Detailed analysis on Giove-B User Equivalent Range Error (UERE)

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Abstract

In satellite navigation system, user positioning accuracy is mainly driven by two factors: the dilution of precision (DOP) and the UERE (User Equivalent Range Error).

The first parameter is computed starting from the satellites positions and it is function of the geometry of the constellation with respect to the user. UERE is instead defined as the root mean square of the sum of the single error contribution not removed by the user that affects pseudorange measurements and it is mainly related to the effect of the propagation on the signals and to the residual system error (navigation message error).

The aim of this paper is to present the results of the experimentation conducted on Giove B signal to assess corresponding User Equivalent Ranging Error obtained as part of an overall Early Experimentation on Giove signals performed in the Navigation and Communication Laboratory (Nav&Com Lab) as risk mitigation activity with respect to Performance Verification of Galileo Final System.

The Navigation and Communication Laboratory (Nav&Com Lab) is the facility developed under the responsibility of the Business Unit Navigation and Integrated Communications of Thales Alenia Space Italy S.p.A and located in the Company premises of Rome.

Its set-up had been started since 2005 in order to undertake the activities at Research & Development level in the field of navigation, starting from the most recent European Space Agency experimental initiatives represented by Giove A/B Project up to Galileo IOV Phase Contract and onward.

As part of Nav&Com Lab facility, in order to evaluate Giove-B UERE, a Septentrio GeNeRx Galileo receiver, driven by an active hydrogen maser atomic clock, has been connected both to a 5.1 m high gain antenna (to obtain multipath free measurements) and to an omnidirectional antenna.

The data collected by the GeNeRx receiver, together with atmospheric parameters collected by a Listem Meteo sensor, have been then post-processed through the UERE Analysis Tool to analyse the overall Giove-B UERE and its components.

BIOGRAPHY

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INTRODUCTION

The UERE Analysis Tool is a software developed in the TAS-I Nav&Com Lab to process GPS and Giove-B raw measurements (pseudorange and navigation messages) in order to estimate the different ranging error contributions that affect navigation signals and to perform corresponding statistical analysis. The software has also the capability to analyze, display and store intermediate data other than final results in order to perform assessment on the obtained results.

Furthermore, in order to estimate each of the UERE components, different techniques has been implemented as part of UERE Analysis Tool to estimate the same parameter, in order to evaluate the results obtained using different models. For example, tropospheric delay can be computed using Hopfield Model (with two different mapping functions), Saastamoinen Model or ESA Blind Model. Outputs of these models can be compared each other to see the benefits whit respect to tropospheric error contribution isolation. The same is done for the ionospheric delay which can be estimated using single frequency models (ie. Kloubuchar), double frequency model and algorithms based on the IGS TEC maps.

In the following a brief recall of main contributors to ranging error is provided to introduce the post-processing implementation adopted as part of Nav&Com Lab UERE Analysis Tool to characterize ranging error and its contributions. Furthermore the results of the experimentation campaign conducted at Nav&Com Lab on Giove-B signals are presented and discussed.

UERE BUDGET CONTRIBUTIONS

Pseudorange measurements can be mathematically modelled as in the following expression:

$$\rho = \rho_{sr} + \rho_{rx} + \rho_{sv} + \rho_{iono} + \rho_{tropo} + \rho_M + \rho_I + \rho_{equip} + n_r$$

where:

- ρ is the pseudorange measurement [m];
- ρ_{sr} is the geometric distance between receiver and transmitter (slant range) [m];
- ρ_{rx} is the receiver clock bias [m];
- ρ_{sv} is the satellite clock bias [m];
- ρ_{iono} is the ionospheric delay [m];
- ρ_{tropo} is the tropospheric delay [m];
- ρ_M is the delay due to multipath [m];
- ρ_I is the error due to interferences [m];
- ρ_{equip} are cable and hardware delay [m];
- n_r is the receiver noise.

Most of these error contributions are compensated at user level by either implementation of corrections broadcasted as part of navigation message (using standard algorithms as implemented at receiver level) or estimated/mitigated at user level. Residual error after compensation at receiver level directly impacts PVT solution accuracy which is usually defined as the product of the UERE and the dilution of precision (DOP):

$$\sigma_{position\_accuracy} = UERE \times DOP$$

The UERE Analysis Tool SW estimates most of the error contributions and removes them from raw pseudorange measurements – as done at receiver level - in order to allow estimation of the residual errors (not mitigated at system or receiver level) coherently with the UERE budget definition.

UERE ANALYSIS TOOL DESCRIPTION

UERE Analysis Tool is a software - developed in MATLAB® - for the analysis of the User Equivalent Range Error of GPS and Giove-B signals. It has been developed in TAS-I Nav&Com Lab in a modular way in order to grant maximum flexibility of its processing capabilities.

