Design and Implementation of a Single-Frequency L1 Multiconstellation GPS/EGNOS/GLONASS SDR Receiver with NIORAIM FDE Integrity

Sabina Viola, Michele Mascolo, Paola Madonna, Luca Sfarzo, *TRS SpA, Fusaro, Italy*
Mauro Leonardi, *Tor Vergata University, Rome, Italy*

BIOGRAPHY

Paola Madonna is a Senior Navigation Engineer in TRS S.p.A., Italy working since 2004. She's been involved in high performance integrity algorithms and in algorithms for the evaluation and prediction of GNSS performances in ATC systems.

Sabina Viola is a Navigation Engineer working since 2008 in TRS S.p.A., Italy. She has been involved in the analysis and development of GBAS integrity algorithms in a program carried out with Selex-SI and Selex-Inc and in the analysis and implementation of the NeQuick algorithm for the Galileo satellite ionospheric correction in the SENECA program.

Michele Mascolo is a Telecommunication Engineer in TRS S.p.A., Italy. He has been working in the satellite navigation field since 2010 and has been involved in the analysis and development of a GBAS prototype in a program carried out with Selex-SI and Selex-Inc.

Luca Sfarzo is the Head of Engineering in Fusaro Office of TRS S.p.A., Italy. He has been working in the satellite navigation field since 2002 and is responsible for the projects developed by TRS in the satellite navigation domain purposes.

Mauro Leonardi. is Assistant Professor at Tor Vergata University in Rome from January 2004. He teaches “Detection and Navigation Systems” and “Radar Systems”, his main research activities are focused on: Air Traffic Control, Advanced Surface Movement Guidance and Control System (ASMGCS); Satellite Navigation, Integrity and Signal Analysis. He is author/co-author of over then 25 papers, two patent and many technical reports.

ABSTRACT

During the last ten years the GNSS scenario has undergone very significant changes since more and more countries have started setting up their navigation systems. GPS and GLONASS are also going through their own phases of modernization with the GPS III programme and the GLONASS M and K programmes introducing CDMA signals in addition to the already existing FDMA ones. Over the next years, Galileo and Beidou/Compass shall become fully operational systems, broadcasting new signals with modern modulations and innovative services. In this ever-changing context, the availability of reliable and flexible receivers is becoming a priority and the use of software receivers instead of commercial hardware receivers is generating widespread interest in the GNSS receiver industry.

The use of a multi-constellation (by now GPS and GLONASS) for PVT computation exhibits several advantages when compared to a GPS only solution. The increased number of satellites improves the constellation geometry, enhances position accuracy and increases the solution availability. The latter is important in situations when part of the sky is blocked by obstructions, so that the signals from several satellites may not be received. In such situations, adding GLONASS constellation to GPS significantly increases the availability, the accuracy and important advantages regarding the Integrity Monitoring can be reached, too.

The scope of the whole work presented in this paper has been the development of a Multi constellation SDR Receiver which had to be easily upgradeable for future GNSS signals exploiting a configurable architecture to use both GPS and GLONASS signals to compute PVT by using EGNOS augmentation system, too. In the next sections the different techniques used for acquisition, tracking and navigation data demodulation of GPS and GLONASS signals due to their different multiplexing

methods will be analyzed. The strategy used to handle different time and spatial reference frames, mandatory to have a real full interoperability, and the way of combining different measurements computed by different constellations are presented.

As known, the common way of computing a combined GPS and GLONASS PVT solution is to solve for two separate solutions and then combining the results (with all the disadvantages in term of availability accuracy and integrity, e.g. the need of at least 4 satellites for each constellation) or, another approach, can be considering a single solution solving the system with five unknowns taking into account the time offset between the GPS and GLONASS time scales.

Here the two navigation systems are referred to a common time (GPStime) and spatial frame (WGS84) computing PVT solution through a weighted least squares technique with only four unknowns. This is possible using the a-priori information concerning the offset between GPS and GLONASS systems time scales broadcast by GLONASS-M satellites.

Integrity monitoring shall take into account of using different constellations simultaneously, too. In this paper a multiconstellation NIORAIM FDE algorithm is proposed and analysed. The experimental results show that the proposed algorithm is able to identify and exclude up to two satellites of the multiconstellation, if affected by a bias, before the position error exceeds the required protection levels.

