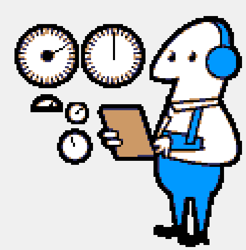
- **GNSS performance assessment:** a periodic off-line activity that may be performed by a State or delegated entity, aiming to verify that GNSS performance parameters conform to the relevant Annex 10 standards. This activity can be done for the core constellation, the augmentation system or a combination of both.
- **GNSS operational status monitoring:** an activity performed by a State or delegated entity, with the main objective of providing timely information to technical staff and ATC services on the operational status of GNSS services in relation to a defined operation in a particular airspace (and therefore to inform the user of any operating restrictions that may be required).
- **GNSS data recording:** an activity performed by a State or delegated entity, with the objective of having historical data of GNSS parameters which can be used to support post-incident/accident investigations.

# Performance assessment process

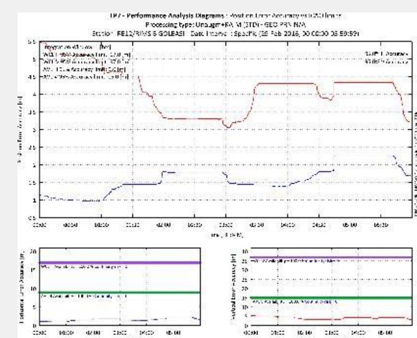
**Input**
- IGS
- RIMS
- Private networks

**Recording**
- Recording policies

**Processing**
- GPS+RAIM
- GPS SPS
- GPS core constellation

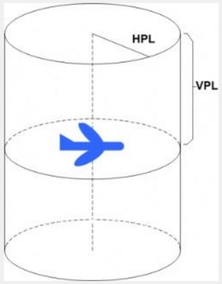


**Reporting**
- Frequency of reports
- Sharing



# Integrity monitoring

- Integrity is the most critical parameter, due to its link to safety. Applicable to total system (including RAIM) and not to the core constellation itself.

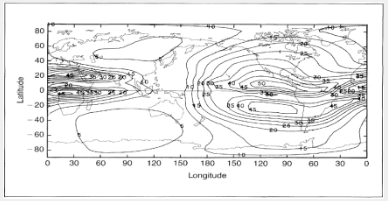



- Different approaches for integrity are taken:
  - For **ABAS**, integrity monitoring is done at airborne level with RAIM. Receivers that are certified in accordance with relevant international standards (e.g. MOPS, TSO series) have been designed to meet the integrity requirement defined in Table 3.7.2.4-1 of Annex 10 assuming GPS is compliant with key parameters defined in GPS SARPs Annex 10 and GPS SPS PS.
  - For **SBAS**, integrity monitoring is done at ground segment level and the verification and assurance is given by the SBAS service provider.
  - For **GBAS** a similar approach to SBAS is taken with responsibilities to local operators .

→ For ABAS, it is suggested that States do not have to implement monitoring capabilities for "integrity" since integrity is provided in real time by RAIM.

# Observations

- Availability, accuracy and continuity may have a different meanings (e.g. the meaning of continuity parameter for SIS performance requirements is different from the one defined for the SPS).


- Development of criteria (taking in account satellite geometry, tropospheric/ionospheric delay) for the determination of density of stations that can produce representative performance reports and can be used for data recording.

# GNSS KPIs

| Performance Parameter | Definition | GPS Targets |
|---|---|---|
| **Positioning accuracy** | 95 percentile of the position error measured, intended as difference between the estimated position by the receiver and the reference position, calculated over any interval of 24hrs, for any point considered within the service volume. | Global average 95% of the time<br>HPE: 9m<br>VPE: 15m<br><br>Worst site 95% of the time<br>HPE: 17m<br>VPE: 37m |
| **Range domain accuracy Instantaneous SIS URE** | Difference between the pseudo range measured at a given location and the expected pseudo range as derived from the NAV message. | Range error of any satellite: 30m (with reliability specified in Annex 10 §3.7.3.1.3) |
| **Service availability** | Percentage of time over any 24hrs interval that the predicted 95 per cent position accuracy is less than a specified value within the service volume. | ≥99% horizontal, average location (17m 95% threshold)<br>≥99% vertical, average location (37m 95% threshold)<br>≥90% horizontal, worst-case location (17m 95% threshold)<br>≥90% vertical, worst-case location (37m 95% threshold) |
| **Probability of major service failure** | Probability that over a specific time interval, a healthy satellite's ranging signal error (excluding atmospheric and receiver errors) exceeds the broadcast range error limit by a given factor. | $p(URE>4.42URA) \leq p_{MSF}$<br><br>with<br><br>$p_{MSF} = 10^{-5}$/hr |
| **Continuity** | Probability that healthy SIS per satellite will continue to be healthy without unscheduled interruptions over a specified time interval. | $> 2\times10^{-4}$ /hr |
| **Probability of simultaneous major failures of 2 or more satellites** | Probability of simultaneous failure (under the same conditions defined for major service failure) of 2 or more satellites. | $p_{MMSF} = 10^{-9}$/hr |

# Implementation aspects

- Error components assigned to Space and Control Segments (error budget components assigned to the User Segment such as the atmosphere, multipath, and receiver noise)

- For some parameters the target "average location" is used for stations disseminated globally so sometimes could be more useful to refer to the worst case target only, depending on the geographical extension of the area considered and number of stations used for the performance computation

- Selection and siting of monitoring receivers

# Approach proposed

**Today**

- Use public reports provided by GNSS service providers or by other Organizations;
- Establish formal agreement with neighbouring State that is publishing performance reports and could cover the national interested area;
- Implement its own solutions in line with the guidelines provided in this document.

