Performance and visibility analysis for different Galileo/GPS receivers with the GRANADA Environment and Navigation Simulator

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ABSTRACT

The Galileo Receiver ANAlysis and Design Application (GRANADA) SW Receiver simulator is one of the reference SW tool for receiver and application developers. It has been developed in the frame of the GAlileo Receiver Development Activities (GARDA) of the European Commission 6th Framework Programme for the Galileo Joint Undertaking (GJU). GRANADA, developed by Deimos Space under Alenia Spazio specification, is composed of two complementary tools: a Bit-True SW Receiver simulation, that recreates in detail the signal processing chain of a Galileo receiver [1], and the GNSS Environment and Navigation Simulator, subject of this paper. This tool, implemented in C-code with an advanced TCL/TK user interface, is being used by application developers who need external access to raw data (i.e. pseudorange and carrier phase), hence acting as a Raw Data Generator (RGD), and to the PVT solution products. It includes realistic characterisation of the effect of the different error components depending on the type of terminal and GNSS receiver configuration. It is possible to configure the GNSS constellation (both Galileo and GPS), the environment conditions, satellites and receiver characteristics, and the navigation algorithms. The simulator runs on a standard Windows PC, allowing the maximum use from people not involved in the development. The simulator architecture is based on GARSIM (Galileo Receiver Simulator), also developed by Deimos and Alenia Spazio, under ESA contract, for the Pre-development of the Galileo Ground Segment Reference Receiver [2].

In this paper, a performance and visibility analysis of different receiver combining Galileo and GPS using the GRANADA simulator are presented. The analysis has been focused on visibility and Dilution of Precision (DOP), which is the key parameter that allows to transfer the User Equivalent Range Error (UERE) into a navigation error. Given a maximum number of channels, the useful satellites of the system are retrieved from all the visible ones, using a selection criterion based on different algorithms: from a simple maximum elevation criterion, to the quasi-DOP optimisation performed in GRANADA as baseline, including a new algorithm ("dartboard" selection) described in this paper. For a particular geometry of the GNSS constellations, different scenarios have been studied, depending on the characteristics of the environment (from open-field, the so-called rural pedestrian environment, to the urban canyon, modelled as a 40º masking angle) and the receiver. The system performances, in terms of visibility, DOP, and navigation reliability have been analysed as a function of the environment and the number of channels. Performances are compared with a Galileo-only and with a GPS-only receiver.

TOOL DESCRIPTION

GRANADA is a SW suite including two complementary tools that allows the user to perform different analyses, or to investigate specific functions and algorithms of the receiver. The two approaches have also different characteristics of modularity, CPU requirements and COTS licenses.

1. Bit-True GNSS SW Receiver Simulator (Matlab/Simulink).

This tool, developed in Matlab/Simulink to provide high modularity, targets receiver experts in the development and analysis of the so-called "Receiver core technologies". It implements a dual-channel receiver (data and pilot channel) of a specific Galileo carrier. The GRANADA bit-true simulator enables analyses and simulations of the receiver critical algorithms and architecture design, such as acquisition and tracking, AltBOC performance, multipath and interference analysis, etc. Auto-coding techniques are used to produce a C code version of the Bit-True GNSS SW Receiver. Once the core technologies design and implementation in Matlab/Simulink is complete, a C-code version of the selected SW receiver configuration is obtained, thus enabling extensive simulations of the chosen receiver architecture.

2. GNSS Environment and Navigation Simulator

A lightened version of the SW receiver, implemented in C-code, is oriented to application developers who only need external access to raw data (i.e. pseudorange and carrier phase). It includes realistic characterisation of the effect of the different error components depending on the type of terminal and GNSS receiver configuration. It is possible to configure the GNSS constellation (both Galileo and GPS, allowing the derivation of the optimal algorithms for a combined PVT solution.), the environmental conditions, satellites and receiver characteristics, and the navigation algorithms. Figure 1 shows the GRANADA Environment and Navigation simulator user interface.