The last important aspect which is analysed in the paper is the error model of the pseudorange measurements for GLONASS satellites. Combining the measurements coming from different constellations is an efficient strategy only if the weights of the pseudoranges for each satellite are well defined and this is not always possible. In the case of GLONASS measurements it is often difficult to find exhaustive and precise error models; for this reason an ad hoc pseudoranges error model was developed starting from an extensive campaign of real data analysis. The model is then used for accuracy performance improvement (WLSE method) but also to properly weights each of the satellites in the NIORAIM FDE algorithm.

All the proposed algorithms are implemented in a SW prototype using the SDR techniques. Signals demodulation, navigation data extraction, observables estimation, GPS corrections and/or SBAS corrections, and PVT are performed in post processing.

INTRODUCTION

The use of a multiconstellation for PVT computation exhibits several advantages when compared to a single constellation (i.e. GPS only) solution. Adding GLONASS constellation to GPS one increases its availability, may improve its accuracy and brings benefits to the Integrity Monitoring function of a navigation system, too. The main objective of the work has been to develop a flexible multiconstellation Software-Defined Receiver (SDR) which shall be easily upgradeable for future GNSS signals exploiting a fully configurable architecture able to work with GPS and GLONASS systems along with EGNOS augmentation system. In particular , this paper analyzes and shows the different techniques used for acquisition, tracking and navigation data demodulation of GPS, EGNOS and GLONASS signals, the strategy used to manage different time and spatial frames, and how different measurements coming from different navigation systems have been combined. The SDR has been developed by TRS laboratories in collaboration with the RadarLab group of the Tor Vergata University (for the development of the GLONASS error model) in the framework of the GANIMEDE program funded by Regione Lazio, Italy.

GNSS SDR OVERVIEW

From a general standpoint, the idea behind a SDR is to develop the overall functionalities, usually integrated in a hardware commercial receiver, via software in order to minimize the hardware section and so making it flexible and configurable. The only hardware components used are in the RF frontend to digitize the radio frequency signals. Then, a software-based digital signal processing section will be used to process the digitized samples.

The HW section of the proposed SDR is made up by a GNSS antenna and a radio frequency (RF) front-end. The incoming signals, received by the GNSS antenna, are given as input to the RF section where they are filtered and mixed down to an intermediate frequency then the resulting signal is sampled by an analog-to-digital converter. Once the signal is digitized, its samples are given as input to the SW section of the SDR that performs the typical GNSS operations: acquisition, tracking , data extraction, observables determination, PVT computation and, optionally, its integrity evaluation.

There are several techniques to perform the acquisition stage, among them the one implemented in the GANIMEDE SDR is called parallel code phase search acquisition, whose block diagram is shown in

Fig. 1 .

The rough synchronization determined during the acquisition stage is the starting point of the tracking procedure to obtain an accurate synchronization and to keep the lock of the signal by tracking its changing of code phase and carrier frequency over time. The tracking techniques used in the SDR is the classical two blocks: code tracking and carrier tracking block. The first one is implemented as a DLL (Delay Lock Loop), used to refine the estimation of code phase. The DLL used in this SDR is an early-punctual- late tracking loop.

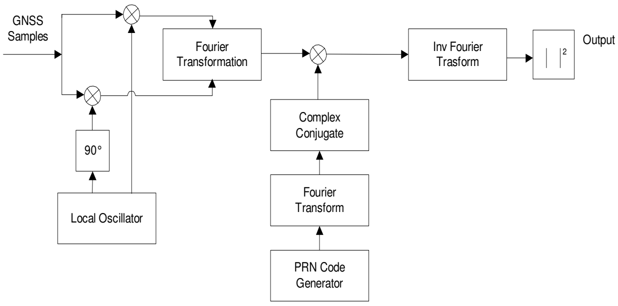

Fig. 1: Block diagram of the parallel code phase search algorithm

The carrier tracking block is implemented as a PLL (Phase Lock Loop) providing a more accurate value of carrier frequency.

After signal tracking is achieved and the local code and carrier wave are synchronized with the ones of the incoming signal, the navigation data samples are extracted wiping off the spreading code and the carrier frequency from the signal.

