GNSS Performance Characterization Framework

P.Crosta, R. Sarnadas, *ESA*
J. Clua, M.Solé, R. Romero, L. Tavira, *Indra*
G. Seco-Granados, A. Tripiana, *SPCOMNAV (UAB)*

BIOGRAPHIES

Paolo Crosta is a Radio Navigation System engineer at the ESA Technical Directorate where he provides support to the EGNOS and Galileo programs. Since 2012, he works in ESA in the pre-developments of the future RIMS ground stations of the EGNOS version 3 system and he is a member of the Galileo Services unit supports the Dual Frequency Alliance for Galileo ready mass-market chips and the GSA Task Force on Android GNSS Raw measurements.

Rui Sarnadas has earned his degree in Electrotectical Engineering from Instituto Superior Técnico in Lisbon, Portugal in 2004. He has been working in Navigation and GNSS Receiver Signal Processing for several years, and since 2014 is working as a Radio Navigation Engineer at the European Space Agency.

Dr Joan Clua received a PhD in Theoretical Physics from the Universitat Autònoma de Barcelona. Joan is a PMP certified senior project manager with more than 15 years of experience in the Industry. After finishing his Doctorate research, he started his career at the industry as a Project Manager. He joined Indra in 2006, managing several projects within the European Satellite Navigation Programs (EGNOS RIMS-A, NLLP, ULS Mission Processor and Galileo Service Center among others). Along these years, he has gathered a solid background in project management in the space and ground segments, a wide knowledge in the European GNSS programs, and the technical insights of satellite navigation. He is currently the Head of the EGNOS program at Indra.

Marc Solé holds a Master's Degree in Telecommunications and a Technical Degree in Aeronautics Engineering, specialized in air navigation, from the Polytechnic University of Catalonia (UPC). Nowadays, he is system engineer responsible of the development of the EGNOS v3 NLES sub-system. With more than 9 years of experience in GNSS domain, in the past, he worked providing support for the development of a GNSS related software and applications. Marc is actively participating in the definition of future Galileo OS and Galileo + GPS MOPS through his participation on WG-62 from EUROCAE. He was also working on the development of Embedded Software for a RTCA-MOPS (Do229D, D178B) compliant receiver.

Dr Rodrigo Romero received a PhD in Electronics and Telecommunications from Politecnico di Torino in Italy. His experience covers several topics related to signal conditioning and processing for satellite navigation receivers: algorithm development for signal tracking and navigation with GPS and Galileo, estimation and mitigation of external errors affecting receiver performance and the set-up and maintenance of monitoring equipment during data acquisition campaigns. He currently works at Indra, where he supports the development of products and solutions for Galileo and EGNOS ground segment.

Lourdes Tavira has a MSc. in Industrial Engineering from Universitat Politècnica de Catalunya (UPC) and a Bachelor's degree in Computer Science from Universitat Oberta de Catalunya (UOC). She accumulates more than 20 years of career, most of them as Technical Manager, combining managerial skills with a deep knowledge of Software Engineering. In the field of GNSS, she has a solid background in the EGNOS and Galileo programs and a hands-on knowledge of GNSS performance analysis after her participation in projects like EGNOS Mission Monitoring or Galileo GSTB v2. She is currently the Technical Manager of a project awarded by the European GNSS Agency (GSA) aimed to support Maritime Service Providers in the transmission of EGNOS corrections via IALA beacons and AIS/VDES stations.

Gonzalo Seco-Granados holds a Ph.D. degree from Universitat Politècnica de Catalunya (UPC) and an MBA from IESE, Universidad de Navarra. Until 2005, he was with the European Space Agency, involved in the design of the satellite-based navigation systems. He is a Professor at the Signal Processing for Communications and Navigation (SPCOMNAV) research group, Department of Telecommunication and Systems Engineering at Universitat Autònoma de Barcelona.

Antonio Tripiana-Caballero is a project engineer graduated in Telecommunications Engineering by the Universitat Autònoma de Barcelona (UAB). Between 2015 and 2018, he has been working as a research assistant at the Signal Processing for Communications & Navigation (SPCOMNAV) research group, involved in three different projects funded by the European Space Agency (ESA) and the European GNSS Agency (GSA), both at the UAB and ESA´s research facilities.

ABSTRACT

With the advent of new constellations, signals and frequencies, the **reference stations** are expected to face a major evolution by incorporating **multi-frequency capabilities** and adopting the **multi-constellation concept**, while including also more demanding requirements in terms of robustness against signal deformations, spoofing, multipath and interferences. This opens a clear business opportunity for a new generation of reference stations needed to comply with the new scenario of GNSS navigation programs.

The European Geostationary Navigation Overlay Service (EGNOS) is Europe's regional Satellite-Based Augmentation System (SBAS) that is used to improve the performance of GNSS such as GPS and Galileo. **EGNOS will experiment a major evolution by 2020**, EGNOS V3, including the fulfilment of the SBAS L1/L5 standard, expansion to dual-frequency and evolution towards a multi-constellation concept. The Ranging Integrity Monitoring Stations (RIMS) are expected to incorporate modernizing features such as:

- Tracking of Galileo Constellation (in addition to the current ones, GPS and GLONASS).
- Incorporation of additional frequencies (GPS L5 / L2C and Galileo E5a).
- Signal processing capabilities (such as integrated signal quality monitoring and in particular evil waveform detection using a multi-correlator architecture).
- Advanced built-in robustness and security functions: Robust tracking algorithms, detection/mitigation of interferences and anti-spoofing/jamming techniques.

In this context, ESA awarded the consortium Indra and SPCOMNAV (a research group from the Universitat Autonoma de Barcelona – UAB) with a contract for the development of an **advanced GNSS reference station breadboard (a.k.a. R3B)** in the frame of the General Support Technology Program (GSTP 6.2) program.

INTRODUCTION

Indra has acquired during the last decades a large experience in the **assessment of GNSS performances**, not only at system level, but also at ground and user levels. This has been achieved thanks to the execution of several GNSS R&D projects and the participation in the development of different European GNSS programs, such as Galileo and EGNOS. This experience has led the company almost naturally to the compilation of previously developed and well-tested tools. The result of this compilation is the **GNSS Performance Characterization Framework** (GPCF).

The GPCF has been customized to the particularities required by the R3B project. The original characterization framework is briefly introduced in this paper. The main focus of the paper is, however, the work performed throughout the R3B project using the GPCF.

