GNSS Performance Characterization Framework

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Lourdes Tavira(1), **Joan Clua**(1), **Marc Solé**(1), **Rodrigo Romero**(1), **Gonzalo Seco-Granados**(2), **Antonio Tripiana**(2), **Paolo Crosta**(3)

(1)***Indra***
Roc Boronat, 133, 08018 Barcelona, Spain
Email: ltavira@indra.es

(2) ***SPCOMNAV (UAB)***
Escola d'Enginyeria, Camppus UAB – Edifici Q
08193 Bellaterra (Barcelona), Spain
Email: gonzalo.seco@uab.cat

(3)***European Space Agency (ESA)***
Keplerlaan 1, PO Box 299
NL-2200 AG Noordwijk, The Netherlands
Email: paolo.crosta@esa.int

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 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 behaviour 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:

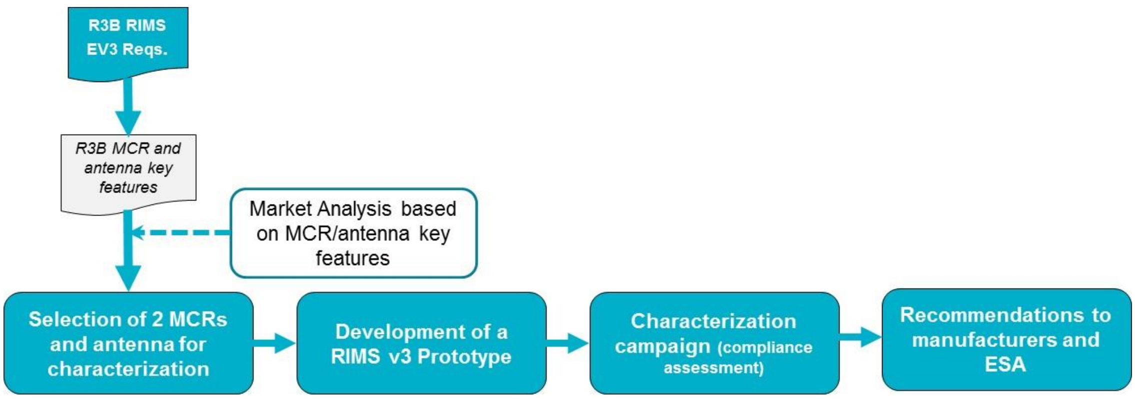


Fig. 1. Project steps

Receivers Key Features

- Signal tracking and navigation message decoding of the following signals:
    - Baseline signals: Galileo E1, E5a, GPS L1CA, L5, SBAS L1/L5, plus L2C and L2P(Y).
    - Expandable signals: 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. 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

Antennas Key Features

- Performance: D/U ratio, phase centre 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.

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 Fig. 2. 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.

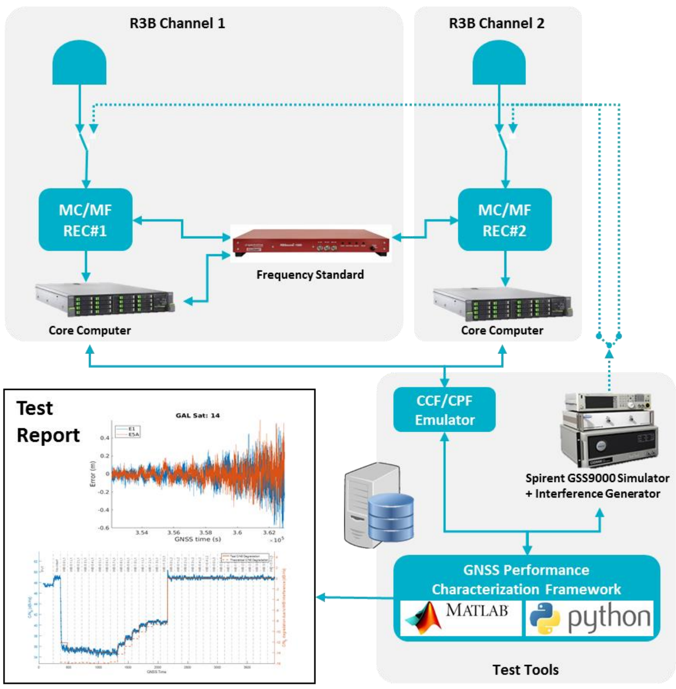


Fig. 2. Advanced GNSS Reference Station for EGNOS v3 prototype with Characterization Framework

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

CHARACTERIZATION CAMPAIGN

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 also developed detailed test procedures that allow an agile and comprehensive testing of the most relevant receiver/antenna parameters. The first step was adapting 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.

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 and carrier phase error** due to ***reflective multipath***, and
- **Code phase error** due to ***diffuse multipath***.