Galileo Receiver ANalysis and Design Application

GRANADA

GALILEO Receiver Analysis and Design Application

ENVIRONMENT AND NAVIGATION SIMULATOR

Version 1.0

Developed by DEIMOS Space as Alenia Spazio subcontractor in the frame of GJU contract LA-GJU-BN-CT-006-04 for GARDA (GALILEO Receiver Development Activities)

Figure 1. GRANADA Environment and Navigation simulator user interface

GRANADA Environment and Navigation Architecture

Figure 2 shows a high-level functionality diagram of the Environment and Navigation simulator, which involves Galileo and GPS constellation, environment generation and overall receiver simulation. The main modules of the tool are:

- *Constellation propagator*: propagation of the position, the velocity, and the ephemeris of both Galileo and GPS constellations have been implemented taking into account keplerian formulation and perturbations due to Earth oblateness effects and gravitational forces of the sun and the moon.
- *User dynamics*: a configurable velocity can be defined in the user interface to simulate non-static receivers.
- *Clock modelling*: the simulator encloses a detailed and realistic model to characterise the timing error of satellites and receivers clocks. It includes different types of random noise characterised by the Allan standard deviation. The timing error is obtained from the relative frequency error, which is randomly generated for each component of the clock noise.
- *Ionosphere and Troposphere delay*: several models to simulate and correct the atmosphere errors are available. For the ionosphere, the simulator implements the IRI and NeQuick models to generate and correct the error, and a Klobuchar-like model to perform the delay correction. The troposphere delay error is simulated with the MSIS model performing the integration of the refractivity, while the correction is implemented with international standard atmosphere values and using refractivity integration or the Saastamoinen-Marini model.
- *Receiver tracking errors*: this module simulates the receiver tracking stage, which causes an error in the pseudorange and carrier-phase measurement due to the code and carrier tracking. GRANADA implements models to simulate all the Galileo services, including the whole BOC modulation receiver types and GPS civil services.
- *Multipath error*: a simple model to simulate the effect of multipath in the receiver has been implemented. A more realistic multipath model is included in the Bit-true simulator.
- *Relativistic Effects and ephemeris error*: the eccentricity of the satellite orbit and the Sagnac effect has been implemented in the simulator.

- *Cycle slips detection and correction*: the initial ambiguity of the carrier-phase measurement remains constant as no loss of the signal lock occurs. This event causes a jump in the instantaneous accumulated phase by an integer number of cycles. Several algorithms to detect and correct this effect have been implemented in GRANADA.
- *PVT computation*: the pseudorange and carrier-phase measurements are used to estimate the receiver position, velocity and clock error. Several algorithms have been implemented in the simulator: Least Squares (LS), the Recursive Least Squares (RLS, equivalent to Kalman filter for fixed users) and Weighed Least Squares (WLS) algorithms. A carrier-phase smoothing algorithm is also included in the simulator. Both single and dual frequency receivers can be selected to perform PVT computation. It is also possible to compute a combined Galileo-GPS navigation solution selecting satellites from either constellation with a DOP maximisation criterion. This paper focuses on the optimisation and analysis of this algorithm.