**2020+**

- Core constellation service providers to provide global periodic performance reports towards relevant SPS parameters identified in Annex 10 vol.I.
- Reports can be used by States in combination or substitution of what already implemented.

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# Considerations

## WHY?

- State Safety Oversight Function (not obligation)
- Ensure performances vs SARPS

## WHAT?

- Positioning Accuracy, URE, Availability, Continuity, Major Service Failure, etc.

## HOW?

- Network of stations (IGS, EDAS, etc)
- Off line activity

## WHO?

- State, International Organizations
- Core constellation service provider

## IF?

- Share reports
- Escalate to International Organization

# ICAO KPI Validation Test-Bed (1)

Telespazio is working on the development of a software test-bed for the calculation of the GNSS Core-Constellation KPIs defined by ICAO with the aim to:

- provide support to the validation of these KPIs and to the demonstration of their implementation feasibility;
- support the clarification or refinement of still imprecise concepts, like:
  - the Instantaneous-URE computation methods;
  - user and atmospheric errors estimation algorithms.
- The basis of this methodology is the determination of the satellites SIS URE:
  - Signal-In-Space User Range Errors are defined as any errors related to the satellite transmission system, mainly satellite position and clock errors.
  - A good understanding and characterization of the signal in space errors are essential for the core-constellation integrity, because the SIS errors are a metric to determine satellite outages or failures.
  - The statistics of the SIS errors are an important factor to monitor the system performance in terms of integrity.

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# ICAO KPI Validation Test-Bed (2)

- KPI-1. Range domain accuracy (Instantaneous URE). Two methods are proposed:
  - "Indirect" URE calculation: exclude atmospheric and user receiver error components.
  - "Direct" URE calculation: subtracting the broadcast ephemeris from a precise real-time orbit and clock solution.
- KPI-2. Probability of major service failure (MSF). It is defined as the probability that over a specific time interval a healthy satellite's URE exceeds the broadcast range error (URA) upper limit by a given factor (=4.42 for the GPS).
- KPI-3. Probability of simultaneous major service failure of 2 or more satellites. It is defined as the probability of simultaneous failure of 2 or more satellites.

RNG

- KPI-4. Positioning accuracy. It is a function of time t, computed as the 95$^{th}$ percentile of the accumulated position error samples from t-24h to t.
- KPI-5.Service Availability. The percentage of time over any 24h interval that the 95% position accuracy is less than a specified value within the service volume.
- KPI-6. Service Continuity. It is the probability that healthy SIS per satellite will continue to be healthy without unscheduled interruptions over a specified time interval.