Finally the PVT exploits the well known weighted least squared method and integrity checks is performed by NIORAIM algorithm.

The hardware platform used in the GANIMEDE SDR to digitize the received GNSS signals, includes:

- Antenna Septentrio PolaNt_MC: high-gain multi-frequency, multi-constellation antenna incorporating a low-noise amplifier. The antenna is able to acquire GPS/GLONASS/GALILEO signals on L-Band
- Splitter TNT PD5020: 2-Way Power Divider, Combiner, Splitter
- Amplifier ZHL-1217MLN: low noise amplifier
- Filter BPF VBF-1575+: low insertion loss bandpass filter
- ADC section: Universal Software Radio Peripheral motherboard model USRP1 equipped with a DBSRX2 receiver daughterboard which covers a wide range of frequencies from 800MHz to 2.4 GHz. Daughterboard turns the USRP motherboard into a complete RF transceiver system. Motherboard and daughterboard combined allow the down-conversion and sampling of the RF input signals with programmable bandwidth, sampling frequency and gain.
- RX Septentrio AsteRx3: multi-frequency GPS/GLONASS/Galileo receiver, used for testing. Its PVT and other intermediate data products has been compared with the ones produced by any GANIMEDE SDR function for verification purposes.
- Personal Computer. Here the SW section of the SDR is deployed.

The hardware platform is shown in Fig. 2.

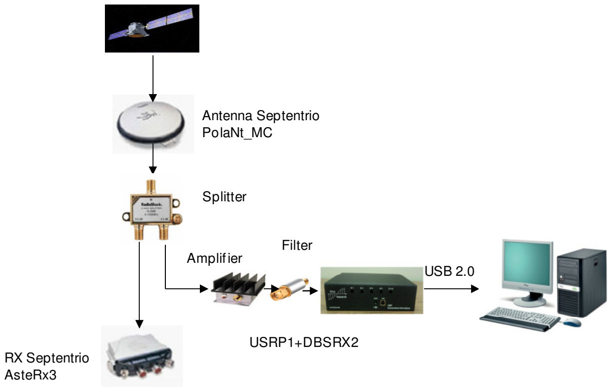

Fig. 2: Ganimede SDR HW Configuration

The output of the RF front-end section is managed by a custom-built SW driver able to interface with the USRP1 and to store the output data stream in binary files. The SW has been developed using the UHD (Universal Hardware Driver) and loads the FPGA image at run time with 2 Digital Down Converters (DDC) and 2 Digital Up Converters (DUC), one per constellation chain, provided by Ettus Research. This driver runs on a Linux OS and manages the communication with USRP1 through a USB 2.0 interface, letting the user setup several parameters of the RF Front End

The USRP1 has been used as a multi-channel receiver by appropriately tuning the DBSRX2 central frequency between the GPS and GLONASS signals and fine-tuning the cordic in each DDC so ending up with two channels of data each of them pinpointed in a different desired frequency. This configuration allows to output the synchronized GPS/SBAS and GLONASS samples, each of them set up as a 32 bits long, 16 bits for the in-phase component and 16 bits for the quadrature component .

Since the maximum data rate transferable across the USB 2.0 is 480 Mbits/s, this sample bit resolution limits the sampling frequency. The sampling rate was set to the maximum usable value which is 4 MSps for channel and so the data rate transferred via USB is 256 Mbits/s.

The GNSS samples acquired by the custom SW driver are stored into two different binary files, one for GPS/SBAS and one for GLONASS, which can then passed to the SW Section of the GANIMEDE SDR for its processing.

That section has been developed in Matlab®. The existing open source Matlab® software receiver, developed by University of Colorado [1] has been used as a baseline for the development and it has been suitable modified to add some new functionalities:

- Concerning the Data Signal Processing section:
    - acquisition and tracking capabilities of SBAS and GLONASS L1 signals;
    - signal quality estimators for GPS, SBAS and GLONASS signals;
    - decode of GLONASS and SBAS navigation data;

- Concerning the PVT section:
  - monoconstellation PVT exploiting either GPS or GLONASS data;
  - multiconstellation PVT exploiting both GPS and GLONASS data;
  - compliance to [5] concerning SBAS augmentation to GPS;
  - integrity monitoring performed by an user selectable RAIM FDE (Receiver Autonomous Integrity Monitoring Fault Detection and Exclusion) algorithm. The algorithm can be either a Weighted RAIM or a NIORAIM algorithm;
  - GNSS signal recording;
  - data presentation via a custom made Graphical User Interface (GUI)
  - PVT data storage using Rinex 3.0 (Receiver Independent Exchange) standard.