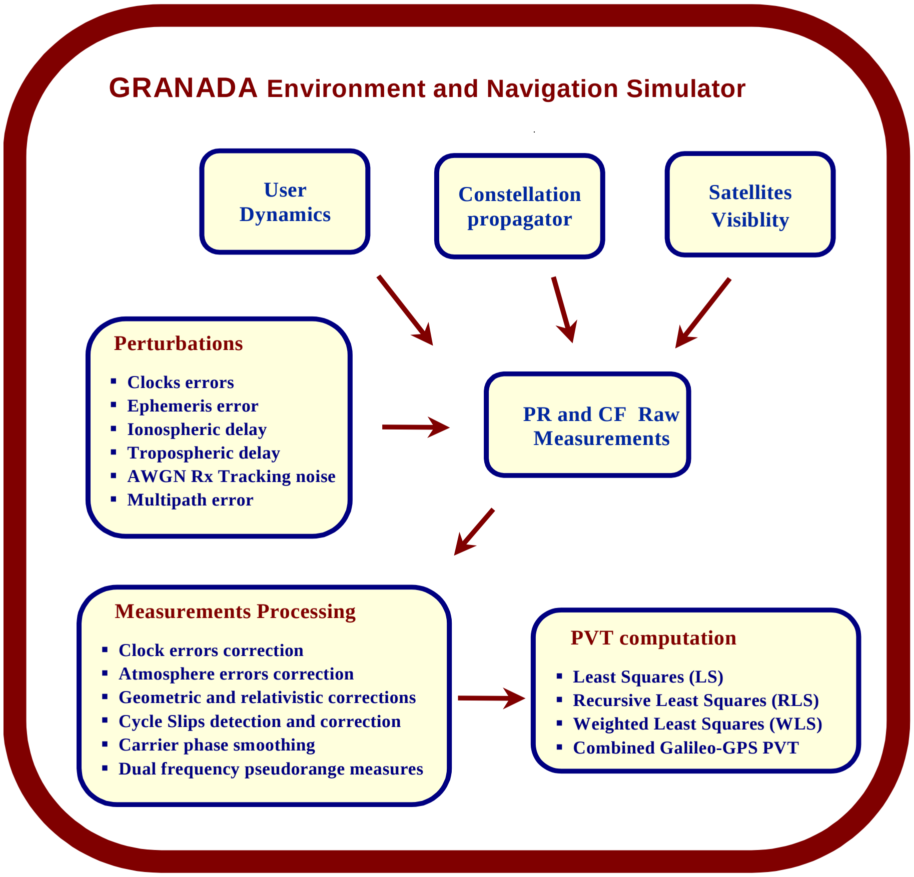

Figure 2. GRANADA Environment and Navigation Simulator high-level functionality

DILUTION OF PRECISION CALCULATION

The concept of dilution of precision (DOP) is the idea that the position error that results from measurements errors depends on the user relative geometry. For comparable measurement errors, a high DOP geometry results in larger errors in the computed location. As it is demonstrated in [3], the dilution of precision parameters D_{ij} are obtained as

$$\left(\mathbf{H}^{\mathbf{T}} \cdot \mathbf{H}\right)^{-1} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & D_{14} \\ D_{21} & D_{22} & D_{23} & D_{24} \\ D_{31} & D_{32} & D_{33} & D_{34} \\ D_{41} & D_{42} & D_{43} & D_{44} \end{bmatrix}.$$

The matrix **H** is obtained as

$$\mathbf{H} = \begin{bmatrix} a_{x1} & a_{x1} & a_{x1} & 1 \\ a_{x2} & a_{x2} & a_{x2} & 1 \\ \cdots & \cdots & \cdots & \cdots \\ a_{xN} & a_{xN} & a_{xN} & 1 \end{bmatrix}, \qquad \begin{aligned} a_{xi} &= \frac{x_i - \hat{x}_R}{\hat{r}_i} \\ a_{yi} &= \frac{y_i - \hat{y}_R}{\hat{r}_i} \\ a_{zi} &= \frac{z_i - \hat{z}_R}{\hat{r}_i} \\ \hat{r}_i &= \sqrt{(x_i - \hat{x}_R)^2 + (y_i - \hat{y}_R)^2 + (z_i - \hat{z}_R)^2} \end{aligned},$$

where the a_{xi}, a_{yi}, and a_{zj} terms denote the direction cosines of the unit vector pointing from the approximate user position to the *i*th satellite, (x_i, y_i, z_i) is the *j*th satellite's position, and ($\hat{x}_R$, $\hat{y}_R$, $\hat{z}_R$) is the estimated receiver position. From the dilution of precision parameters, typical DOP figures are obtained as

$$\text{PDOP} = \sqrt{D_{11} + D_{22} + D_{33}}, \qquad \text{HDOP} = \sqrt{D_{11} + D_{22}},$$
$$\text{VDOP} = \sqrt{D_{33}}, \qquad \text{TDOP} = \sqrt{D_{44}},$$

where PDOP, HDOP, VDOP, and TDOP are the position, horizontal, vertical and time dilution of precisions respectively. Figure 3 shows an example of this outputs obtained with GRANADA. It can be appreciated that DOP decreases when a new satellite is visible and grows if a satellite leaves the visibility area.

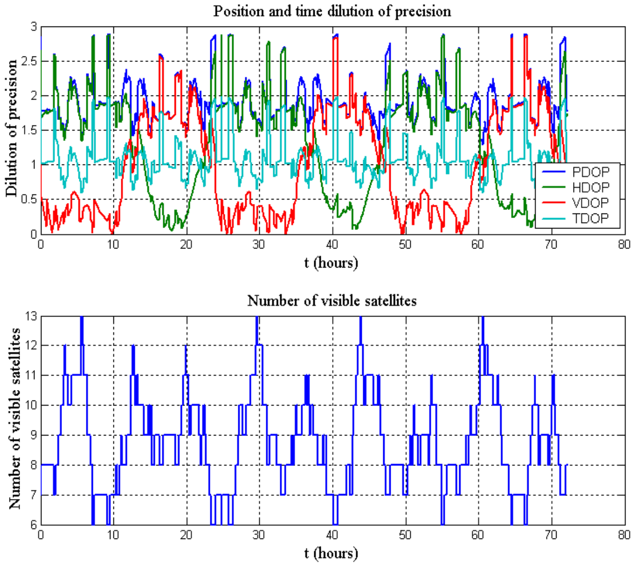

Figure 3. Dilution of Precision and visibility example.