TEST 1: CODE AND CARRIER PHASE ERROR DUE TO *REFLECTIVE MULTIPATH*

Two GPS satellites [L1CA, L2PY, L2C, L5], two Galileo [E1, E5] and one EGNOS[L1 L5] were included in the test. Galileo satellites were in the same orbit as those of GPS in order to simulate both intra-system and inter-system interferences. Additionaly, in Receiver #1, where the multipath mitigation option is available, this option was set to active during all the simulation. Receiver #2 does not include the possibility of applying any multipath mitigation technique.

Two ideal scenarios with a high signal power (noise effect is negligible) were generated: one without multipath and another with one multipath component. The code and carrier phase error for the signals and elevations were measured by comparing the code and carrier phase observable with the one obtained without multipath.

In order to isolate the impact of reflective multipath, no extra sources of noise were added. The signal power was aligned with SIS-ICD power as in [1], [2], and [3] + 10dB (in order to minimize other sources of error such as thermal noise and assess the error due to multipath only).

Reflective multipath depends on the satellite elevation and shall be represented for any multipath delay and any phase shift in the range [0,180°]. In order to do so, a channel of multipath for each visible PRN was manually selected. Each multipath channel Desired-to-Undesired (D/U) power ratio was controlled by a pattern file based on elevation and the delay of the undesired ray was controlled by a random multipath delay from 0 to 30 meters for each elevation and azimuth. Besides, the real antenna pattern was included for L1, L2 and L5 bands to do the simulation more realistic, and the results were computed in elevation windows.

Results: Pass/Fail criteria analysis

The RMS errors on code and carrier phase measurements due to reflective multipath must be below figures given in PER-270/PER-290 requirements. These requirements are included hereafter:

[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.

[PER-290] Carrier phase error due to reflective multipath

The 1sigma error on carrier phase measurements due to reflective multipath for all signals in conditions specified in [HYP-020] shall be lower than:

Elevation (Degrees)	*L1/E1 Carrier Phase Error (mm)*	*L2 Carrier Phase Error (mm)*	*L5/E5 Carrier Phase Error (mm)*
5	*0,50*	*0,60*	*0,60*
10	*0,40*	*0,50*	*0,50*
20	*0,30*	*0,40*	*0,40*
30	*0,30*	*0,30*	*0,30*
40	*0,20*	*0,30*	*0,30*
50	*0,20*	*0,30*	*0,30*
60	*0,20*	*0,30*	*0,30*
70	*0,20*	*0,20*	*0,30*
80	*0,20*	*0,20*	*0,20*
90	*0,20*	*0,20*	*0,20*

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

The conditions specified by the above requirements in [HYP-020] are as follows:
[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°].

Green cells indicate the receiver was compliant with the requirement, whereas yellow cells mean it was not compliant. A grey cell indicates there was no data available to evaluate the requirement at that specific elevation. The estimated code-based pseudorange errors for the two receivers can be seen in Table 1 and Table 2. As depicted in the tables, the receivers are not compliant with ESA's PER-270 requirement for any signal at any elevation.

Table 1. Receiver #1 code errors due to reflective multipath [m].

Elev. / SIS	5	10	20	30	40	50	60	70	80	90
GPS L1CA	3.883	3.126	2.869	2.115	1.954	2.181	1.914	1.724	1.775	0.903
GEO L1CA	No Data	No Data	No Data	No Data	0.311	No Data	No Data	No Data	No Data	No Data
GAL E1c	3.372	3.361	2.468	1.958	2.032	1.988	1.650	1.473	1.616	1.290
GAL E5a	2.272	2.634	1.551	1.633	1.175	1.696	1.122	1.234	1.252	1.200
GPS L5	2.451	2.715	1.756	1.755	1.346	1.482	0.993	1.274	1.201	1.047
GEO L5	No Data	No Data	No Data	No Data	0.176	No Data	No Data	No Data	No Data	No Data
GPS L2C	4.046	3.360	2.881	2.356	2.190	1.982	1.862	1.668	1.627	1.082
GPS L2PY	2.892	3.018	2.330	1.852	1.879	1.519	1.400	1.266	1.329	0.942

Table 2. Receiver #2 (with multipath mitigation active) code errors due to reflective multipath [m].