Fig. 3 depicts a conceptual block diagram of the SW Section of the GANIMEDE SDR.

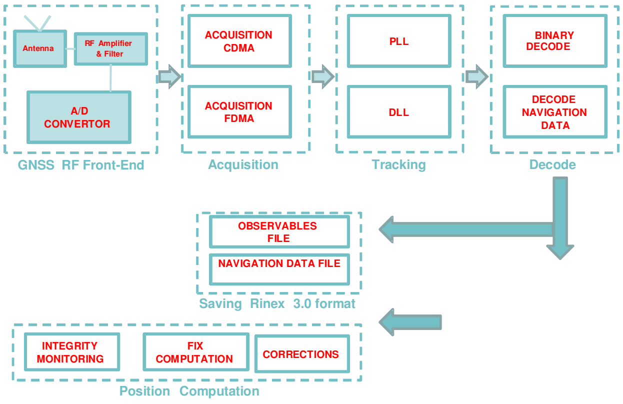

Fig. 3: Block diagram of SW Section of the GANIMEDE SDR

GPS AND GLONASS PVT

In order to compute a multiconstellation PVT further analysis has been required in order to combine the measurements of the two systems which use two different coordinate reference frames and time scales; so a relationship has been established between them for their concurrent use.

As known, GPS and GLONASS systems employ different geocentric Cartesian coordinate frames to express the positions of their satellites (WGS-84 and PZ-90.02, respectively). Both systems are ECEF systems and the two coordinate frames are brought substantially into coincidence by a simple translation of the axis of either system, according to the changes of the reference frame for GLONASS introduced in September 2007 (no more rotation). In this work the WGS-84 reference system has been adopted, so GLONASS satellite positions are converted in WGS-84 through the following equations (in meters):

$$\begin{cases} x_{WGS84} = x_{PZ90.02} - 0.36 \\ y_{WGS84} = y_{PZ90.02} + 0.08 \\ z_{WGS84} = z_{PZ90.02} + 0.18 \end{cases} \tag{1}$$

GPS and GLONASS use their own time scales which are related to different realizations of UTC. GPS time is synchronised to UTC(USNO), while GLONASS time is synchronised to UTC(SU). The relationship between GPS an GLONASS time is:

$$t_{GLONASS} = t_{GPS} - LeapSeconds + 3hours \tag{2}$$

where *LeapSeconds* is the integer number of seconds between GPS time and UTC (at this date in June 2012: 16 seconds).

In order to compute GLONASS satellite positions using the received GLONASS ephemeris datathe GPS time (chosen as reference time for both GPS and GLONASS measurements) shall be converted into the GLONASS time.

So, the steps required to process GPS and GLONASS data can be summarized as follows:

- Reference GPS time is translated into GLONASS time for the GLONASS satellite position calculation;
- GLONASS satellite positions are calculated using the received GLONASS ephemeris data according to the GLONASS Interface Control Document (Edition 5.1) in the PZ-90.02 coordinate system;
- GLONASS satellite positions are converted from the PZ-90.02 coordinate system to the WGS84 coordinate system;
- GPS satellite positions are calculated, according to the GPS Interface Control Document, in WGS-84 coordinate system;
- Finally, GLONASS and GPS measurements are combined to compute the user position

As the receiver clock offset is different for GLONASS and GPS system, this would involve an additional unknown in the positioning equations by raising to five the minimum number of satellites needed to obtain a position solution. In the GANIMEDE SDR a different approach has been used. The two different time scales are synchronized by taking into account the GLONASS time scale correction with respect to the GPS oneSuch a data is broadcast by the GLONASS-M satellites. So the relationship between GPS an GLONASS time becomes:

$$t_{GLONASS} = t_{GPS} - LeapSeconds + 3hours - \tau_{GPS} \tag{3}$$

where τ_{GPS} represents the further time scale correction between the two systems. Such difference is no more 30 ns, according to the Russian ICD. In such a way the user state vector is formed by 4 unknowns and the required minimum number of satellites in view shall not be increased by one increasing redundancy, too.