FRAMEWORK FOR PERFORMANCE CHARACTERIZATION

GPCF is a toolset that allows analysis of GNSS data collected from different receiver types (mass market, differential, precision, etc.) and systems (SBAS, GBAS and GNSS). It can then be easily integrated within any test environment allowing the assessment of receiver and system performances such as:

- Position-Velocity-Time (PVT) solution accuracy and integrity.
- Code and carrier phase measurements accuracy, including estimation of effects such as inter-frequency biases, group delays, channel biases, noise errors, etc.
- Signal in Space acquisition and re-acquisition for GNSS and GEO satellites.
- Impact on the measurements and behavior of the receiver under a wide variety of complex scenarios including
  - Multipath errors of different nature (diffuse, reflective, etc.)
  - Interfering signals of different types (narrowband or wideband, pulsed or continuous, inter-system or intra-system, etc.)
  - Ionospheric Scintillation (IS) errors of different nature (high or low latitude IS)
- Orbit estimation accuracy.
- Code-carrier measurements coherence

- Availability of GNSS systems or augmentation systems

The tools and methodologies provided by GPCF are well suited for the **assessment of the performances and the validation of**:

- **Any kind of receiver** (from mass market to professional or geodetic receivers); or
- **An entire GNSS-based system**.

Furthermore, the GPCF can also be used as a **part of a system to detect potential threats** (especially interferences) in real time.

USE CASE: ADVANCED GNSS REFERENCE STATION FOR R3B PROJECT

The main objectives of the R3B project were:

- **Development of a Reference Station Prototype/Breadboard** integrating two state-of-the-art GNSS receivers, including
  - Selection of multi-constellation/multi-frequency (MC/MF) receiver and COTS antenna candidates to become part of future SBAS reference station product;
  - Design and development of a reference station prototype;
  - Issue of a development plan to industrialize the prototype.
- **Assess the compliance** of two MC/MF receivers against requirements of the SBAS reference stations, in particular EGNOS requirements studied during V3 definition phase (Phase B). The outputs of this assessment were used to:
  - **Consolidate the requirements for the final RIMS V3 tender phases** with the recommendations identified during the project;
  - **Provide design recommendations** to the manufacturers of the receivers evaluated, in order to increase compliance with the consolidated requirements.
  - **Issue a development plan** for the development of a RIMS V3 station.

The following figure summarizes the steps followed through the project:

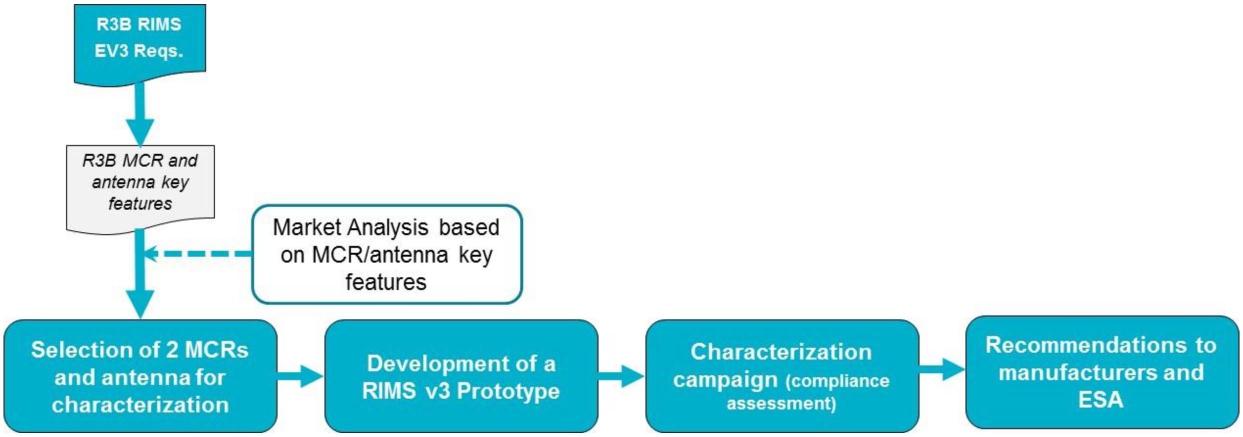

Figure 1. Project steps

RECEIVERS AND ANTENNA SELECTION

The equipment (receiver and antenna set) selection procedure was divided in two main phases, as follows:

- First, a list of potential candidates was derived from a simple market analysis. Based on the assessment of most basic R3B features, a reduced set of receiver and antenna sets was selected.
- Second, the previously selected candidates were analyzed (by review of design), with the support from the manufacturers, against R3B requirements to support the final selection phase. So, at the end, two receiver plus antenna sets were selected for characterization.

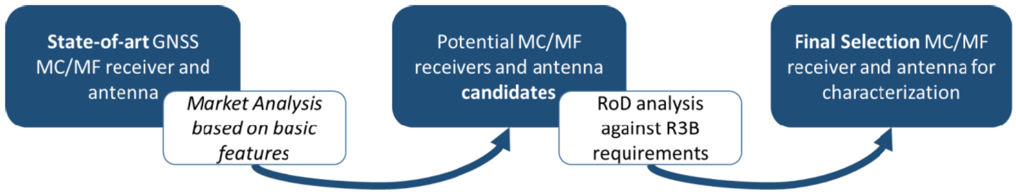

Figure 2. Receiver and antenna selection process

Receivers Key Features

Receiver candidates shall cover, at least, the following key aspects:

- Signal tracking and navigation message decoding of the following signals:
    - <u>Baseline signals</u>: Galileo E1, E5a, GPS L1CA, L5, SBAS L1/L5, plus L2C and L2P(Y) for transition from v2 to v3.
    - <u>Expandable signals</u>: Galileo E5b, Galileo E6, GPS L1C, GLONASS L1OCI, L5OC- I&Q, BeiDou B1-C-D&P, B2a-D&P. Note that these expandable signals are just some examples of RIMS HW Scalability. Hence, these signals are not confirmed in terms of constellation, frequency and number of channels needed. Full compliance to such requirement is considered as not mandatory.
- For each signal tracked, provide the following observables: pseudo-range, carrier-phase, C/N0, freq. Doppler, multipath and interference flags.
- Having enough channels to cover all the satellites in view.
- Performance accuracy of pseudo-range and carrier-phase measurements.
- Robustness against multipath and interference.
- Scintillation indicators
- Spoofing/meaconing countermeasures
- COTS product

Antennas Key Features

- Performance: D/U ratio, phase center stability, group delay variation
- Supported environmental conditions: blast outdoor, temperature, humidity, shipping and storage
- Robustness against Hostile Environment: humidity, corrosion, dust
- Robustness against out-of-band (OOB) interferences

The manufacturer's names and models of the selected equipment will not be unveiled in this paper.