SATELLITE SELECTION AND DOP OTIMISATION

GRANADA baseline algorithm

The simulator allows the inclusion of GPS and Galileo measurements in the same navigation filter, to evaluate the performances of a combined PVT and perform visibility and DOP analysis.

The default algorithm for the combinations of both systems foresees the use for a given number of channels of the satellites with the minimum DOP, independently on the constellation they belong. A full DOP optimisation gives an excessive number of cases and hence an unaffordable computational load. Hence, in order to improve the simulation run-time, a "relative minimum" approach is followed, calculating the DOP values only for some groups of all possible combination. For a given number of channels (N_{CH}, greater than four), not all the combination of visible satellites forming groups of N_{CH} satellites are considered, but only the groups resulting from a search-logic. This logic foresees the choice of N_{CH} indices from the vector of visible satellites. The first three indices (i, j and k) can vary respectively:

- i: from 0 to (N_{VS} - N_{CH})
- j: from (i + 1) to (N_{VS} - N_{CH} + 1)
- k: from (j + 1) to (N_{VS} - N_{CH} + 2)

N_{VS} is the number of visible satellites. All the remaining indices, i.e. (N_{CH} -3) indices, are defined sequentially starting from the (k + 1).

Dartboard DOP algorithm

This simple criterion has been inspired by comparing the GNSS Skyplots to a dartboard. A skyplot is the representation of the satellites azimuth and elevation in a single flat plot. Intuitively, one may think that the optimum geometry is chosen when the satellites are more distributed in the available azimuths and elevation. This idea is the basis of the proposed heuristic criterion. The idea is to divide the skyplot in a number of zones equal to the number of receiver channels. Since we aim to maximise the dispersion in the plot, the objective is to maximise the number of zones involved in the PVT computation. Figure 4 shows the 12 considered zones for a 12 channel receiver. The criterion is:

- Select a satellite from each zone if possible: when more than one satellite is visible in a particular zone, the closest to the zone centre is selected. This is somewhat equivalent to rotate 45º the zones corresponding to the middle elevations.
- If a zone does not contain any satellite, select the closest satellite to the zone.

Maximum elevation algorithm

This algorithm follows a simple criterion based on selecting the satellites with higher elevation.