INTEGRITY: THE NIORAIM ALGORITHM

Those GNSS Navigation Systems whose intended operations require high integrity performances use autonomous functions to perform reliable and independent integrity monitoring. Integrity monitoring at user level is performed through the application of special techniques such as RAIM (Receiver Autonomous Integrity Monitoring). One of the best-known variants of RAIM is the Weighted RAIM[4]: it allows to improve both accuracy and integrity of the position solution using non-uniform weights. Through the assignment of different weights to the measurements of satellites in view, it allows to under-weight the noisiest measurements while over-weighting the contribution of the less noisy ones.

NIORAIM[2][3] (Novel Integrity Optimized Receiver Autonomous Integrity Monitoring) is a weighted RAIM variant which improves RAIM availability by using non-uniform weights applied to the pseudo-range measurements of each satellite involved in the position solution. Each weight is determined ad hoc by an iterative search method.

Such method uses a multidimensional matrix, the look-up table, processed off-line, whose elements are the values of the integrity levels computed following a worst-case philosophy for integrity monitoring. In particular, each element of the look-up matrix corresponds to the largest of the integrity limits computed using a mathematical technique which is repeated for different biases. By numerical integration of the Gaussian density function it is ensured that that the probability within the missed detection region is exactly equal to the specified allowable rate for a given phase of flight.

The authors described a detailed analysis of the algorithm from a statistical point of view and verified its performances by applying it, at the beginning, to a constellation of GPS only satellites under a single fault hypothesis, as shown in previous papers [8], [9]. The experimental results showed a reduction of the computed integrity levels, when compared with the ones computed by other legacy RAIM algorithms, thus improving the integrity availability at the cost of a very slight degradation of accuracy of the position solution.

In addition the good sensitivity of the FDE (Fault Detection and Exclusion) section was also assessed by injecting the bias on the most-difficult-to-detect satellites, in order to simulate a GPS satellite malfunction. The FDE algorithm confirmed its capability to detect an unexpected bias on a satellite before that the position errors could exceed the protection levels or the alert limits for a given phase of flight under all the simulated scenarios ([10]). Then the authors' researches obtained a NIORAIM algorithm able to monitor a dual satellite navigation system (GPS and GLONASS) PVT integrity. So the performance (in terms of integrity and accuracy) of the algorithms has been analyzed to explore if it may meet more demanding flight categories when applied to the air navigation domain.

During these works the problem of handling two simultaneous satellite faults was examined, the integrity fault tree was re-designed and the re-computation of some parameters, such as the missed detection probability, was made as the integrity limits stored in the look-up table are function of this probability, [11].

The look-up table approach, as considered in the single satellite fault hypothesis, was preserved and the whole matrix was only re-computed as the maximum allowable probability of missed detection for the combined GPS and GLONASS multiconstellation was changed, now following a double-worst-case satellite philosophy. The performances of the NIORAIM algorithm, applied to a multiconstellation were analyzed showing the algorithm promptness in detecting double bias on the ranging sources so enabling the PVT algorithm to re-compute an usable position solution before protection levels exceed the alert limits, [12].

The NIORAIM FDE algorithm has been integrated inside the SW Section of the GANIMEDE SDR as an additional functionality that can be enabled through appropriate settings parameters. Together with the NIORAIM algorithm, the Weighted RAIM algorithm was implemented, so letting the final user decide which one or the two algorithms use by varying a simple configuration settings.

THE ERROR MODEL FOR THE GLONASS SIGNAL

As shown before in the algorithms used for RAIM/Integrity it is mandatory to know the error model for the pseudorange measurements. but in the current literature it is very difficult to find error models for the GLONASS navigation system, especially, when the safety of the users must be assured. In the same time a lot of recorded data from receiver stations installed all over the world are available for any kind of analysis, for example using the IGS network [15].

The idea is to use these data to better understand the GLONASS pseudorange error behavior and to create a precise, but simple, model to be used in the proposed GAIMEDE SDR.