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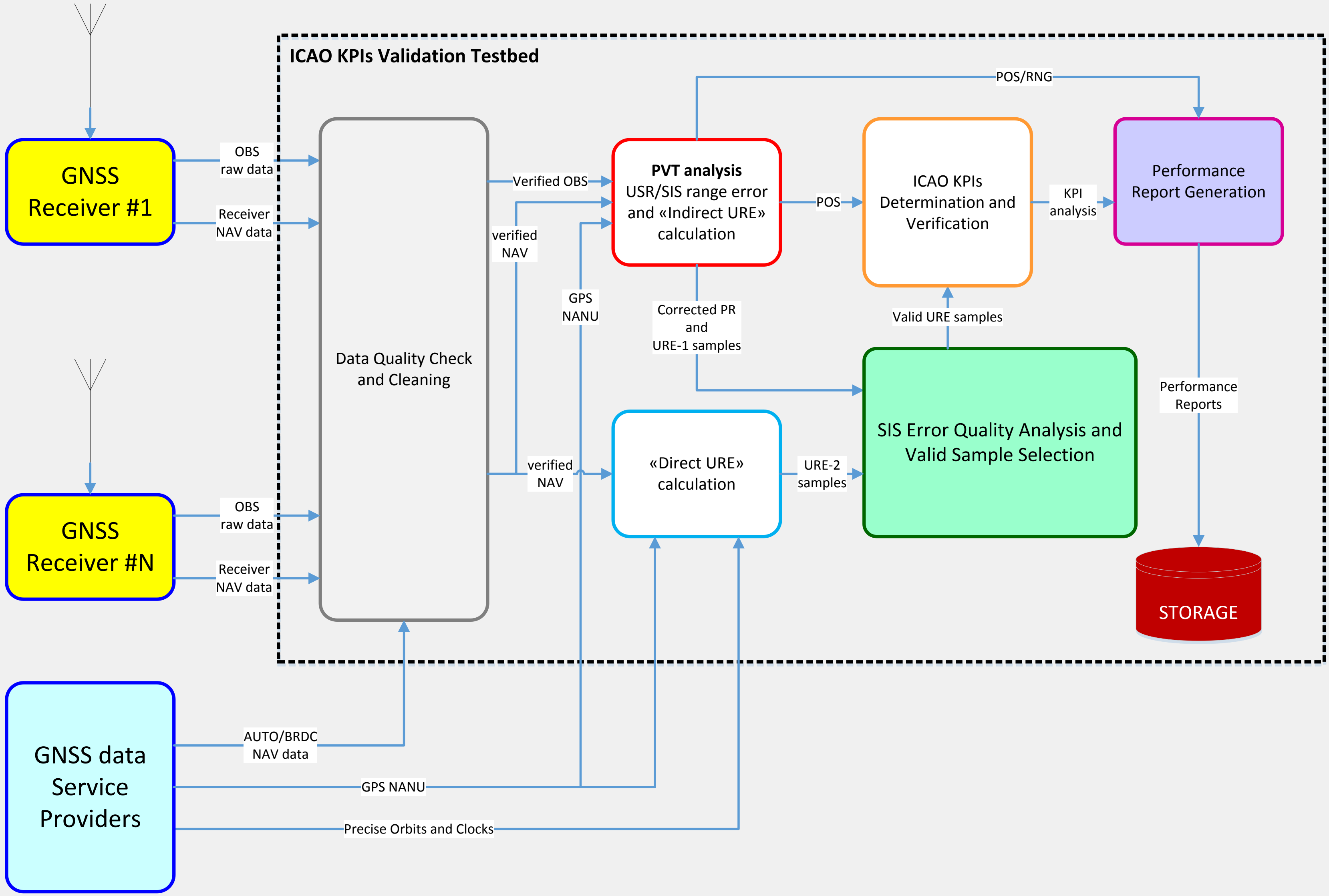
# ICAO KPI Validation Test-Bed (3)



# Direct and Indirect URE Estimation

- Indirect URE estimation Method
  - This method consists of removing from the total pseudo-range error all the non-SIS errors: ionosphere, troposphere, multipath and receiver clock errors:
    - dual-frequency ionosphere-free combination;
    - accurate troposphere modeling, smoothing multipath residuals;
    - estimating the receiver clock bias through the PVT computation process;
  - URE estimation accuracy depends on algorithms implementation and tuning.
  - Suitable for real-time (RT) or near real-time (NRT) implementation as both SIS URE and position accuracy can easily be obtained by receiver PVT calculation.
  - The URE determined by adopting this method is often referred to as Instantaneous URE.
- Direct URE Estimation Method
  - The SIS errors is approximated with satellite position errors and clock errors; SIS errors are built by summing up satellite position and clock errors.
  - The satellite position and clock errors are calculated by differencing the true ephemeris with the broadcast ephemerides.
  - “True” ephemerides and clocks are obtained from specialized data providers, like the International GNSS Service (IGS) network, the National Geospatial Intelligence Agency (NGA) network or the Center for Orbit Determination in Europe (CODE).

# Comparison between methods

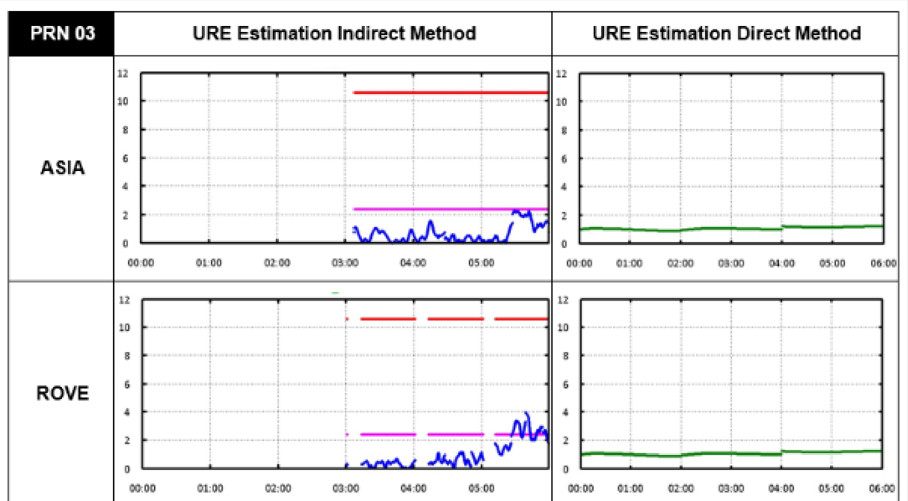
| | Advantages | Disadvantages |
|---|---|---|
| **Indirect Method** | 1. Allows Real-Time or Near-Real-Time URE monitoring implementation.<br>2. Allows continuous URE generation (when required observations are available).<br>3. 1Hz processing supports detection of fast anomalies<br>4. Both URE and position accuracy analyses are available from a complete PVT calculation (all the 6 KPIs can be determined). | 1. In some cases URE estimation may be not accurate and noisy, leading to undesired false alarm generation. Post-filtering model-based techniques to be tested; error compensation methodologies need further investigation and improvement.<br>2. Instantaneous URE availability reduced due to filtering transient<br>3. PVT calculation on real observation data requires a higher computational burden and software complexity. |
| **Direct Method** | 1. Highly reliable UREs as obtained from independent and validated computation process.<br>2. High accuracy: precise ephemerides and clocks are an order of magnitude or more accurate than the broadcast ephemerides/clocks.<br>3. URE computation is easy and fast as obtained directly from the sp3 files (no observation files needed, no error estimation and compensation, no need to implement PVT calculation). | 1. Smooth solution from interpolating models.<br>2. Inter-sample monitoring not available: one sample every 5 – 15 min. Fast anomalies (shorter than 5 min) could get lost.<br>3. RT or NRT capabilities based on orbit and clocks forecast due to latency in sp3 file availability.<br>4. Only ranging/URE analysis is currently available (only KPI#1, KPI #2 and KPI #3 are determined). Extension to position domain using satellite geometry-based analysis to be assessed. |