Main software functional blocks are depicted in the following diagram (Figure 1):

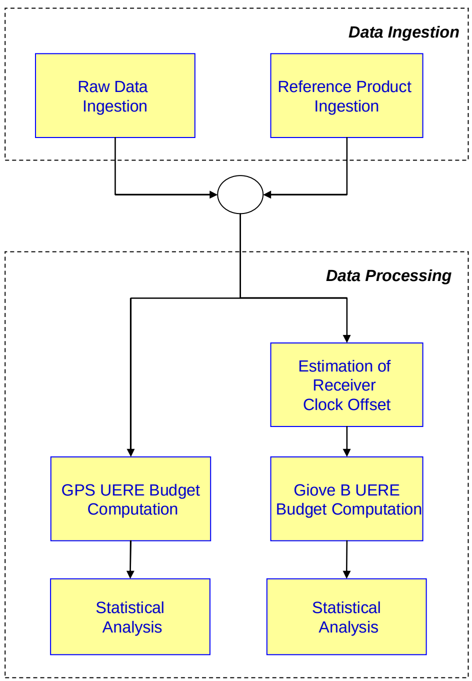

Figure 1 - UERE Analysis Tool functional blocks

Data Ingestion

Data Ingestion modules have been developed to ingest input data and to organize them in internal data structures in order to allow an efficient processing. Two functionalities are implemented:

- Ingestion of raw data collected by GNSS receivers and by the Meteo Station;
- Ingestion of reference products from IGS (International GNSS service) and GPC (Giove Processing Centre) server.

Regarding raw data, the tool is able to import data stored both in standard format files (i.e. RINEX) and in proprietary format files (i.e. Septentrio GeNeRx ASCII files). This allows the processing of data collected with TAS-I Nav&Com Lab equipments as well as data collected by external receivers able to produce standard RINEX files.

Regarding reference products, accurate orbit and clock solutions are needed for both GPS and Giove-B processing. For GPS analysis final orbit and clock products - together with final ionospheric TEC grid used for the analysis of ionospheric delay - are retrieved from IGS ftp server. For Giove-B analysis Restituted Satellite Clock and Restituted Orbit Core Products together with Restituted GGTO files, (needed to align Giove-B system time to GPS system time) are downloaded from GPC ftp server.

Data Processing

The following sections describe each block showed in Figure 1.

UERE Analysis Tool is able to perform UERE analysis, processing both GPS and Giove-B data. Most of the algorithms implemented in the software can be used in both analysis (GPS and Giove-B): for this reason only the Giove-B UERE Analysis is accurately described in the following.

As visible from Figure 1 a first difference between the GPS and Giove B processing is relative to the estimation of the term ρ_{rx} (receiver clock bias).

✓ *Estimation of Receiver Clock Offset*

The receiver clock bias shall be referred to GPS System time in the GPS UERE analysis, while the Giove System Time (GIEN) shall be considered for Giove B UERE analysis. This implies that the term ρ_{rx} shall be estimated in two different ways.

GPS UERE analysis: if the receiver clock bias is not known a-priori (i.e it is not provided by the receiver), it is possible to estimate it from raw measurements. The software implements a reverse PVT solution where P and V are well known because the receiver location is fixed and previously geo-referenced. In this case the estimation of the PVT solution is done using accurate orbit and clocks instead of ephemeris broadcasted by satellite in order to be as much accurate as possible. The estimation of the receiver clock bias can be used to retrieve GPS System Time and start the UERE analysis.

This approach cannot be followed for Giove B UERE analysis because no PVT solution is available using just one satellite. In this case a pre-processing based on GPS measurements is needed. A GPS PVT solution is computed – as previously described - to retrieve the bias between the receiver clock and the GPS system time. Then GGTO values contained in GPC Core Products are used to bring back the GPS system Time to the Giove-B system time (GST). Once the bias between receiver clock and GPS time and the bias between GPS and Giove system time scales are accurately estimated, it is possible to estimate the receiver clock error contribution (with respect to Giove System Time) as the difference between *RX_time-GPS_time* and *GST_time-GPS_time*.

✓ *Giove B UERE Budget Computation*

The data processing flow implemented in the UERE Analysis Tool to obtain Giove B UERE budget results is depicted in Figure 2 and described in the following sections.