DEVELOPMENT OF A RIMS V3 PROTOTYPE

In the frame of R3B project, GPCF was used as the basis of the final characterization framework to assess performances of the two selected COTS receivers and the selected COTS antenna for SBAS reference stations. The complete setup of the characterization framework, as it was configured at the ESA ESTEC Radio Navigation laboratory for the R3B project, can be seen in Figure 3.

The R3B architecture integrated two RF chains built with different MC/MF receivers and their own core computer. The antenna (i.e. input signal), frequency standard and test tools, including the GPCF, were common elements shared between the chains.

R3B design allowed the use of real SiS or, when necessary, simulated signals generated by means of a Spirent GSS9000 simulator coupled with an Agilent Interference Signal Generator (ISG E4431B). The architecture also included emulators of SBAS Central Control Facility and Central Processing Facility in charge of emulating, respectively, the collection of raw measurements data and the handling of commands and monitoring data from the receiver.

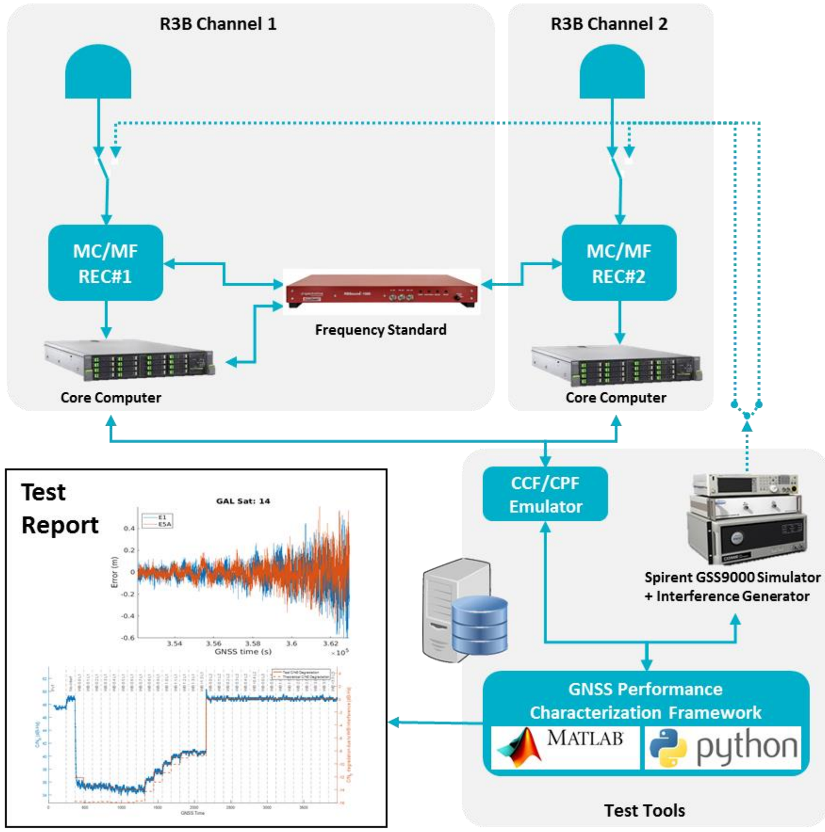

Figure 3. Advanced GNSS Reference Station for EGNOS v3 prototype with Characterization Framework

Set of additional tools

The following **set of tools** was required to stimulate all functions implemented in the prototype:

- **CPF Emulator:** it emulates CPF behavior by collecting all RIMS raw measurements data.
- **CCF Emulator:** it emulates CCF behavior by sending commands to the receivers and by collecting commands responses. It also collects monitoring data from the receivers.
- In the case of the simulated SiS configuration, it includes a **GNSS simulator** to generate the SiS data required in some of the validation tests, especially those dedicated to validate system performance. The GNSS simulator substitutes or complements the real SiS data when this one cannot easily model the scenario under test.

CHARACTERIZATION CAMPAIGN

General test approach

With the aim of creating a test tool that could be used to recreate the scenarios needed to check ESA's specifications and requirements for the EGNOS V3 reference station prototype (EGNOS V3 phase B requirements), Indra has developed, along with the test tool, a detailed test procedure that allows an agile and comprehensive testing of the most relevant receiver/antenna parameters. To validate the requirements, a three-step process was followed:

- The first step was to adapt ESA´s scenario requirements (in terms of interferences, scintillation, etc.) to the real testing capabilities. The reason behind this is that, in many cases, the requirements contemplate a high number of possibilities and variables included in the same scenario that cannot always be represented even with the most advanced testing tools. The aim of the tool is to perform tests in an agile and efficient manner, granting for a highly responsive test campaign that allows for rapid changes on the go, working within narrow space frames and allowing the reduction of test campaign timings.

- After adapting the scenario, the process continued with the description of the steps for the execution of the test.
- The third step was the execution of the test following the detailed description stated above.
- The fourth and final step consisted of the data post-processing and the reporting of the test results.

In this section of the paper, the results of two relevant tests performed during the characterization of EGNOS V3 base station prototype are presented:

- **code phase error** due to ***noise*** and ***interferences***, and
- **satellite re-acquisition** in different ***scintillation*** conditions

TEST 1: CODE PHASE ERROR DUE TO *NOISE AND INTERFERENCES*

The complete test of code phase error due to noise is presented and developed in this section. The test was performed with nominal constellations of GPS, Galileo and SBAS signals including GPS L1CA, L2PY, L2C, L5, GALILEO E1b, E5a and SBAS L1, L5 signals. The noise was a combination of thermal noise, weak scintillations, Out-Of-Band (OOB) interferences and in-band interferences at different frequency offsets and signal bands. More specifically, the requirement defines that the 1-sigma error due to RIMS receiver noise on raw code observables shall be lower than the values reported in **Table 1**, in the environmental conditions specified below:

1. Signals and minimum received power as specified in SIS-ICD **[1] [2] [3]**.
2. In band interference conditions as specified in **Table 2**.
3. Out of band interference conditions as specified in **Figure 4**. This refers to out-of band continuous wave (CW) interfering signals that can be as high as the levels shown in **Figure 4**, measured at the output port of a 0 dBi gain antenna. Also, refers to pulsed out-of-band interference. In this case, the maximum peak power level for pulse interference received for the points defined in **Figure 4** shall be below the following values:
   - Pulse Peak Power = 0 dBW
   - Pulse Width≤ 1ms.