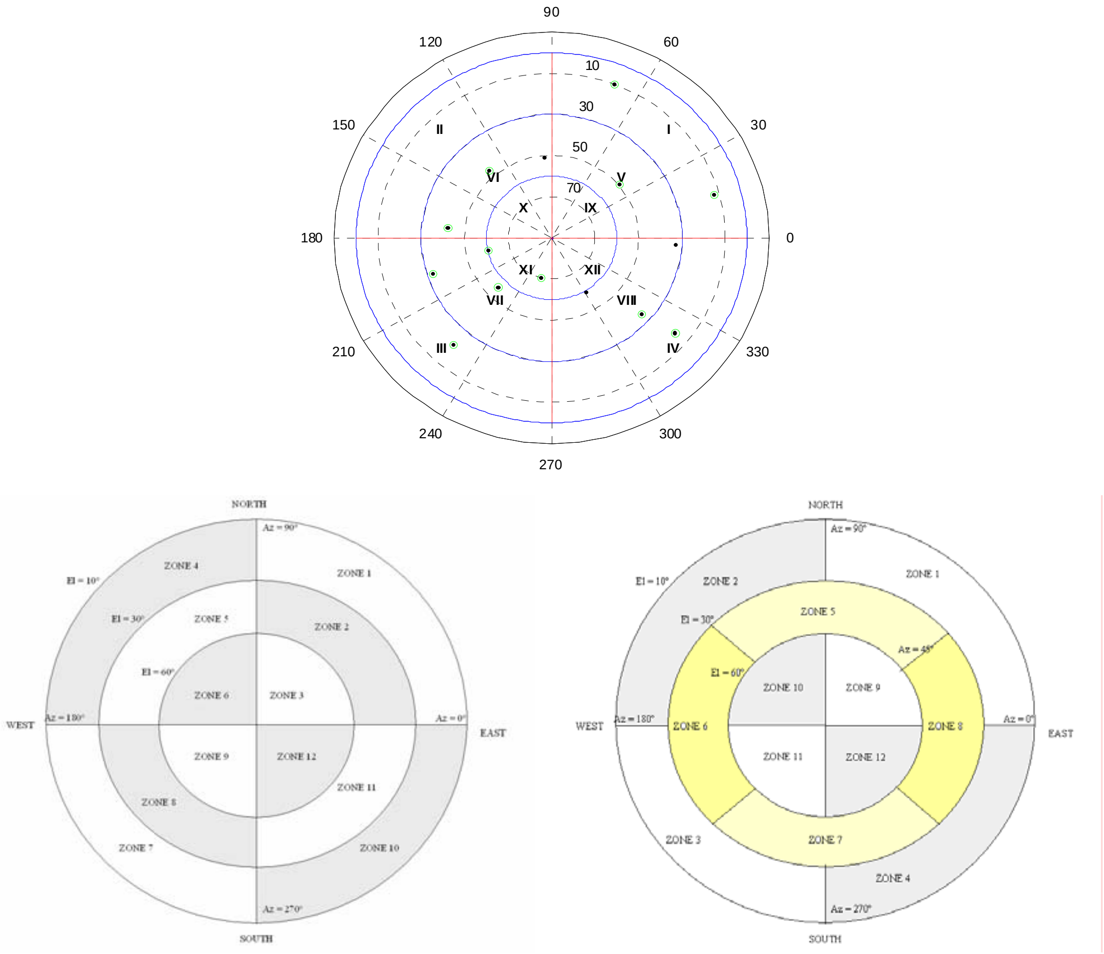

Figure 4. Skyplot defining the 12 considered zones

SIMULATIONS AND ANALYSES

The three above described algorithms have been implemented in the GRANADA Environment and Navigation simulator and a complete simulation campaign has been carried out, for five different locations over the Earth, as shown in Table 1. For each location, a Monte-Carlo simulation was performed for different situations (Table 2):

- A Galileo only receiver with all satellites in view
- A GPS only receiver with all satellites in view
- A combined GPS/Galileo receiver with either 12 channels or an all in view strategy

Two masking angles were applied for each configuration: 10º, corresponding to a clear sky situation, and 40º masking angle, simulating a urban canyon environment.

Table 1. Receiver location

Receiver ID	**Receiver name**	**Region**	**Longitude [deg]**	**Latitude [deg]**	**Height [m]**
R_{X1}	Ushuaia	Tierra del Fuego	-68.300	-54.800	39
R_{X2}	Madrid	Madrid	-3.683	40.400	612
R_{X3}	Adelaide	South Australia	138.600	-34.933	72
R_{X4}	Bethaven	Devonshire	-64.750	32.283	0
R_{X5}	Abacate	Amapa	-50.883	0.317	1

Table 2. Simulation tests

Constellation	**Masking angle**	**Max channel**
Galileo **27 satellites**	10º	All in view
	40º	
GPS **24 satellites**	10º	All in view
	40º	
Galileo and GPS **27+24 satellites**	10º	All in view
		12
	40º	All in view

Table 3 and Table 4 show the obtained results. An example of the results for RX3 is also shown graphically in Figure 5, while Figure 6 provides a histogram plot of the results for each of the satellite selection algorithm for a 10º masking angle. It is noticeable that:

- A Galileo only receiver performs better that a GPS only receiver
- A combined Galileo/GPS only receiver obtains much better results in terms of DOP optimisation than a single system receiver. With any of the three proposed DOP optimisation method, the results for a 12-channel receiver is much better if satellites from both systems are used
- The navigation availability increases dramatically when using a combined receiver. For a urban environment modelled as a 40º masking angle, it is always possible to compute position with a combined receiver, while availability is reduced at x% of the time by using GPS only and y% of the time when using only Galileo.
- The GRANADA default algorithm performs very well.
- The proposed “dartboard” criterion provides even better results, giving a lower mean DOP value (although the maximum DOP is higher than with the GRANADA default algorithm) withough increasing the computational load.
- The maximum elevation algorithm offers worse performances than the other two algorithms.