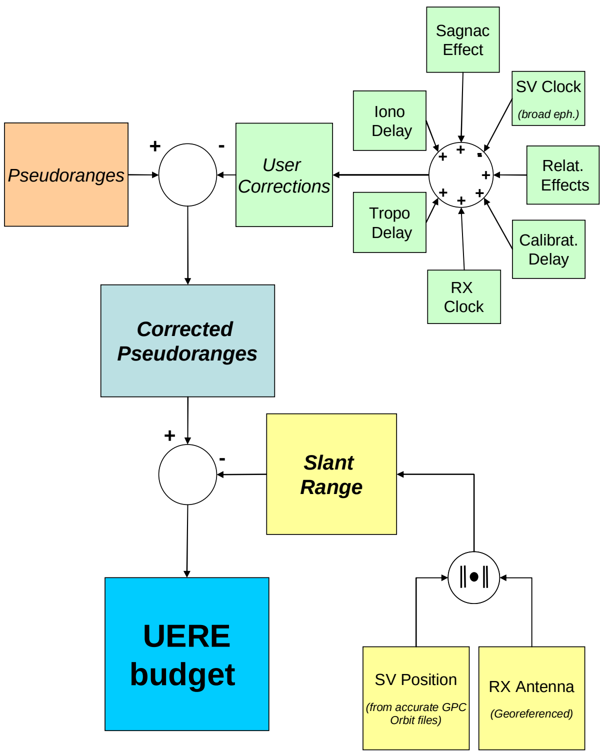

Figure 2 – UERE budget high level diagram

User Correction Computation

The aim of this processing block is the estimation of the error contributions that can be modelled with standard algorithms at receiver level. For certain type of errors (e.g. tropospheric error, ionospheric error), the UERE Analysis Tool implements different algorithms – related to different users typologies - that can be selected during the configuration phase.

Ionospheric Delay

Ionospheric delay is computed by the UERE Analysis Tool according to different models such as NeQuick (currently under testing) and Klobuchard model for single frequency user and dual frequency technique for multi frequency users. Ionospheric delay computed starting from IGS TEC maps are used to compare the difference between user models and accurate reference. Details about implemented models can be found in [4], [6] and [7].

Sagnac Effect

The Sagnac-Effect is estimated by the tool using standard formula in order to compensate Earth rotation effects on the propagation of satellite signals.

SV Clock

SV clock bias is computed by the tool starting from clock correction coefficients broadcasted by Giove-B navigation message according to [2].

Relativistic Effects

Relativistic time correction, needed to compute the overall time correction term, is taken into account by the UERE Analysis Tool according to the following formula [3]:

$$\Delta t_r = F e_s \sqrt{a_s} \sin E$$

where F is a constant, e_s is the eccentricity of satellite orbit, a_s is the semi-major axis of the satellite orbit and E is the eccentric anomaly.

Calibration Delay

Calibration delay (e.g. cable delay) are taken into account in the data processing as a configuration parameter that can be set by the user during configuration phase.

Rx Clock Bias

Rx clock bias is computed, as described before, through the following steps:

- *RX_time-GPS_time* estimation;
- *GST_time-GPS_time* estimation (using GGTO values);
- *RX_time-GST_time* estimation as the difference between *(RX_time-GPS_time)-(GST_time-GPS_time).*

Tropospheric Model

Tropospheric delay is computed by UERE Analysis Tool according to the following models:

- ✓ Hopfield Model with Seeber Mapping function,
- ✓ Hopfield Model with Series Expansion of Integrand,
- ✓ Saastamoinen Model,
- ✓ ESA Blind Model

Each model is able to work with input atmospheric data coming from a Meteo Station or without Meteo data, as done by commercial receivers. Details on implemented models can be found in [5].

Corrected Pseudorange Computation

Once all user corrections have been computed they are subtracted from raw measurements, obtaining corrected pseudorange measurements.

Slant Range Computation

In order to provide final UERE budget values, slant ranges shall be subtracted from corrected pseudorange measurements. To this aim, two solutions are possible: the satellite position can be found starting from the Ephemeris data broadcasted in the navigation message or from the interpolation of the precise orbits solutions. The computation of the satellite position through the ephemeris is based on the algorithm well known in literature and accurately described in [2] and [7], while the estimation through the sp3 orbits solutions is made implementing a 10th Order Lagrange Interpolation algorithm able to calculate the satellite position starting from 15 minutes sampling data (IGS or GPC sp3 files).

UERE Budget Computation

Following the approach described in the previous paragraphs, UERE budget can be modelled using the following expression:

$$UERE = \rho_M + \rho_I + n_r + \varepsilon$$

where ρ_M is the error due to multipath, ρ_I is the error due to interference and ε is the sum of all residual errors still present in the corrected measurements after implementation of user corrections (residual error due to the accuracy of the model itself).

✓ *Statistical Analysis*

Statistical analysis are finally performed on the outputs of UERE Analysis Tool. In particular mean values, standard deviation, root mean square and percentile (68% and 95%) are computed for each UERE error component and for the overall UERE budget.