This model shall depend on a limited number of parameters and will be used both to perform PVT estimation and its integrity assessment.

The model will return the estimated total error (the sum of all the errors and residual errors) that affect the

GLONASS pseudorange measurements, such as: satellite clock offset, Troposphere error/residual error, Ionosphere error/residual error, satellite position error etc. in function of a limited number of measurable parameters (e.g. elevation angle of the satellite, satellite number, hour of the day, day of the year depending on a measurable parameters).

Otherwise receiver clock error, multipath error and receiver noise error must be excluded from that model because they depend on the particular receiver used and on the particular installation and must be modeled separately considering the specific set-up of the receiver.

To create such a model the data coming from the IGS were elaborated to minimize the unwanted errors and to discover any correlation between the remaining pseudorange error and the simple parameters listed above.

To reduce the noise of the receiver and the multipath effect data coming from station with particular combination of antenna and receiver (e.g. station with choke ring antenna and modern powerful receiver) was selected.

To reduce the receiver clock offset error stations with atomic clock are preferred and a specific algorithm to precisely estimate this offset is used (see below). The sum of the previous error contributions can then be analyzed to understand which are the dominant effects and the dependence from the measurable parameters. Data coming from stations installed at different latitude are selected, in particular data from three IGS station was analyzed: vis0 (Visby, Gotland Sweden), mar6 (Maartsbo, in Sweden), pdel (Ponta Delgada, Azores). The data collected are relative to one year of recording.

The processing algorithm, first of all, precisely estimates the position of the station (with data of 24 hours of observations) then uses this data to estimate the true distance station-satellite and the offset of the receiver. At the end, it computes the residual error for every possible configuration of satellites-receivers (elevation, time of the day, day of the years, etc.). The model used to estimate the troposphere delay and the ionosphere delay are derived from the literature [5], [13], [14], [16] and can be also excluded from the computation to study also the raw case without any corrections from the receiver. The used algorithm is shown in Fig. 4**Errore. L'origine riferimento non è stata trovata.**. **Errore. L'origine riferimento non è stata trovata.**All the computed pseudorange errors are then organized in function of the basic parameters to be analyzed (satellite number, elevation angle, hour of the day, day of the year) to be statistically investigated and to obtain the needed model.

Fig. 5**Errore. L'origine riferimento non è stata trovata.**, for example, shows the measured pseudorange error for the satellite #5 on September 24, 2010: the behavior of the measured pseudorange error clearly shows a satellite (clock drift or satellite position) dependant error, in fact, the error has jumps synchronized with the update intervals of the navigation message. Moreover it is similar for all the station considered.

Not all the satellites experiment this behavior, and the same satellite can be affected or not depending on the time. It seems that it often happens when the satellite are "not monitored" for long period by the GLONASS Ground Segment.

Concerning the other investigated dependences: very small dependence from the day of the year was found and no significant dependence from the hour of the day was found, at least for the pseudorange measurement corrected with troposphere and ionosphere model.