   The duty cycle can vary according to the environmental conditions for the V3 sites acceptance document **[4]**. A typical value of duty cycle that is used for testing purposes is 14%.
4. Weak scintillation conditions. These conditions are defined in terms of the following scintillation parameters: $S4 \sim U(0,0.3)$ and $\sigma\Phi \sim U(0,0.3)$.
5. Inter-system and Intra-system interference conditions are included in addition to the thermal noise floor determined by the RIMS overall noise figure. This effect of inter-system and intra-system interference produced by all the GNSS signals transmitting in the same frequencies shall be assessed.

The above-mentioned scenario could not be directly applied to the Spirent scenario generator. For this reason, an agreement was reached with the ESA in order to make some modifications to adapt those requirements. Following the same structure as above, the applied modifications were as follows:

1. Power aligned with SIS-ICD, taking into account the link budget of the whole testing system (simulator, cables, LNA, splitter and receivers) to adjust the signal power levels.
2. In-band interferences. In order to simplify hundreds of possible combinations that would arise from applying all of the initial ESA requirements, selected cases of in-band interference in terms of errors induced to the code measurements, both narrowband (Continuous Wave) and wideband were selected. Such interferences, selected from previous tests through the assessment of the impact of interferences during the characterization, would induce sufficiently large code errors on the receivers but would still allow them to track the GNSS signals. The simulation takes for a certain time the worst case wideband interference for GPS L1CA + L2PY + L5, GAL E1 + E5 and EGNOS L1 + L5 signals. The same approach was followed for the worst case narrowband interference.
3. Out of band interference simplified (added 1 dB C/N0 degradation) to simulate impact of continuous and pulsed interferences. This was agreed after a detailed study of the behavior of the selected antenna out-of-band interference rejection filter.
4. Weak scintillation (using Cornell model, with parameter S4=0.3) **[5]**.
5. Intra-system and inter-system interferences were automatically considered by the simulator when selecting a nominal constellation with the following simulated signals: GPS L1 + L2 + L5, GAL E1 + E5 and EGNOS L1 + L5.

Besides, the real antenna pattern was included to do the simulation more realistic, and the results were computed in elevation windows. The interferences were injected every 30 minutes across the selected bands, leaving 5 minutes without interference between each step, in order to restore the C/N0 level, so a total of 25 minutes per worst-case interference were simulated. In order to isolate the impact on code measurements due to noise, a reference scenario was also simulated with the same configuration of satellites but without injecting interference and scintillation effects. The code error was evaluated in the following three cases:

- **Case 1**: Code errors due to **thermal noise** (reference scenario)
- **Case 2**: Code errors due to **worst-case narrowband interference**, **weak scintillation and Out of band interference**. The latter is simulated as C/N0 degradation.
- **Case 3**: **Code errors due to worst-case wideband interference, weak scintillation and Out of band interference**. The latter is simulated as C/N0 degradation.

Elevation (degrees)	5	10	15	20	30	40	50	60	90
GPS&GEO L1CA Code Phase Error (m)	0,42	0,14	0,13	0,13	0,13	0,15	0,13	0,11	0,13
GAL E1C Code Phase Error (m)	0,28	0,09	0,09	0,09	0,09	0,10	0,08	0,07	0,09
GAL E5aQ Code Phase Error (m)	0,13	0,05	0,04	0,04	0,04	0,04	0,03	0,03	0,02
GPS&GEO L5 Code Phase Error (m)	0,13	0,05	0,04	0,04	0,04	0,04	0,03	0,03	0,02
GPS L2C Code Phase Error (m)	0,66	0,33	0,33	0,33	0,35	0,35	0,31	0,25	0,18
GPS L2PY Code Phase Error(m)	1,47	0,72	0,72	0,72	0,76	0,76	0,68	0,54	0,40

Table 1: Code phase error vs elevation

EMI Frequency Offset [MHz] wrt L1 carrier	Max. Power Level RF EMI on L1 (BW 1 MHz)	Max. Power Level RF EMI on L1 (BW 1kHz)	EMI Frequency Offset [MHz] wrt L2 carrier	Max. Power Level RF EMI on L2 (BW 1 MHz)	Max. Power Level RF EMI on L2 (BW 1kHz)	EMI Frequency Offset [MHz] wrt L5 carrier	Max. Power Level RF EMI on L5 (BW 1 MHz)	Max. Power Level RF EMI on L5 (BW 1 kHz)
0.0	-125.0	-130.0	0.0	-118.2	-123.2	0.0	-116.1	-121.1
0.1	-124.8	-129.8	0.1	-118.1	-123.1	0.5	-116.0	-121
0.2	-124.6	-129.6	0.2	-117.9	-122.9	1.0	-115.9	-120.9

0.3	-124.2	-129.2	0.3	-117.4	-122.4	1.5	-115.9	-120.9
0.4	-123.5	-128.5	0.4	-116.8	-121.8	2.0	-115.6	-120.6
0.5	-122.6	-127.6	>0.4	-116.4	-121.4	2.5	-115.2	-120.2
0.6	-121.7	-126.7				3.0	-114.9	-119.9
0.7	-120.7	-125.7				3.5	-114.6	-119.6
0.8	-120.8	-125.8				>3.5	-114.5	-119.5
0.9	-120.7	-125.7						
1	-120.4	-125.4						
1.1	-119.9	-124.9						
1.2	-119.2	-124.2						
1.3	-118.3	-123.3						
>1.3	-117.5	-122.5						