# Validating Direct and Indirect Methods

- A good validation method is comparing direct and indirect URE estimation as solutions obtained by independent processes and generated by using different input data.
- First tests revealed discrepancies between direct and indirect URE estimation methods, showing gaps of ±2m between them. An example of this analysis is shown below for GPS satellite PRN-03.
- Both methods are affected by errors and such discrepancies can be explained.
- Direct UREs frequently exhibit oscillations due to the noise floor level increased by the filtering techniques adopted to cancel ionospheric delay and to the error residuals of troposphere, multipath, receiver clock and thermal noise compensation models.

This validation example is based on 6h data analysis for two selected reference stations located in northern Italy: ROVE (Rovereto) and ASIA (Observatory of Asiago).

- ➢ short relative distance (around 35 km) to reduce effects due to the dependence on user position
- ➢ 1Hz dual frequency observations.

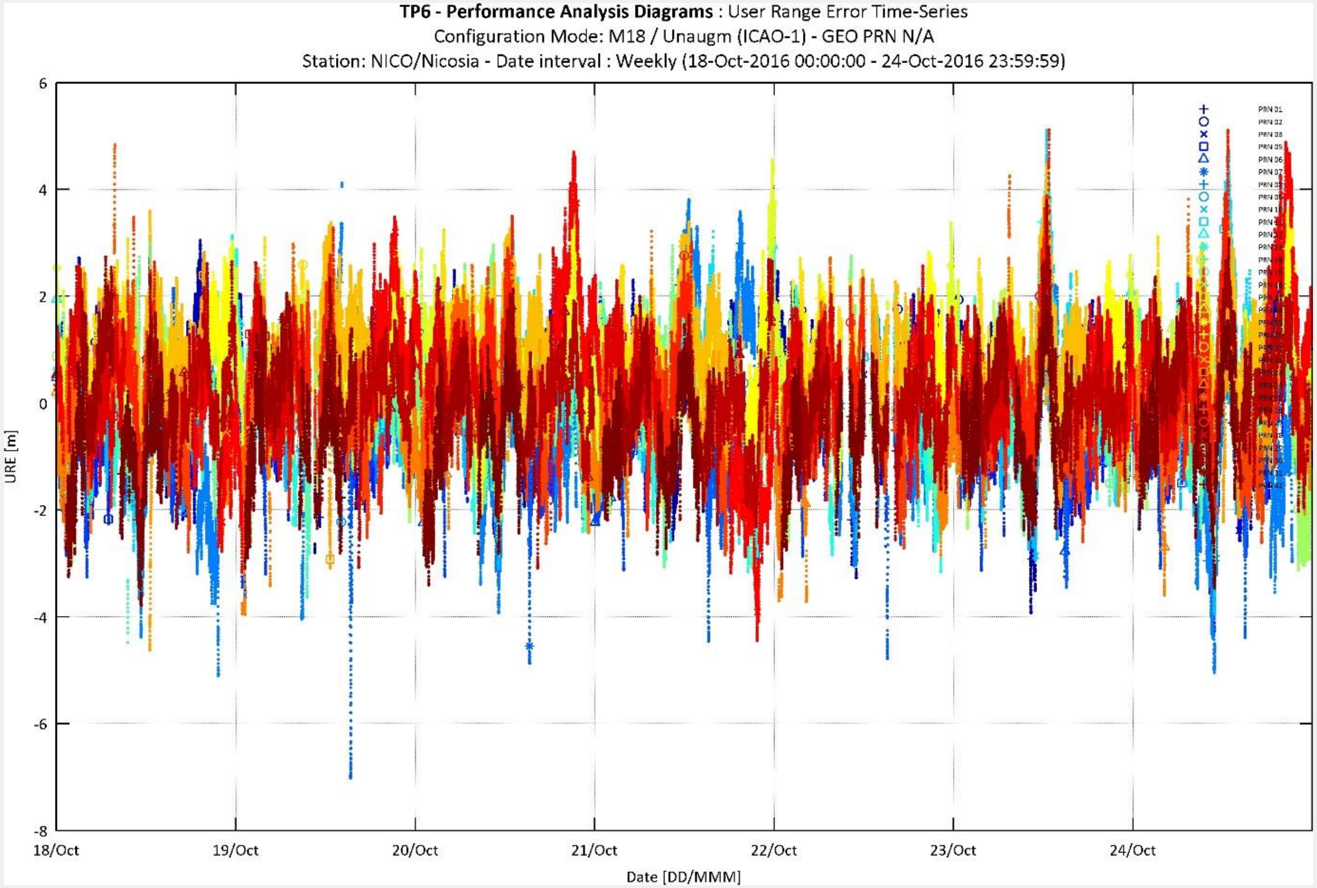