NAVCOM LAB SET-UP FOR UERE EXPERIMENTATION

Figure 3 shows the test set-up used for the acquisition of the input data needed to perform Giove B UERE analysis as presented in present paper:

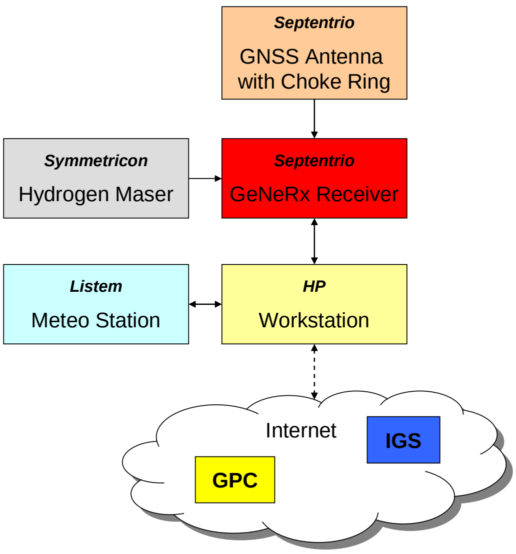

Figure 3 – Giove-B UERE analysis test set-up

A Septentrio GeNeRx receiver, driven by an atomic clock (an active hydrogen maser), has been configured to collect Giove B measurements on L1 and E5 bands. Data collected by GeNeRx receiver, together with environmental parameter collected by the Meteo Station (Pressure, Temperature and Relative Humidity), have been stored on a workstation in hourly files.

The antenna has been geo-referenced using GPS measurements. Its coordinates are:

- Lat = 41° 56' 11.5468'';
- Lon = 12° 36' 34.67494'';
- Alt = 110.7091m.

The variance of the error of the position accuracy obtained in post-processing is 0.0031 m (X coordinates), 0.0029 m (Y coordinate) and 0.0031 m (Z coordinate).

Giove-B signals have been collected during GPS week 1524 for five satellite passages. During this period Giove-B satellite was transmitting the E1, E5a and E5b signals in PHM mode. Following table summarizes the data acquisition time intervals

Pass	Start Time (UTC)	End Time (UTC)	Duration (h)	Max El. (deg)
1	20/03/2009 00:00:00	20/03/2009 09:00:00	8.77	82.4
2	21/03/2009 05:30:00	21/03/2009 14:00:00	7.91	82.2
3	24/03/2009 02:40:00	24/03/2009 12:15:00	9.37	78.2
4	25/03/2009 09:30:00	25/03/2009 16:00:00	6.29	47.3
5	25/03/2009 20:15:00	26/03/2009 03:00:00	6.53	54.5

Table 1 – Giove B passages

The overall number of sample analysed is 173952 samples @1Hz.

Giove B UERE CHARACTERIZATION

This section presents the results of the UERE analysis performed with TAS-I UERE Analysis Tool on Giove-B signals collected at Nav&Com Lab. Aim of this section is to present UERE results related to a dual frequency fixed user (L1-E5b) together with environmental parameter monitored during data collection.

The results presented in the following are obtained processing data acquired from five different passages of the Giove B (as detailed in the previous section) between19th March 2009 and 26th March 2009.

Software Configuration

Through the use of its MMI (depicted in Figure 4) the UERE Analysis Tool has been configured as follow:

- Dual frequency model for the estimation of ionospheric delay;
- ESA Blind Model for the estimation of tropospheric delay;
- SV position computed using navigation message broadcasted by Giove B satellite and stored by GeNeRx receiver;
- Masking angle of 5°;
- Reference orbit & clock from GPC (ESA web site [1]).

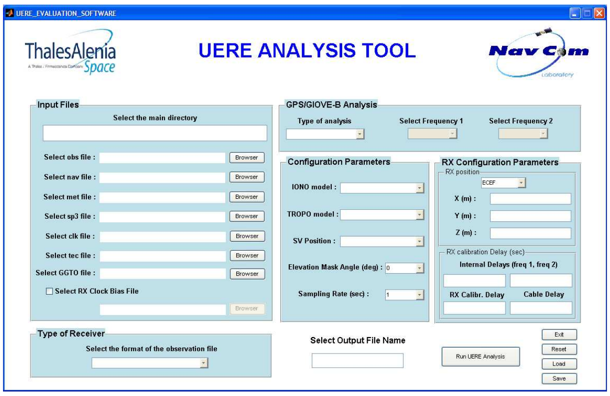

Figure 4 – UERE Analysis Tool MMI

Giove-B UERE Analysis Results

Outputs of UERE Analysis Tool can be grouped into two categories: outputs related to the environment in which the data acquisition is conducted and outputs related to the Giove-B UERE analysis. Both type of outputs have been produced for the considered time periods.

✓ *Environmental Parameters Analysis*

Figure 5 shows an example of the output related to the environment characterization analysis performed by the software. The figure plots the ionospheric delay (double frequency approach and TEC maps) and the tropospheric delay (ESA Blind Model) as function of the elevation angle and the trend of the VTEC during the data acquisition period as function of the time. In the boxes on the bottom of the figure the worst environmental condition related to time period under analysis are summarized: maximum VTEC, maximum ionodelay and maximum zenith tropodelay. The example refers to Giove B passage number 3 (March, the 24th).