Table 3. Results for 10º masking angle

Algorithm	**DOP**		
	Minimum	Maximum	Mean
GRANADA baseline algorithm	1.24	2.19	1.54
Dartboard heuristic algorithm	1.28	2.29	1.52
Maximum elevation	1.28	2.21	1.67
Galileo only	1.56	2.96	2.04
GPS only	1.47	4.4	2.31
All in view	1.09	1.96	1.37

Table 4. Results for 40º masking angle

Algorithm	**DOP**			**% Availability**
	Minimum	Maximum	Mean	
Galileo only	3.74	4023	43.91	61.9 %
GPS only	4.45	2944	37.01	24.5%
All in view	2.91	2105	12.39	100%

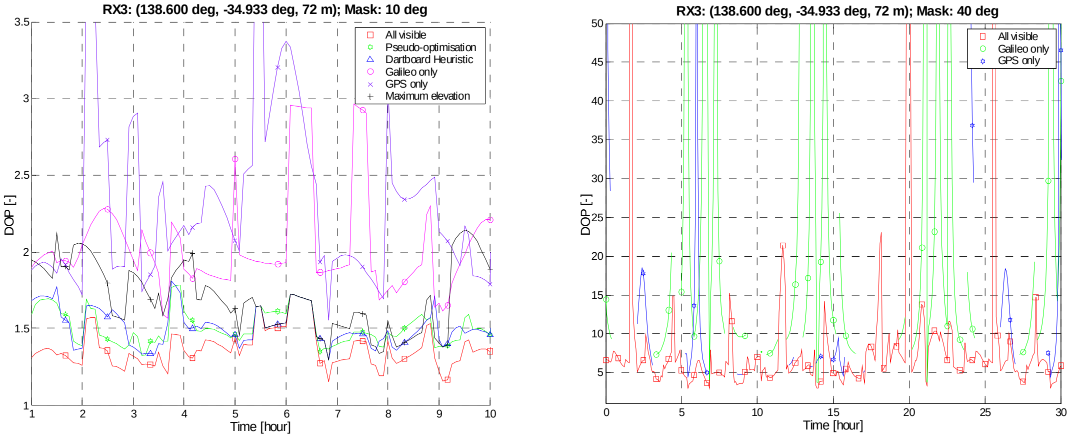

Figure 5. Results examples for R_{X3}

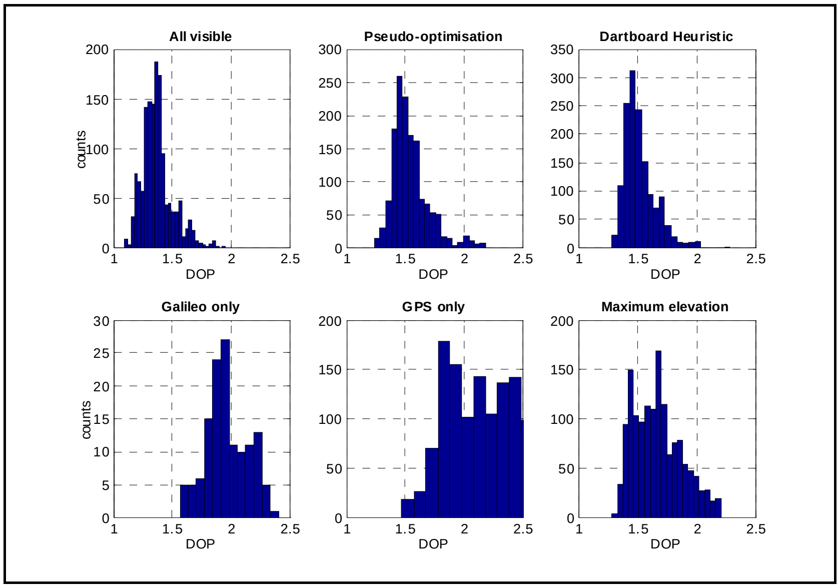

Figure 6. DOP statistics histograms

CONCLUSIONS

GRANADA is the first open tool, running on a commercial PC under Windows, to precisely replicate a GNSS receiver HW and algorithms, integrating both GPS and the new Galileo signals. The Galileo Joint Undertaking is in position to grant licenses to the user community and application developers, proposing GRANADA as a reference SW suite for GNSS receivers and application developers.

After a general introduction on the suite, the GRANADA receiver architecture has been presented. The simulator has been used for assessing DOP and visibility performances for a variety of receiver and situations. Three different satellite selection algorithms have been analysed. Performances of a combined Galileo / GPS receiver have been derived for both a clear sky and a urban canyon-like situation. The benefits of such combined receiver have been demonstrated. Both the GRANADA default satellite selection algorithms and the new proposed dartboard algorithms presents better results than the maximum elevation criterion.

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