Table 2: In-band interference mask

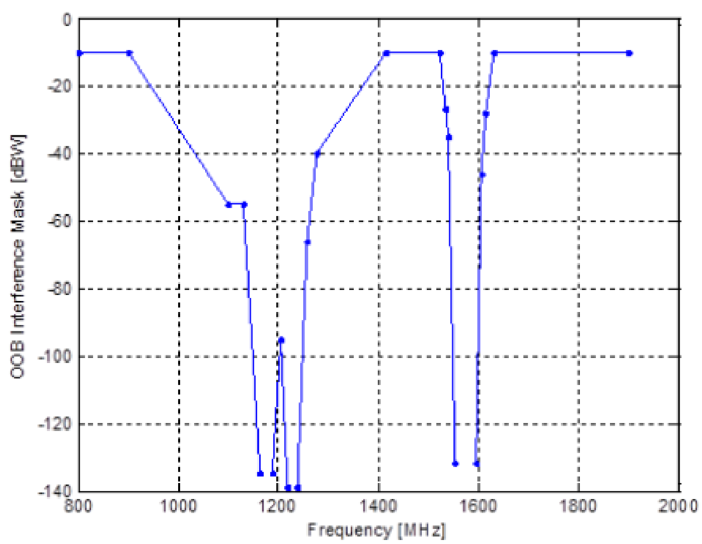

Figure 4: HYP-080 out-of band CW interference mask for all baseline signals

Once all of the above was configured in the simulator scenario, the following sequence was performed to execute the test:

1. Load SimGen scenario to the simulator with the configuration explained above.
2. Execute start-up sequence for the receiver.
3. Configure the receiver, including receiver channels and signals to be tracked.
4. Start data logging (observables) the receiver.
5. Run simulator.
6. Confirm receivers enter into operational state and start capturing signals as expected.
7. Wait until the end of the simulation.
8. Stop data logging.

Once all the data was correctly saved, the code phase observables for each PRN and signal were fed into Indra's post-processing software in order to obtain the code phase error for each satellite and signal and elevation window. The code phase error was calculated using the third order difference formula:

$$\hat{\varepsilon}_{c1}^{\rho}(n) = \frac{\rho_{c1}(n) - 3\rho_{c1}(n-1) + 3\rho_{c1}(n-2) - \rho_{c1}(n-3)}{\sqrt{20}}$$

Where $\rho_{c1}(n)$ is the measured code phase measurement at epoch n on channel (or signal) $c1$.
The resulting code phase errors were classified in elevation windows and averaged for each signal and PRN.

Results: Pass/Fail criteria analysis

Code phase observables 1sigma error must be below figures shown in **Table 1**. Test results are included in **Table 3**, **Table 4** and **Table 5,** which summarize the Pass/fail outcomes of the test for each one of the three cases evaluated. Table cells in green indicate the receiver was compliant with the requirement, yellow cells indicate that the code phase error was larger than required (and thus not compliant with the requirement) and red color indicates the receiver was not able to keep track of the signal. A grey cell indicates there was no data available to evaluate the requirement at that specific elevation.

Case 1. Code errors due to thermal noise (reference scenario)

This scenario was evaluated to have a **reference** performance of the receiver without the interference conditions specified in the requirement and considering only the effect due to thermal noise. The receiver was compliant with the requirement except at low-mid elevations (10 to 40 degrees) mainly for L5 band signals, as it is seen in **Table 3**.

Elevation (degrees)	5	10	15	20	30	40	50	60	90
GPS L1CA	0.159	0.134	0.116	0.085	0.061	0.046	0.037	0.031	0.027
GEO L1CA	No Data	No Data	No Data	No Data	0.744	0.744	No Data	No Data	No Data
GAL E1c	0.123	0.098	0.080	0.063	0.043	0.033	0.030	0.023	0.019
GAL E5a	0.110	0.097	0.082	0.066	0.048	0.035	0.027	0.022	0.019
GPS L5	0.103	0.088	0.074	0.059	0.042	0.031	0.024	0.020	0.017
GEO L5	No Data	No Data	No Data	No Data	0.039	0.039	No Data	No Data	No Data
GPS L2C	0.312	0.299	0.260	0.192	0.146	0.105	0.080	0.065	0.053
GPS L2PY	0.013	0.014	0.015	0.012	0.012	0.018	0.019	0.013	0.009

- Compliant
- Not Compliant
- Signal not tracked by receiver
- Data not available at that elevation

Table 3: (Case 1) Receiver code-phase error due to thermal noise [m].

Case 2. Code errors due to worst-case narrowband interference + scintillations

Both receivers showed tracking issues at low elevations due to the presence of interference. As seen in **Table 4** the receiver is mostly compliant above 40 degrees but struggles to track the signals at low-mid elevations (0 to 40 degrees).

Elevation (degrees)	5	10	15	20	30	40	50	60	90
GPS L1CA	NT	NT	0.206	0.194	0.134	0.110	0.091	0.066	0.065
GEO L1CA	No Data	No Data	No Data	No Data	1.209	1.209	No Data	No Data	No Data
GAL E1c	0.144	0.104	0.085	0.080	0.043	0.041	0.031	0.027	0.022
GAL E5a	No Data	0.115	0.090	0.072	0.060	0.027	0.032	0.027	0.022
GPS L5	NT	0.098	0.084	0.065	0.050	0.038	0.032	0.024	0.022
GEO L5	No Data	No Data	No Data	No Data	0.045	0.045	No Data	No Data	No Data
GPS L2C	NT	NT	0.250	0.204	0.159	0.133	0.086	0.071	0.073
GPS L2PY	NT	NT	NT	0.012	0.012	0.008	0.008	No data	0.007

- Compliant
- Not Compliant
- Signal not tracked by receiver
- Data not available at that elevation

Table 4: Receiver code-phase error due worst-case narrowband interference [m].

Case 3. Code errors due to worst-case wideband interference + scintillations

Similar to the previous case, **Table 5** show the receiver had issues tracking signals at low elevation and it was not compliant with the requirement. In general, the receiver showed similar performance as before except for L5 band signals where it was not compliant at any elevation.

Elevation (degrees)	5	10	15	20	30	40	50	60	90
GPS L1CA	NT	0.175	0.156	0.147	0.085	0.078	0.065	0.043	0.048
GEO L1CA	No Data	No Data	No Data	No Data	1.941	1.941	No Data	No Data	No Data

GAL E1c	0.185	0.179	0.109	0.071	0.073	0.055	0.053	0.035	0.034
GAL E5a	No Data	NT	NT	NT	0.087	0.123	0.103	0.054	0.042
GPS L5	NT	NT	0.091	0.078	0.061	0.083	0.070	0.037	0.031
GEO L5	No Data	No Data	No Data	No Data	0.051	0.051	No Data	No Data	No Data
GPS L2C	NT	NT	NT	NT	NT	No Data	0.155	0.137	0.110
GPS L2PY	NT	NT	NT	0.029	0.024	0.014	0.015	No data	0.019

Compliant
Not Compliant
Signal not tracked by receiver
Data not available at that elevation

Table 5: Receiver code-phase error due worst-case wideband interference [m].