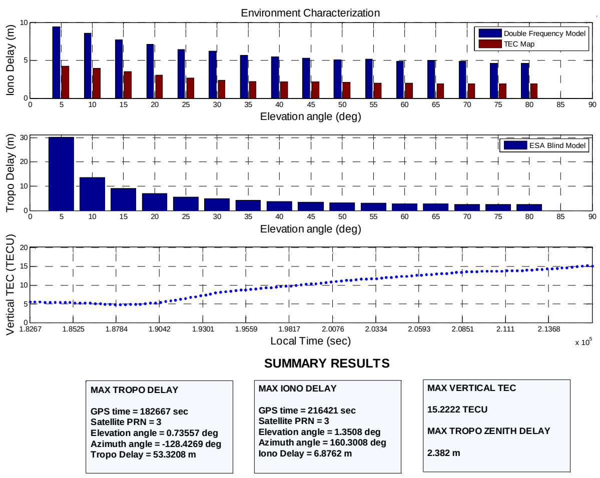

Figure 5– Environment Data (24th March 2009)

Table 2 summarizes the environment characterization (in terms of maximum Vertical TEC and maximum zenith tropospheric delay) related to the five Giove-B passes under analysis.

Pass	Max Zenith Tropo Delay	Max VTEC
	[m]	[TECU]
1	2.4	10.0
2	2.4	14.6
3	2.4	15.2
4	2.3	12.8
5	2.4	7.8

Table 2 – Maximum VTEC and Zenith Tropo Delay Values.

Regarding Giove-B passes under analysis it can be noticed that:

- the maximum observed VTEC value is 15.2 TECU and it is related to March, the 24th;
- the maximum observed zenith tropodelay is 2.4 m;
- the maximum observed ionospheric delay is 6.8762 m and it has been computed on March, the 24th at GPS time 216421 (~12:00 UTC time, 14:00 Local Time);
- the maximum observed tropospheric delay is 54.5395 m and it has been computed on March, the 20th at GPS time 464232 s (~09:00 UTC time). The delay is relative to a satellite elevation angle of 0.26°.

It has to be considered that tropospheric models are not well representative of the real tropodelay for elevation angles lower than 5 degree (see also [5]). For this reason a masking angle of 5 degree is considered for further analysis.

✓ *UERE budget results*

Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10 show the UERE results obtained processing L1 and E5b pseudorange measurements during the five Giove B passes under analysis. Each figure plots the total UERE [m] as function of the time (GPS time scale), the corresponding satellite elevation angle [deg] and some preliminary statistic analysis (maximum ranging error value, 95% percentile, mean and standard deviation per elevation angle).

It has to be noticed that statistics values presented in the following graphics are related to a beam of five degrees around the mean values. This means that statistics related to a generic α angle are computed considering all measurements related to elevation angles included between α-2.5 and α+2.5 degrees.