Similarly to PRN01, the indirect URE curves ranges from 0 to 2m. The direct URE curve have a very stable trend around 1m.

# SIS URE time-series - Failure Analysis

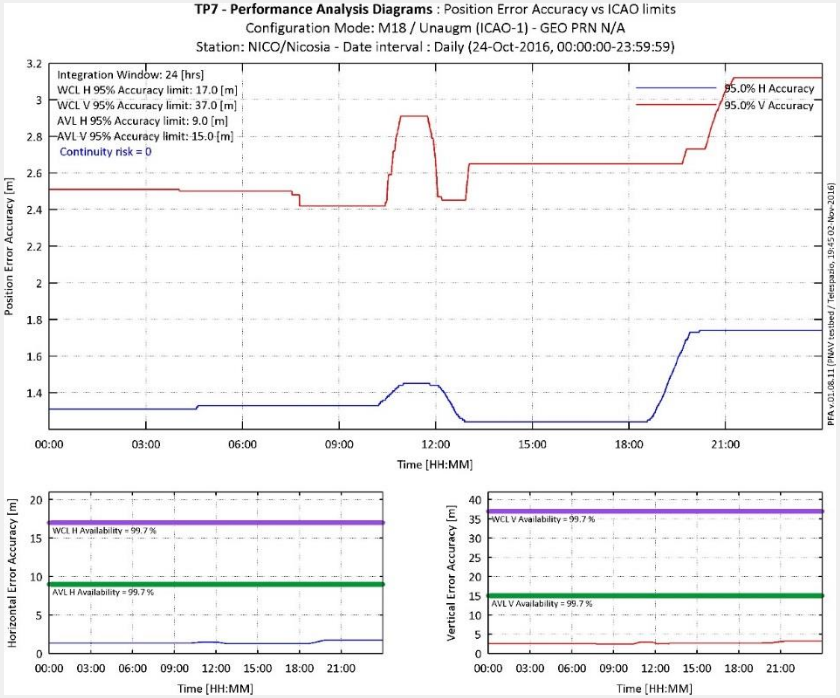
This diagram shows:

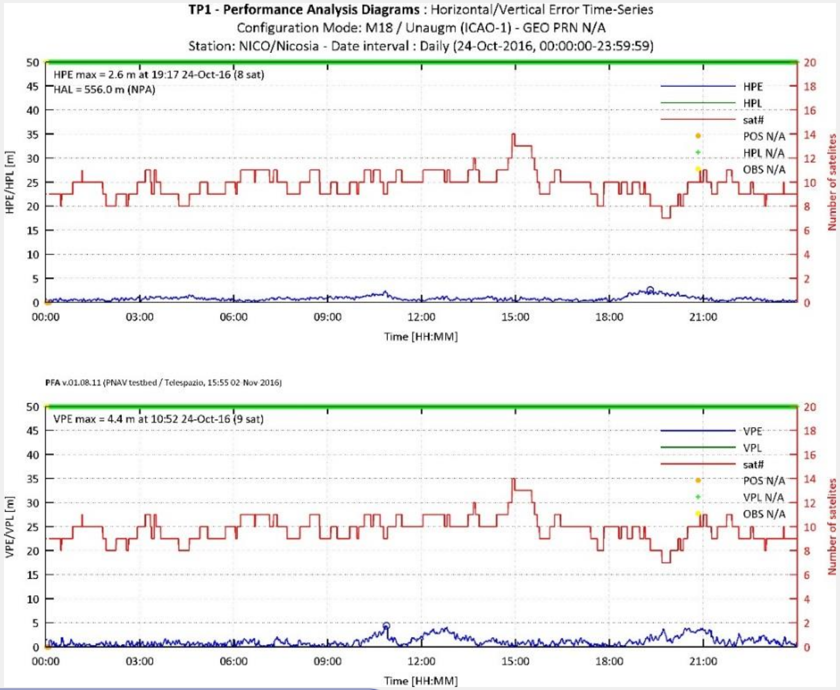
1. Indirect estimation of URE for each satellite in the interval of analysis;
2. Calculation of number of Major Service Failures (MSFs) and probability of occurrence in the interval of analysis
3. Calculation of number of simultaneous MSFs (SMSF) and probability of occurrence in the interval of analysis



# SIS Position-domain Analysis

1. 95% Horizontal and Vertical Accuracy time-series (95th percentile of H/V position error PDF on the last 24 hours).
2. System H/V Availability: computed checking the instantaneous accuracy against accuracy limits for both Worst-Case Location and Global-Average scenarios.
3. System Continuity: the probability that healthy SIS per satellite will continue to be healthy without unscheduled interruptions over a specified time interval.