SUMMARY: The receiver presents difficulties when working with the levels of interference imposed by the requirement. The scenario conditions are too stringent for the receiver and fails compliance to the requirement for quite a few elevations/band signals.

TEST 2: SIGNAL REACQUISITION CAPABILITIES

In this section, the test regarding the signal re-acquisition capabilities of the receiver is explained. In particular, the test measured the time it took for the receivers to recover all signals following loss of lock under specific scenarios. The test was performed with nominal constellations of GPS, Galileo and SBAS signals including GPS L1CA, L2PY, L2C, L5 and GALILEO E1b, E5a, with 5 space vehicles per constellation. The requirement pointed out that the subsystem shall be able to re-acquire all signal-in-space within 1 second following a signal tracking loss of few hundreds of milliseconds in the environment conditions specified below:

1. Signals and minimum received power as specified in SIS-ICD **[1] [2] [3]**.
2. In band interference conditions as specified in **Table 2**.
3. Out of band interference conditions as specified in **Figure 4**. This refers to out-of band continuous wave (CW) interfering signals that can be as high as the levels shown in **Figure 4**, measured at the output port of a 0 dBi gain antenna. Also, refers to pulsed out-of-band interference. In this case, the maximum peak power level for pulse interference received for the points defined in **Figure 4** shall be below the following values:
   - Pulse Peak Power = 0 dBW
   - Pulse Width ≤ 1ms.

   The duty cycle could vary according to the environmental conditions for the V3 sites acceptance document **[4]**. A typical value of duty cycle that was used for testing purposes was 14%.
4. Inter-system and Intra-system interference conditions in addition to the thermal noise floor determined by the RIMS overall noise figure. This effect of inter-system and intra-system interference produced by all the GNSS signals transmitting in the same frequencies shall be assessed.

Besides, the signals re-acquisition capabilities were assessed in high/mid latitude scintillation conditions and low/mid latitude scintillation conditions, with the following specifications:

- High/Mid Latitude scintillation environment was defined in terms of the following scintillation parameters:
  - S4 ~ U(0, 0.3)
  - $\sigma\varphi$ ~ 0.7 + Exp(λ) [rad] with λ equal to 10 (L1), 7.8 (L2), 7.5 (L5)
    where ~ means that the parameter follows a particular distribution that can be:
  - Exp(λ), exponential distribution with mean value 1/ λ
  - N(x, y), normal distribution with mean value x and standard deviation y

- U(x, y), uniform distribution in the range [x, y].

- Low/Mid Latitude scintillation environment is defined in terms of the following scintillation parameters:
  - S4 ~ 0.6 + Exp(λ) with λ equal to 6 (L1), 4.1 (L2), 3.9 (L5)
  - σφ ~ 0.35*S4 + N(0,0.15) [rad]

    where ~ means that the parameter follows a particular distribution that can be:
  - Exp(λ), exponential distribution with mean value 1/ λ
  - N(x, y), normal distribution with mean value x and standard deviation y
  - U(x, y), uniform distribution in the range [x, y].

Such scintillation conditions could be simulated with **time series generated by ESA** or by **using recorded real stations data** made available by ESA.

As before, an agreement was reached with ESA in order to make some modifications to adapt those requirements to the Spirent simulator. The test was divided in three runs of one hour, each one simulating the impact of both In-band and Out-of-Band Interferences as a C/N0 degradation. Different levels of interference degradation were simulated resulting on overall C/N0 of 30, 33 and 36 dB-Hz respectively on each run. This was done due to the high impact of the worst-cases of the interferences, degrading the C/N0 up to 20 dB-Hz that led the receiver to not be able to even acquire the signals at the beginning of the test simulation. The following modifications were applied:

1. Signal power aligned to have the desired C/N0 levels for each case (C/N0 = 30, 33 and 36 dB-Hz).
2. In-band interference conditions are included as C/N0 degradation.
3. Out-of-band interference conditions are included as C/N0 degradation.
4. Intra-system and inter-system interferences were automatically considered by the simulator when selecting a nominal constellation with the following simulated signals: GPS L1 + L2 + L5, GAL E1 + E5 and EGNOS L1 + L5.
5. No multipath effect added.
6. High-Mid latitude scintillation using both time series provided by ESA and real stations data recorded at Kiruna station. Low-mid latitude scintillation using time series provided by ESA.

The real antenna pattern was not included in order to maintain the desired C/N0 levels for all elevations. Once the scenario configuration was complete, the test simulation was performed in a way that allows having hundreds of cases in order to extrapolate reliable statistics for the behavior of the receivers:

1. Leave the scenario running for 15 minutes at the beginning of the test to allow the receivers compute PVT solution and collect almanac.
2. After the first 15 minutes, generate a loss of lock of 100 ms every 30 seconds through the scenario user action file. This was done by powering off all the simulator channels, this is, shutting down all the PRNs in view and all the signals for each PRN for 100 ms.

Once all of the above was configured in the simulator scenario, were the following sequence was performed to execute the test:

1. Load SimGen scenario to the simulator with the configuration explained above.
2. Execute start-up sequence for the two receivers.
3. Configure the receivers, including receiver channels and signals to be tracked.
4. Start data logging (observables) on the two receivers.
5. Run simulator.
6. Confirm receivers enter into operational state and start capturing signals as expected.
7. Wait until the end of the simulation.
8. Stop data logging.

Results: Pass/Fail criteria analysis

As stated in the requirement, the sub-system shall be able to re-acquire all SIS within 1 second following a signal tracking loss. Considering this, re-acquisition probabilities were evaluated on the basis of all signals having been re-acquired within 1 sec (2 consecutives samples). Once all the data was correctly saved, the observables for each PRN and signal were feed in Indra's post-processing software in order to observe if the signals were reacquired by checking if there was a lack of measurements in 2 consecutive samples at the time that the loss of lock was generated in the simulator. If there was a lack of measurements for a certain signal for a certain PRN then a re-acquisition fail was considered.

Case 1. High/Mid latitude scintillation conditions using time series

Figure 5 shows the outcome of GPS signals re-acquisition test at C/N0=30dB-Hz in high/mid scintillation conditions provided by time series. It was observed that the receiver was unable to acquire L2PY for all test cases and also that at certain time the receiver started failing to re-acquire L1CA signal. For this particular test the receiver showed a good performance of L2C and L5 signals with no re-acquisition failures. **Figure 6** shows the outcome of the same test for Galileo signals. In this case the receiver showed good performance on E1 and E5 with no failures for all the cases tested.