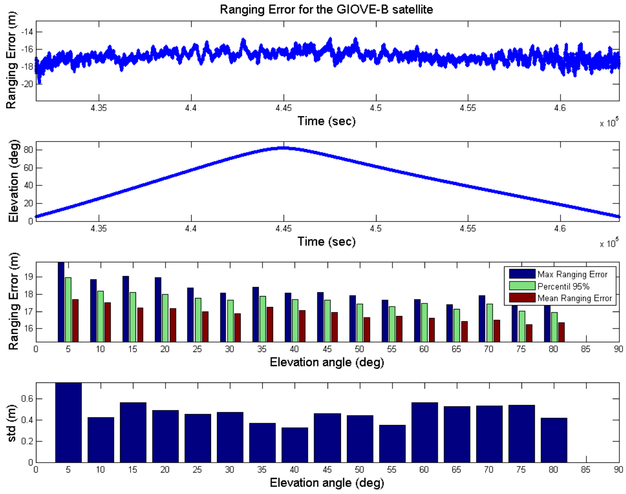

Figure 6 – UERE Analysis on the Giove B pass of 20th March 2009

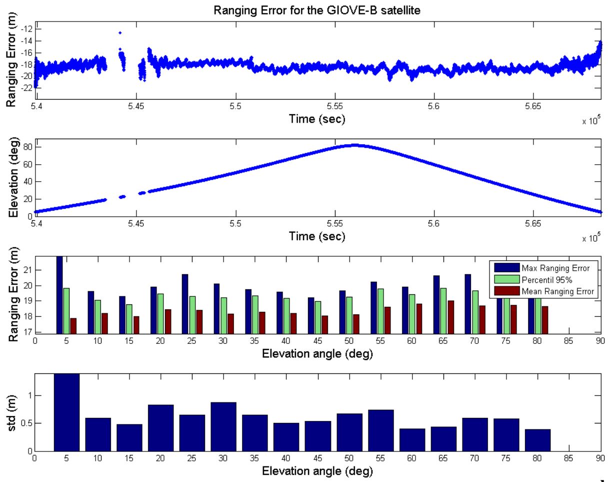

Figure 7 – UERE Analysis on the Giove B pass of 21th March 2009

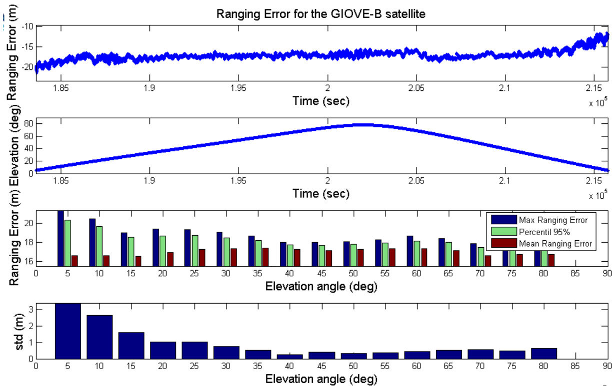

Figure 8 – UERE Analysis on the Giove B pass of 24th March 2009

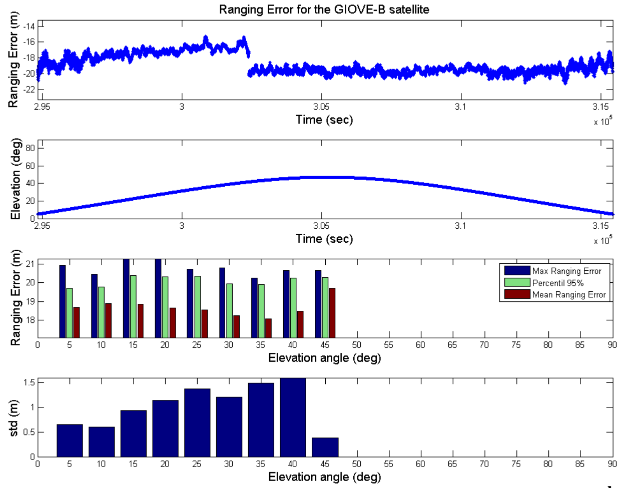

Figure 9 – UERE Analysis on the Giove B pass of 25th March 2009

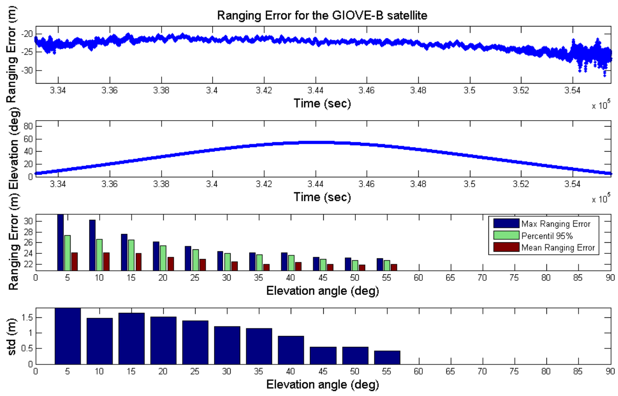

Figure 10 – UERE Analysis on the Giove B pass of 25th – 26th March 2009

The UERE results plotted in the previous figures show a bias of about -17.6 m. This bias has been revealed comparing the ranging errors for the Giove-B passes analyzed, as evidenced in below figure.

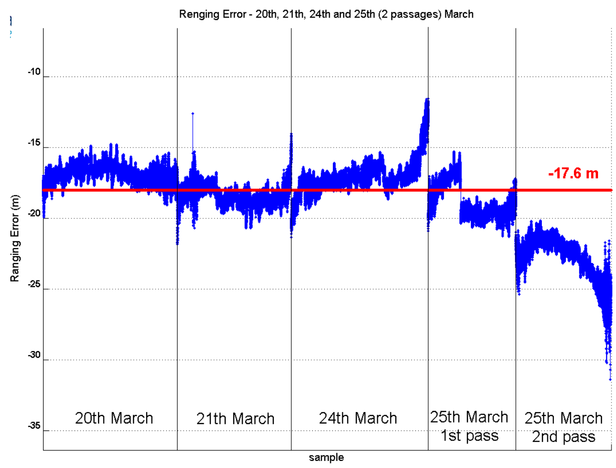

Figure 11 – UERE budget related to overall passes

A fine tuning of the whole receiver chain has then been performed in order to mitigate the detected bias.

In the following figures overall statistics results of the UERE analysis performed on the five Giove-B passes as function of the elevation angle are displayed, as obtained after re-calibration of the receiver chain.

Figure 12 shows maximum ranging error, 95 and 68 percentile per elevation beams computed on the five Giove-B passes under analysis.

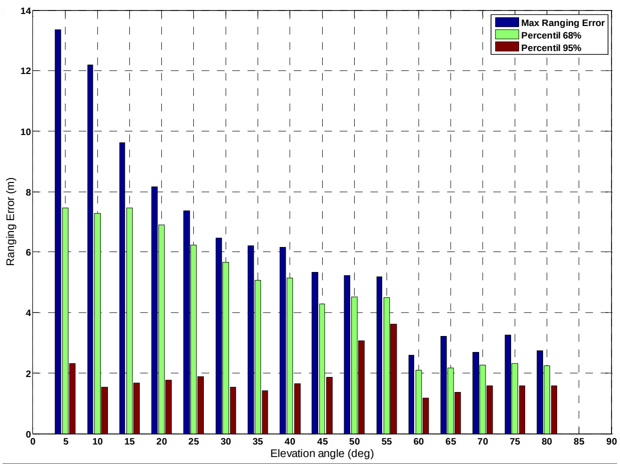

Figure 12 – Maximum, 68% percentile and 95% percentile of the UERE

Figure 13 displays UERE mean values per elevation beams.