Position error and integrity time-series :

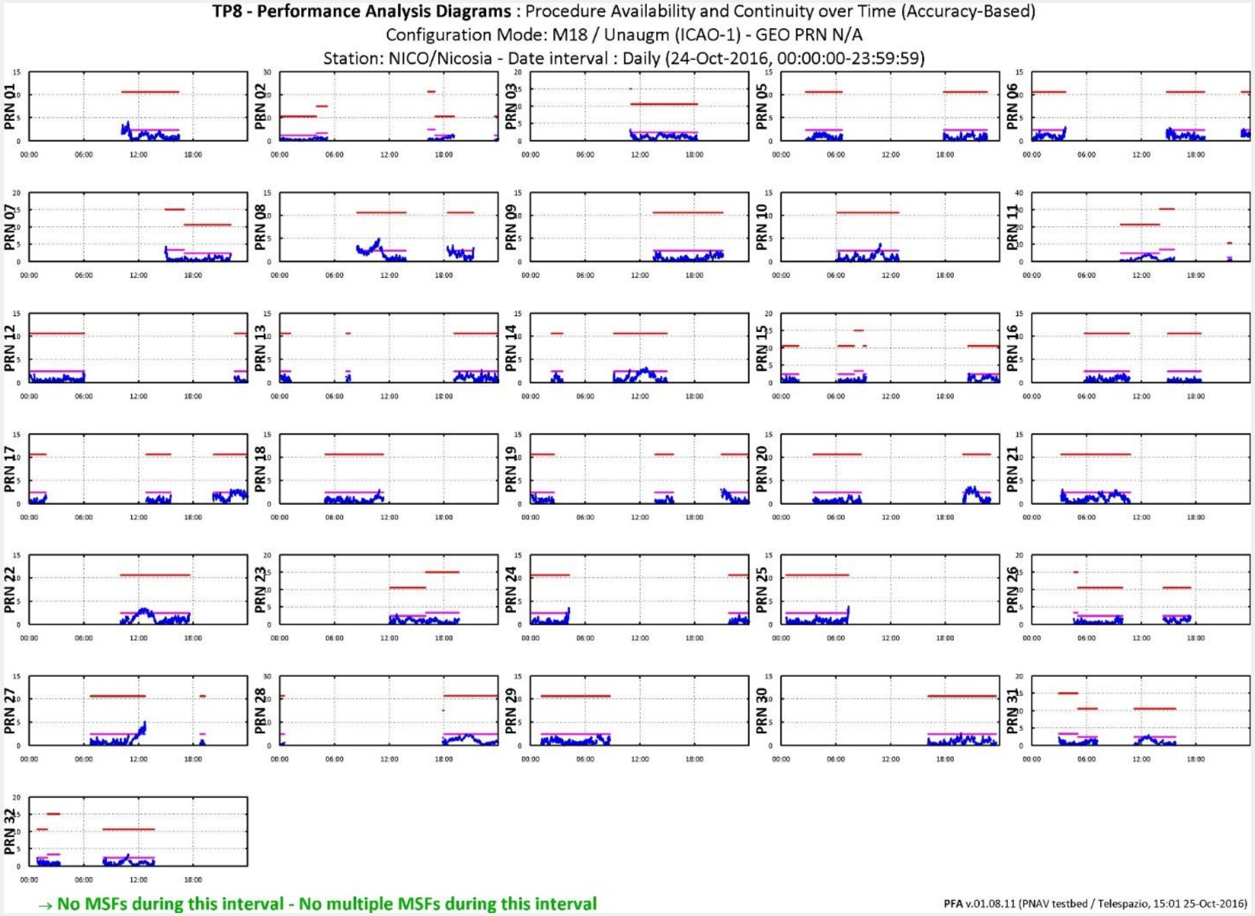
1. Horizontal / Vertical position error;
2. Horizontal / Vertical protection level (if applicable);
3. Horizontal / Vertical alarm limits (if applicable);
4. Number of satellites used in the PVT calculation;

In line with ICAO recommendations, the autonomous integrity monitoring function has been disabled in this analysis mode.