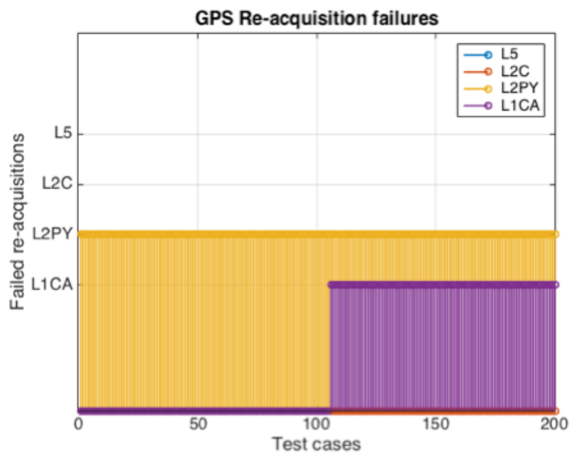

Figure 5: GPS signals re-acquisition test at C/N0 = 30 dB-Hz.

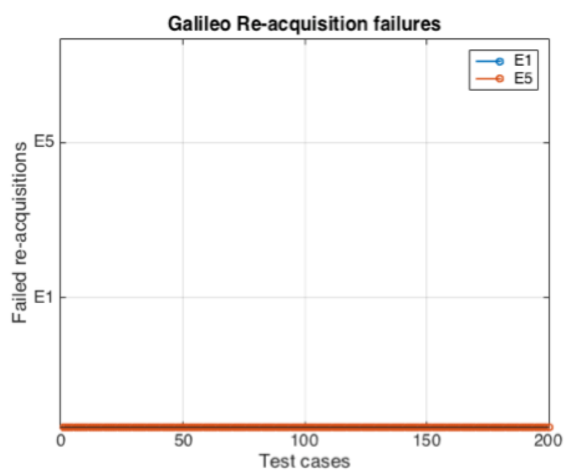

Figure 6. Galileo signals re-acquisition test at C/N0 = 30 dB-Hz.

A summary of the results for the high/mid scintillation case using time series is presented through **Table 7**. There were 595 re-acquisition test cases, obtained from the number of 100ms signal interruptions times the number of satellites (119*5). Given that any individual signal re-acquisition failure affects the pass/fail outcome, the re-acquisition probabilities for the individual signals are provided as well in order to give an insight into which signal(s) are the more problematic to be re-acquired. Furthermore, re-acquisition probabilities after 5,10 and 25 seconds after the signal tracking loss are also provided, in order to observe if the compliance of each receiver improves if more time is given for the re-acquisition of the signals.

CN0 (dBHz)	**#test cases**	**Re-Acq. Probability (1 sec)**	**5Sec Prob.**	**10Sec Prob.**	**25Sec Prob.**	**Signal re-acquisition probabilities (1 sec)**					
						L1CA	**L2PY**	**L2C**	**L5**	**E1**	**E5**
30	595	0%	0%	0%	2.2%	17.65%	0%	100%	100%	100%	100%
33	595	11.0%	11.0%	11.0%	100%	100%	11.0%	100%	100%	100%	100%
36	595	11.0%	11.0%	11.0%	100%	100%	11.0%	100%	100%	100%	100%

Table 7. Re-acquisition test results for mid-high latitude scintillation (using time series)

Case 2. High/Mid latitude scintillation conditions using real data recordings from Kiruna station

Table 8 summarizes the second version of this test, where mid-high latitude scintillation fluctuations were injected into GPS signals using real data recordings from Kiruna station. As the Kiruna scintillation file provided by ESA did not include Galileo, only GPS signals were simulated. Compared to the previous scenario, only one satellite was available for the test, thus the number of test cases is reduced. As before, individual signal probabilities and re-acquisition probabilities after 5, 10 and 25 seconds are provided. Results show that the receiver has a very poor re-acquisition performance for GPS L2PY signal. For this reason, its global re-acquisition probabilities are very low. The performance for L2C and L5 signals is excellent for the three C/N0 cases, while for L1CA signal is poor at C/N0 of 30 and 33 dB-Hz.

CN0 (dBHz)	**#test cases**	**Re-Acq. Probability (1 sec)**	**5 Sec Prob.**	**10 Sec Prob.**	**25 Sec Prob.**	**Individual Signal re-acquisition success (1 sec)**			
						L1CA	**L2PY**	**L2C**	**L5**
30	111	0%	0%	0%	0.9%	17.12%	0%	99.1%	99.1%
33	111	0.9%	0.9%	0.9%	17.12%	19.82%	0.9%	99.1%	99.1%
36	111	5.41%	5.41%	5.41%	78.38%	91.89%	5.41%	99.1%	99.1%

Table 8. Re-acquisition test results for mid-high latitude scintillation (using real data from Kiruna station)

Case 3. Low/Mid latitude scintillation conditions using time series

Table 9 shows the results obtained in the third version of this test. This test simulated low-mid latitude scintillation fluctuations as time series provided by ESA, on top of the interference degradations (induced as three C/N0 cases). Because the scintillation file provided by ESA did not include the effect for Galileo satellites, Galileo signals were not simulated. With 59 losses of lock induced during the simulation, the total number of test cases in each run was 531. For this particular test it was difficult for the receiver to have all the signals available given the low C/N0 conditions and stronger scintillation fluctuations. When compared to the previous case in Kiruna for high latitudes, scintillations at low latitudes induce stronger signal fading that can heavily impact the performance of receivers to acquire and keep track of the signals. As before, the re-acquisition probabilities were estimated over the total number of cases simulated in each run.

Due to scintillations there were cases where no signal from a particular satellite was detected after the loss of lock was induced. This can be observed in Error! Reference source not found.**7** for the case of C/N0=30dBHz. Having in mind that the total number of satellites was 5, the receiver could detect up to 5 SV in some cases it still failed to achieve re-acquisition success for all signals, as shown in **Table 9**.