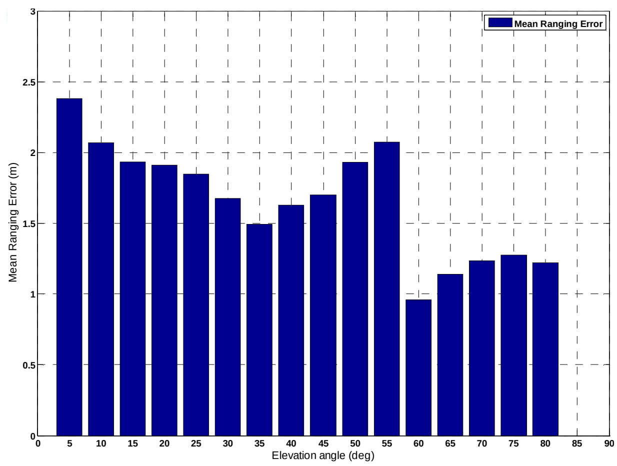

Figure 13 - Mean UERE

Figure 14 displays RMS values while Figure 15 displays standard deviation grouped per elevation beams.

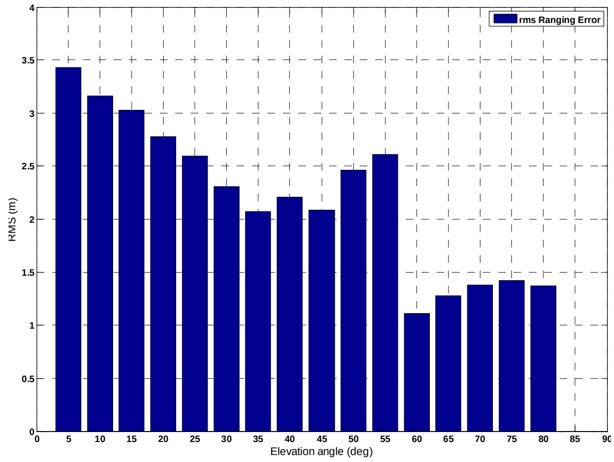

Figure 14– Root Mean Square of the UERE

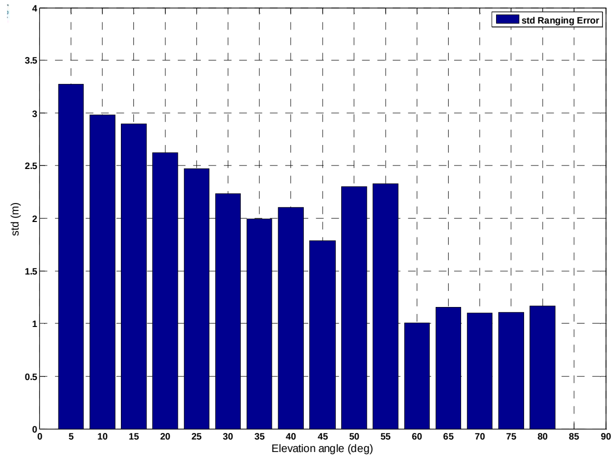

Figure 15– Standard Deviation of the UERE

Figure 13, Figure 14 and Figure 15 show some standard statistics (mean, rms and std) that are usually computed for UERE analysis. In principle it is expected that UERE values decrease for increasing elevation angles but the observed results seems not in line with this statement. In particular there are two aspects that it is possible to highlight: the presence of high UERE values for elevation angles between 47.5° and 57.5° (not in line with a general decreasing trend) and a trend inversion after the 60°.

While the behavior of the UERE results for elevation angles above 60° can be considered as a result of low number of samples (implying a lower accuracy of results, thus less meaningful), the same does not apply to justify the anomalous trend between 47.5° and 57.5° (for which enough samples are available as shown in here below Table).

El	Num sample	El	Num sample
5	5120	50	8448
10	10051	55	8675
15	9857	60	5479
20	8985	65	5523
25	8866	70	5744
30	9433	75	6909
35	9770	80	7470
40	10205	85	0
45	12975	90	0

Table 3 – Available sample per elevation beams.

In order to analyze this anomalous trend, UERE budgets displayed in the previous figures has been grouped.

Figure 11 compares UERE results computed during the five Giove-B passes under analysis. It include also the UERE mean value computed considering all the passes. It is possible to note that the second Giove B pass of 25th of March shows a trend not in line with UERE budgets computed on the previous passes.