# Satellites URE (Indirect Method)

This report gives an overall view of the **indirect** URE and failure detection results showing the URE time-series against the alarm threshold:

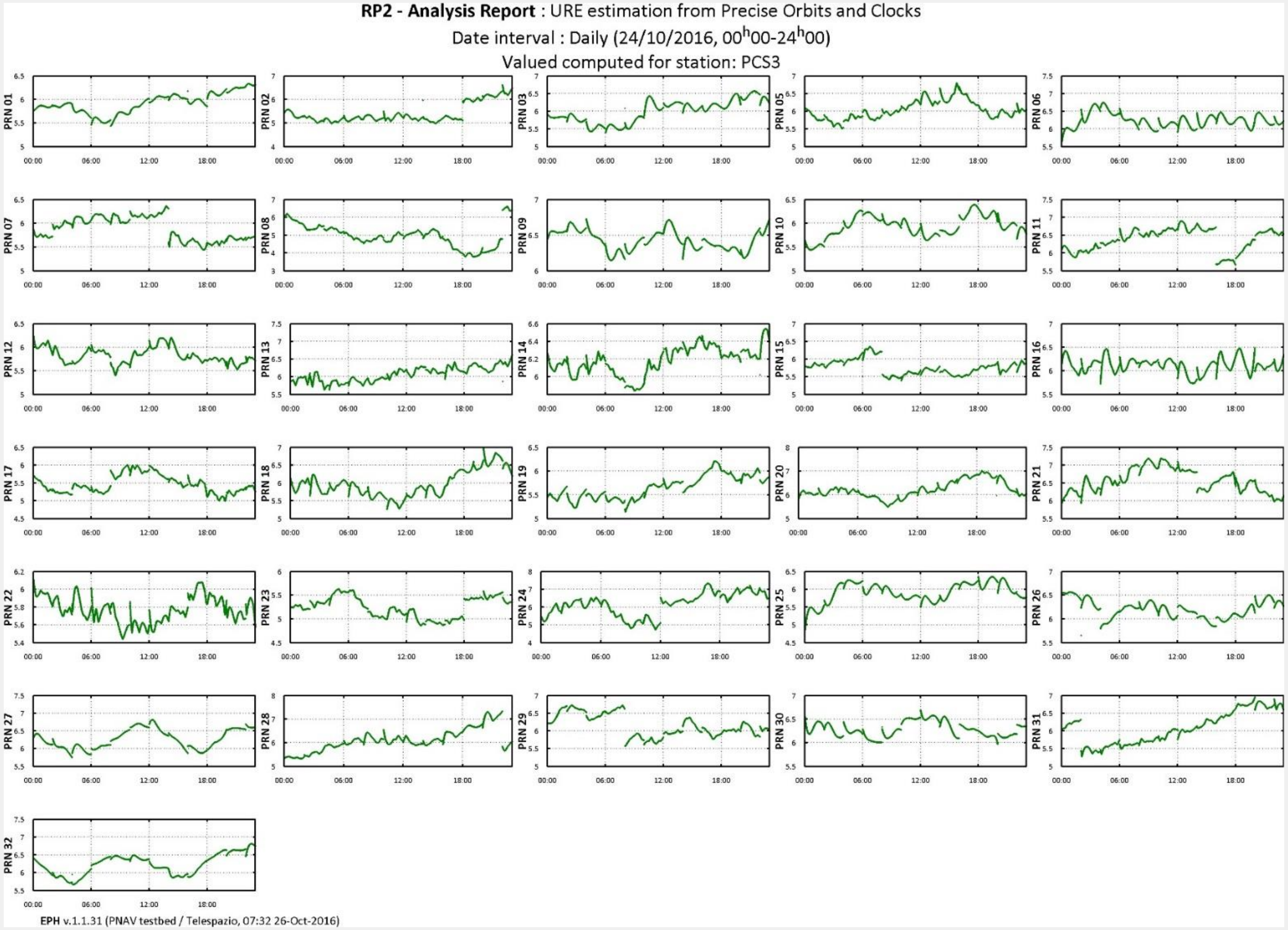
1. the blue plot is the URE;
2. Purple line is the URA upper bound. Most frequent URA values broadcast are:
    1. 0 (upper bound = 2.4m)
    2. 1 (upper bound = 3.4m);
3. Red line is the alarm threshold = 4.42 * URA upper bound.
   If URE gets above the alarm threshold, an MSF event is generated. URA values of 0 and 1 correspond to alarm thresholds of 10.608 and 15.028 m respectively.



# Satellites URE (Direct Method)

This report shows URE time-series for all the satellites derived from the analysis of precise orbit and ephemerides sp3 data.

This is the output of the URE **direct** estimation method.