Elev. / SIS	5	10	20	30	40	50	60	70	80	90
GPS L1CA	1.268	1.017	0.931	0.894	0.803	0.715	0.472	0.418	0.670	0.668
GEO L1CA	No Data	No Data	No Data	No Data	0.560	No Data	No Data	No Data	No Data	No Data
GAL E1c	0.954	0.866	0.783	0.625	0.691	0.493	0.528	0.350	0.355	0.335
GAL E5a	1.223	1.077	0.878	0.630	0.736	0.524	0.649	0.561	0.460	0.505
GPS L5	1.250	0.945	0.831	0.855	0.956	0.803	0.533	0.462	0.569	0.422
GEO L5	No Data	No Data	No Data	No Data	0.173	No Data	No Data	No Data	No Data	No Data
GPS L2C	1.208	1.076	0.937	0.659	0.657	0.657	0.515	0.443	0.552	0.391

GPS L2PY	2.026	2.279	1.935	1.494	1.587	1.504	1.192	1.068	1.187	0.834

The estimated carrier-phase pseudorange errors for Receiver #1 can be seen in Table 3. Results for Receiver #2 are similar and have been omitted. As before, the receivers were not compliant with ESA requirements due to the lack of an advanced antenna with multipath mitigation.

Table 3. Receiver #1 carrier phase errors due to reflective multipath [mm].

SIS \ Elev.	5	10	20	30	40	50	60	70	80	90
GPS L1CA	9.982	10.07	6.838	5.843	6.615	5.193	4.893	4.946	4.644	4.215
GEO L1CA	No Data	No Data	No Data	No Data	1.651	No Data	No Data	No Data	No Data	No Data
GAL E1c	8.941	9.718	6.807	5.854	6.013	5.931	5.023	5.193	5.926	4.496
GAL E5a	8.341	9.181	6.655	5.351	6.078	5.135	4.905	4.292	5.099	3.904
GPS L5	9.325	8.533	6.435	5.425	5.652	5.562	4.944	3.813	4.244	5.081
GEO L5	No Data	No Data	No Data	No Data	1.571	No Data	No Data	No Data	No Data	No Data
GPS L2C	12.43	12.08	8.227	7.432	5.946	9.301	7.463	6.610	5.623	4.747
GPS L2PY	10.757	8.346	6.573	5.901	4.223	6.059	4.344	5.015	4.143	3.841

Results for code and carrier phase error have shown that the receivers under test were not compliant with ESA requirements due to the lack of an advanced antenna with multipath mitigation. This is true even in Receiver #2, where multipath mitigation techniques were applied.

TEST 2: CODE PHASE ERROR DUE TO *DIFFUSE MULTIPATH*

The complete test of code phase error due to diffuse multipath is presented and developed in this section. The test was performed with signals from the three different constellations GPS, Galileo and SBAS including GPS L1CA, L2, L5, GALILEO E1b, E5a and SBAS L1, L5 signals. More precisely, the simulated constellation was as follows:

- 4 GPS satellites used for PVT computation, 2 of them were used to assess the requirements.
- 2 GAL satellites in the same orbits than the 2 GPS satellites used to assess the requirements.
- 1 EGNOS satellite (PRN 120)

Additionally, the following conditions were also simulated:

- All the satellites were set at a high power in order to minimize the error coming from other sources (e.g. noise) different to diffuse multipath, and to be able to measure its contribution.
- Intra-system and inter-system interferences were considered.
- The following multipath effect was introduced, affecting all satellites from start to end of the simulation.
  [HYP-030] Diffuse Multipath
  The diffuse multipath component shall be modelled as the result of 500 point diffractors evenly spread out in a circular area with radius 100 m around the antenna phase centre. Each diffractor, whose distance from the antenna is equal to dr [m], shall be considered as an uncorrelated source of a spherical wave, with a power P equal to:

  $$P = P_{diff} \frac{0.2}{dr^2}$$

  Where P_{diff} is the signal power [Watt] that would be received by the same antenna at the diffractor location.
- In order to derive the impact of multipath effect, the test was repeated in the same configuration but removing multipath effect defined above.

The timeline of the simulation was as follows:

- From 00:00:00 - 00:10:00 the receiver was running to acquire nominal operation, this data was not used for the assessment of the tests results.
- From 00:10:00 – end. Data from two GPS and two GAL satellites were collected. One of the PRN was passing through all elevations 90º to 0º, the other from 50º to 0º (approx.) 1 EGNOS satellite was also present. This is the set of data used to assess the results of the tests.