CN0 (dBHz)	#test cases	Re-Acq. Probability (1 sec)	5 Sec Prob.	10 Sec Prob.	25 Sec Prob.	Individual Signal re-acquisition success (1 sec)			
						L1CA	L2PY	L2C	L5
30	531	**0%**	0%	0%	0%	3.95%	0%	3.38%	17.13%
33	531	**2.25%**	2.07%	1.88%	17.89%	57.81%	3.01%	68.54%	82.86%
36	531	**4.14%**	4.14%	5.64%	58.38%	91.14%	4.14%	95.85%	96.61%

Table 9. Re-acquisition test results for low-mid latitude scintillation (using time series)

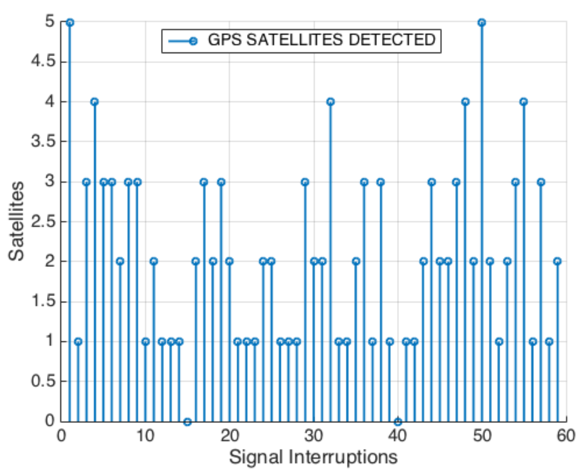

Figure 7. Satellite detection after losses of lock for low-mid latitude scintillation (C/N0 = 30dB-Hz).

SUMMARY: The receiver **always** presents difficulties re-acquiring L2PY signal. When the scintillation conditions are worse (cases 2 and 3), the receiver also shows problems re-acquiring L1CA signals, especially for CN0 = 30 and 33 dB-Hz (i.e. high levels of interference). This means that the **receiver struggles in scenarios presenting a combination of high levels of interference together with strong scintillation fluctuations** and is not compliant with the requirement.

RECOMMENDATIONS FOR IMPLEMENTATION

The following is the list of recommendations elaborated in the frame of this project, and considering the available version of requirements in [6], towards EGNOS v3 requirements.

Recommendations to receivers' manufacturers:

- To **minimize MCR signal processing configurability** to minimum necessary to accomplish with EV3 operations and to avoid possible MCRs underperformance.
- To **limit the number of ACF discriminators** to nine points (or a number on this order), and if many more points are needed, alternative solutions such as for example using a collaborative approach should be studied.

Recommendations to ESA:

- In relation to the following performance requirement:
  [PER-025] SIS acquisition for rising satellite
  RIMS shall acquire all SIS from any rising satellite with an acquisition probability of 99.99% before the satellites cross 5° elevation in the environment conditions specified in [DEF-020] and multipath conditions specified in [HYP-020].
  [DEF-020] defines environment conditions with received power, interferences and scintillation levels (weak) as the one described in Test 1.
  [HYP-020] Reflective Multipath
  The reflective component of the multipath shall be represented by considering the following conditions:
  • D/U equal to the values reported in the following table:

Elevation (degrees)	*5*	*10*	*20*	*30*	*60*	*90*
D/U (dB)	*6.0*	*7.3*	*9.6*	*11.0*	*13.2*	*14.8*

  • Any multipath delay,
  • Any phase shift in the range [0, 180°].
  To critically review this requirement taking into account additional system requirements, such as the **probability that a RIMS can be under high interference conditions**, **CPF requirements covering the need of satellite measurements for new rising satellites**, the **period that the CPF shall monitor a given satellite before providing the associated corrections**, etc.
  That analysis should lead to a refined specification of PER-025, potentially considering different minimum elevation angles for satellite signals acquisition:
    - per constellation;
    - per signal;
    - per local conditions (RFI level).
- To stress the need of **detecting when RIMS site is under a non-nominal scenario** (RFI, multipath, scintillation), more than designing a product that maintains good performance even under those undesired conditions. As it has been demonstrated in the two test cases included in this paper, the receivers analyzed present difficulties in scenarios that combine high level of interferences together with strong scintillation fluctuations.
- To **clarify the applicability of requirements** [SEC-220] and [SEC-230] (implementation of **protection measures against RF interference or jammers, spoofing and meaconing**) to the RIMS sub-system. Clarification should address whether these requirements are directly applicable to the receiver or to another potential module within the RIMS.
- To clarify that the **reflective multipath** figures in requirements [PER-270] and [PER-290] can only be achieved by using an **antenna with multipath mitigation techniques**. Requirement [PER-270] is included hereafter for illustration:
  [PER-270] Code phase error due to reflective multipath
  The 1sigma error on code phase measurements due to reflective multipath for all signals in conditions specified in [HYP-020] shall be lower than:

Elevation (degrees)	*5*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*
GPS&GEO L1CA Code Phase Error (m)	*0,11*	*0,09*	*0,07*	*0,06*	*0,05*	*0,05*	*0,05*	*0,04*	*0,04*	*0,04*
GAL E1C Code Phase Error (m)	*0,11*	*0,09*	*0,07*	*0,06*	*0,05*	*0,05*	*0,05*	*0,04*	*0,04*	*0,04*
GPS L2PY Code Phase Error (m)	*0,29*	*0,25*	*0,20*	*0,17*	*0,15*	*0,13*	*0,13*	*0,12*	*0,12*	*0,12*
GPS L2C Code Phase Error (m)	*0,11*	*0,09*	*0,07*	*0,06*	*0,05*	*0,05*	*0,05*	*0,04*	*0,04*	*0,04*
GPS&GEO L5/GAL E5a Code Phase Error (m)	*0,11*	*0,09*	*0,07*	*0,06*	*0,05*	*0,05*	*0,05*	*0,04*	*0,04*	*0,04*

over all possible phase values between desired and undesired signal, and for any multipath delay.

CONCLUSIONS

The outcomes of the project have reported benefits at multiple levels by means of:

- Recommendations to ESA for the consolidation of future EGNOS requirements;
- Recommendations to receiver manufacturers to improve their compliance to future EGNOS requirements;
- A prototype of an advanced multi-constellation and multi-frequency reference station candidate for future industrialization, to be used in local or regional augmentation systems or any system relying on MC/MF GNSS reference stations;
- An improved characterization framework (methodology and tools), which now offers the possibility to assess receivers performance against complex scenarios combining various error sources such as multipath, interfering signals and ionospheric scintillation.

ACKNOWLEDGMENTS

This research was supported by ESA through GSTP 6.2 program. We thank ESA team who provided insight and expertise that greatly assisted the research. We also thank ESA for providing access to ESA Radio navigation Laboratory at ESTEC and the support they provided during the test phase.

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