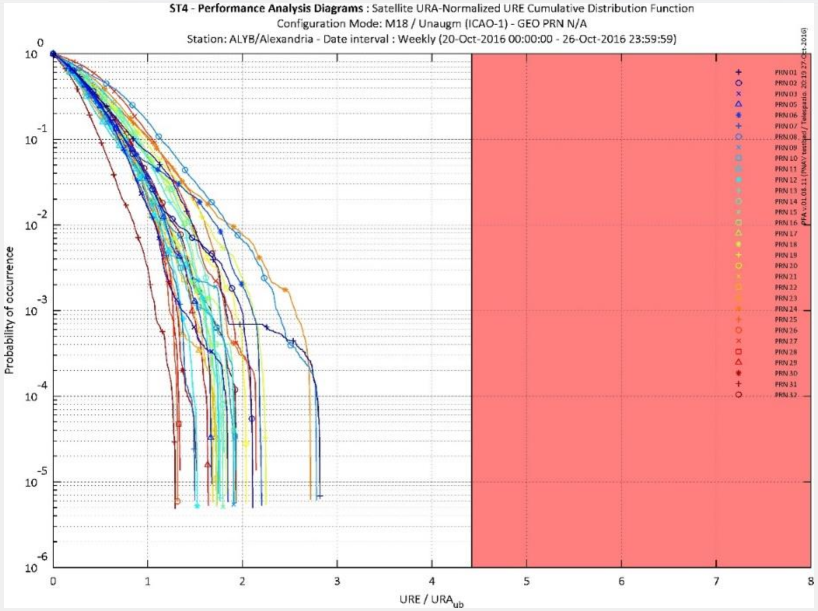


# Statistical Characterization of SIS URE

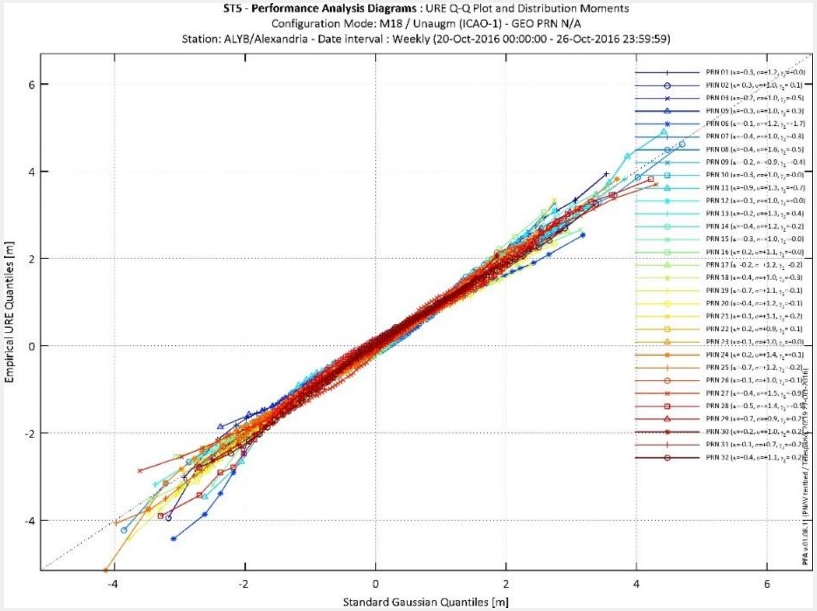
1. the absolute URE normalized to the URA upper bound, namely for the quantity:

$$URA_n = \frac{|\text{URE}|}{URA_{ub}}$$

2. Immediate knowledge of major service failure probability (point of intersection between the complementary CDF curve and the red region of satellite failure delimited by the abscissa value 4.42)




1. Q-Q plot: testing for the URE gaussianity or normality of its empirical distribution function.
2. Distribution moments:
   - Mean value $\mu_1$
   - Standard deviation $\sigma$
   - Kurtosis $\gamma_2 = \frac{\mu_4}{\sigma^4} - 3$



# Final Considerations (1)

- A Performance Monitoring Methodology has been presented to support the ICAO KPIs verification & validation and prove their implementation feasibility;
- The Methodology is built around the ICAO KPIs Validation Test-Bed (IKVT) developed by Telespazio for their calculation and the verification of the related requirements.
- The determination of precise satellite's URE has a crucial role in the determination of all the KPIs listed above. Two methods are available.
- Indirect method:
  - Embedded into the PVT calculation; its is not accurate and subject to local effects, filters transient and error models ➔ usage at site level as standalone solution is not recommended;
  - It may allow Real-Time or Near-Real-Time continuous URE monitoring and detection of fast anomalies when high frequency sampled data is available (e.g. 1Hz).
- Direct method:
  - It allows reliable and faster URE calculation for a set of "reference locations";
  - It doesn't allow detection of fast anomalies due to 5 - 15 minutes data sampling period;
  - Not clear how to extend its usage to the position-domain analysis;
  - ➔ suited to be more a complement to the indirect method than an alternative solution.

# Final Considerations (2)

- It is suggested to adopt a high level of **redundancy** to implement reliable core-constellation monitoring and failure detection functions:
  - Both Direct and Indirect URE estimation methods should be implemented. Being them independent estimation techniques, they improve robustness and reliability of URE estimation process.
  - Network-based approach, extending monitoring function to more than one station :
    - to have redundancy of URE measurements (for the same satellite at the same time).
    - to remove the not negligible dependency on the user location; about 20 stations evenly spread worldwide would allow to effectively average and remove local effects.
  - Multiple data sources are required for each type of input product to reduce the probability to introduce corrupted data into the analysis process. E.g. this is the case of automatic generated navigation data, precise orbits and clocks products, etc.

# Conclusions

- The ICG WG-C is invited to:
  - Take note of recent developments in ICAO
  - Identify if it is needed to coordinate with other sub WGs
  - Comment the methodologies implemented in Beyond project
  - Discuss on criteria for the identification of representative sites for performance criteria
  - Invite Core Constellation Service Providers to publish and share in the future ICAO KPI reports
  - Disseminate “Aviation GNSS Monitoring concept” among scientific communities

# Thanks for your attention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