Results: Pass/Fail criteria analysis

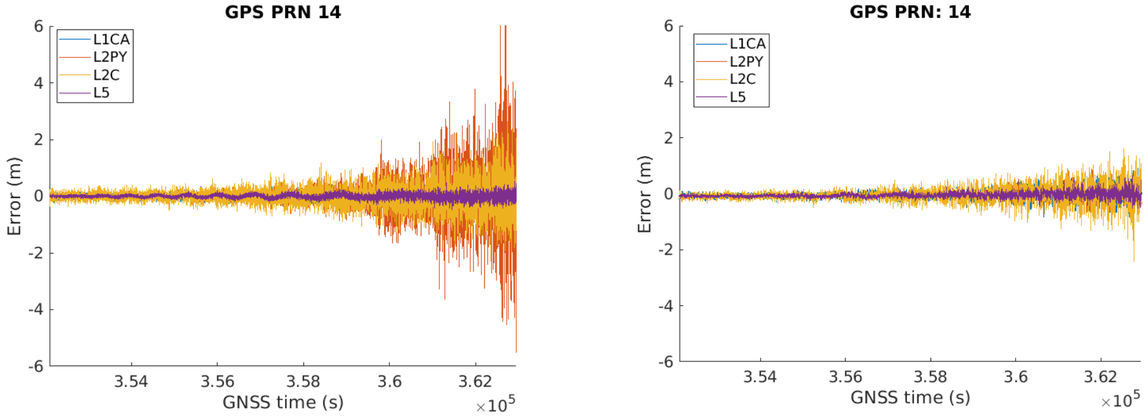
Code phase error due to diffuse multipath must be below figures shown in requirement [PER-280]:

[PER-280] Code phase error due to diffuse multipath

Elevation	*5*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*
Unsmoothed pseudo-range Error 67% [m]	*0.50*	*0.40*	*0.30*	*0.21*	*0.15*	*0.12*	*0.11*	*0.10*	*0.10*	*0.10*

In order to have a reference scenario to compute multipath errors, the first simulation ran with nominal conditions (no multipath effect added) while the second one added the effect of diffuse multipath on top. Galileo satellites were in the same orbit as those of GPS in order to simulate both intra-system and inter-system interferences. Fig3 shows the code errors observed on GPS PRN 14 with the multipath scenario on both receivers.

Test results are included in Table 4 and **Error! Reference source not found.**5. Green cells 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). A grey cell indicates there was not enough data available to evaluate the requirement at that specific elevation.



a. Receiver #1

b. Receiver #2

Fig. 3. Code phase errors due to diffuse multipath on GPS signals

Table 4. Receiver#1 code errors due to diffuse multipath [m].

SIS \ **Elev.**	5	10	20	30	40	50	60	70	80	90
GPS L1CA	0.315	0.315	0.227	0.199	0.109	0.082	0.072	0.056	0.055	0.055
GEO L1CA	No Data	No Data	No Data	No Data	0.338	No Data	No Data	No Data	No Data	No Data
GAL E1c	0.254	0.240	0.218	0.203	0.079	0.057	0.050	0.053	0.037	0.033
GAL E5a	0.148	0.139	0.105	0.073	0.068	0.059	0.070	0.040	0.029	0.026
GPS L5	0.163	0.171	0.125	0.107	0.069	0.058	0.045	0.038	0.028	0.024
GEO L5	No Data	No Data	No Data	No Data	0.257	No Data	No Data	No Data	No Data	No Data
GPS L2C	0.627	0.650	0.463	0.358	0.241	0.179	0.146	0.119	0.111	0.111
GPS L2PY	1.078	1.008	0.528	0.285	0.164	0.103	0.084	0.058	0.048	0.041

Table 5. Receiver#2 code errors due to diffuse multipath [m].

SIS \ **Elev.**	5	10	20	30	40	50	60	70	80	90
GPS L1CA	0.247	0.246	0.181	0.140	0.107	0.116	0.096	0.097	0.096	0.090
GEO L1CA	No Data	No Data	No Data	No Data	0.663	No Data	No Data	No Data	No Data	No Data
GAL E1c	0.199	0.171	0.136	0.105	0.089	0.058	0.049	0.053	0.042	0.040
GAL E5a	0.178	0.173	0.136	0.109	0.085	0.056	0.066	0.038	0.034	0.028
GPS L5	0.157	0.154	0.130	0.101	0.085	0.086	0.092	0.086	0.086	0.083

GEO L5	No Data	No Data	No Data	No Data	0.178	No Data	No Data	No Data	No Data	No Data
GPS L2C	0.455	0.411	0.314	0.247	0.179	0.145	0.121	0.114	0.112	0.105
GPS L2PY	0.323	0.277	0.183	0.154	0.086	0.084	0.083	0.084	0.083	0.078

Both receivers are compliant with the code phase error due to diffuse multipath defined for all signals, expect for GPS L2 where they exceed the minimum required error. It is also observed that Receiver #2 outperforms Receiver #1 in terms of code phase error for all signals. This is due to the fact that Receiver #2 implements multipath mitigation techniques, which were active throughout the simulation.

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 [5], 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:

- It has been pointed to ESA that some requirements were too stringent since none of the two receivers analysed could comply with them. More specifically, it has been stressed the need of **detecting when RIMS site is under a non-nominal scenario** (RFI, multipath, scintillation) as specified in [4], more than designing a receiver that maintains good performance even under those undesired conditions.
- Outcomes from Test 1 included in the paper have been used to indicate to ESA about the need 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**.

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;
- 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.

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