Figure 16 displays the absolute values of the UERE values of Figure 11 in function of the satellite elevation angle.

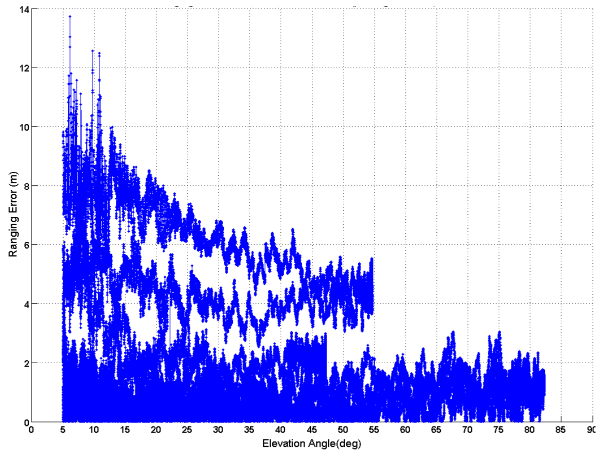

Figure 16 – UERE budget related to overall passes per elevation angle.

In order to understand which is the cause of the anomalous observed behavior, the residual OD&TS error is evaluated as shown in Figure 17. The OD&TS error has been computed comparing the satellite orbit and clock data obtained from the navigation message broadcasted by Giove-B with the reference satellite orbit&clock data retrieved from GPC. Both satellite orbit&clock error contributions have been evaluated independently and then opportunely combined to compute an overall OD&TS contribution. In particular, the contribution due to the orbit error has been projected into the line of sight and then opportunely combined with the satellite clock error.

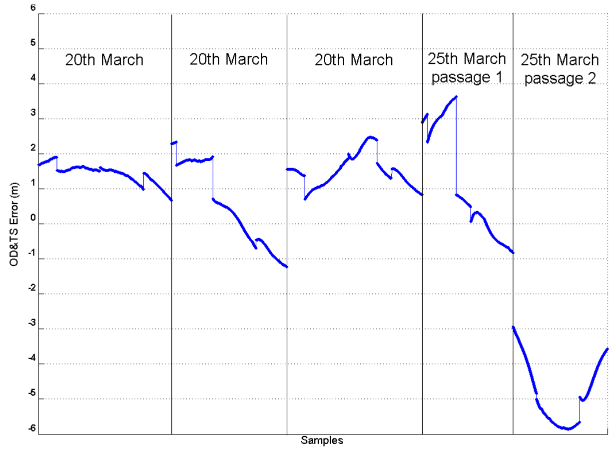

Figure 17 – Residual OD&TS Error

Assuming that reference files downloaded from GPC are not corrupted and that the accuracy of the GPC Orbit&Clock core products is the same per different time intervals, from the figure above it is possible to note a degradation of the accuracy of the ephemeris data received on the 25th March during the 2nd Giove B pass (OD&TS error between -3m and -6m). The residual OD&TS error observed in Figure 17 justifies the (negative) increment of UERE showed in Figure 11. A negative increment of around -4m can be observed in the UERE results obtained during the 2nd satellite pass of 25th March: it is possible conclude that the observed anomalous behavior is due to a degradation of the Giove B navigation message accuracy.

Statistics displayed in the previous figures are detailed in the following tables (sample related to 85 and 90° was not available):

El deg	Num sample	max m	68% m	95% m	mean m	rms m	std m
5	5120	13.40	2.32	7.46	2.37	3.42	3.27
10	10051	12.20	1.54	7.29	2.07	3.16	2.98
15	9857	9.62	1.67	7.45	1.93	3.02	2.89
20	8985	8.16	1.77	6.90	1.91	2.77	2.62
25	8866	7.36	1.88	6.24	1.84	2.59	2.47
30	9433	6.46	1.53	5.67	1.67	2.30	2.23
35	9770	6.22	1.41	5.08	1.49	2.07	1.99
40	10205	6.17	1.65	5.15	1.62	2.21	2.10
45	12975	5.34	1.86	4.29	1.70	2.08	1.79
50	8448	5.23	3.07	4.53	1.93	2.46	2.30
55	8675	5.18	3.61	4.50	2.07	2.61	2.33
60	5479	2.59	1.17	2.10	0.96	1.10	1.01
65	5523	3.21	1.37	2.17	1.13	1.28	1.15
70	5744	2.69	1.57	2.26	1.23	1.37	1.10
75	6909	3.25	1.57	2.32	1.27	1.42	1.10
80	7470	2.74	1.58	2.24	1.22	1.37	1.16

Table 4 - Summary of the UERE per satellite Elevation angle

CONCLUSIONS

The facility developed by TAS-I to support the characterization of GPS and GIOVE-B UERE has been presented in this paper, with focus on the UERE Analysis Tool implementation. The results of the UERE analysis conducted over the selected 5 passes of GIOVE-B satellites are presented and discussed and anomalous behavior detected justified through deeper analysis and investigation.

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