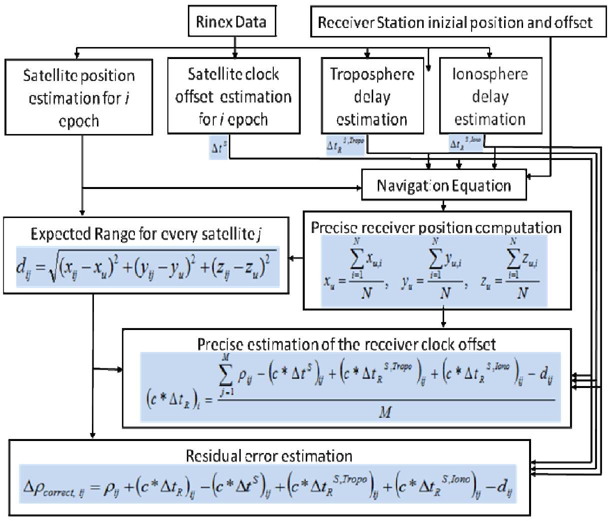

Fig. 4: Processing algorithm to calculate the pseudorange error

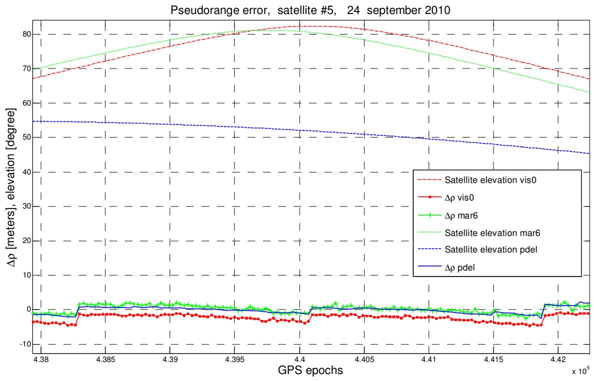

Fig. 5: Pseudorange error for satellite #5, 24 September 2010

Otherwise, as expected, significant correlation with satellite elevation was found when no correction iono and tropo was applied to the measured pseudorange.

In Fig. 6 **Errore. L'origine riferimento non è stata trovata.** the RMS pseudorange error as function of the elevation angle of the satellite is shown for iono-tropo corrected/not corrected data.

Considering the above results and the corresponding statistical analysis showing that the error distribution can be modeled with a Gaussian distribution (Fig. 7**Errore. L'origine riferimento non è stata trovata.**), the GLONASS pseudorange error can be easy modeled by two polynomials that depend only on the elevation angle giving out the mean and the standard deviation of the Gaussian distribution to be used for a specific elevation angle of the satellite.

In case of corrected pseudorange is possible to use two five order polynomial of the type:

$$\xi(\theta) = p_1 * \theta^4 + p_2 * \theta^3 + p_3 * \theta^2 + p_4 * \theta + p_5 \qquad (4)$$

A seven order/ five order polynomials for the mean/ standard deviation respectively can be used for the non corrected pseudorange.

The value of the coefficients calculated on over 2 millions of measurements are reported in Table 1**Errore. L'origine riferimento non è stata trovata.**.

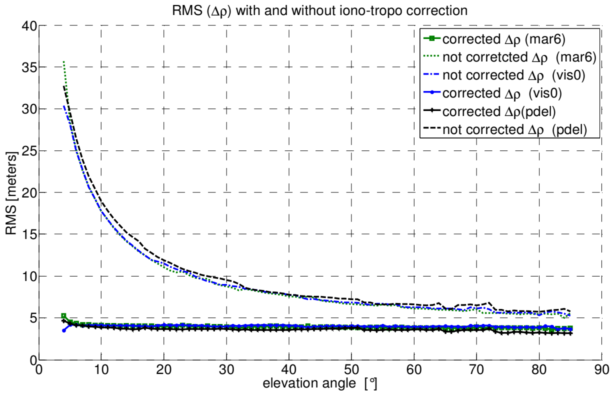

Fig. 6: Measured RMS pseudorange error in function of angle of elevation of the satellite, with or without iono and tropo correction

Table 1: Polinomial Coefficients of the Mean and Standard Deviation of corrected/non corrected pseudorange

Corrected pseudorange	
μ	**Σ**
$p_1 = 9.531*10^{-8}$	$p_1 = 2.666*10^{-8}$
$p_2 = -2.107*10^{-5}$	$p_2 = -8.088*10^{-6}$
$p_3 = 0.001277$	$p_3 = 0.0007628$
$p_4 = -0.0166$	$p_4 = -0.03046$
$p_5 = -0.1278$	$p_5 = 4.308$
Non corrected pseudorange	
μ	**Σ**
$p_1 = 3.405*10^{-9}$	$p_1 = 1.039*10^{-7}$
$p_2 = -1.02*10^{-6}$	$p_2 = -2.513*10^{-5}$
$p_3 = 0.0001223$	$p_3 = 0.002172$
$p_4 = -0.007517$	$p_4 = -0.08373$
$p_5 = 0.2526$	$p_5 = 5.226$
$p_6 = -4.6$	
$p_7 = 45.07$	

It can be noted that iono-tropo corrected pseudorange error is a little bit bigger than the equivalent error in case of GPS measurements (usually smaller than 3 meters after iono and tropo corrections); this behaviour should be due to the fact that GLONASS satellite sometimes may be affected by error related to the navigation data updating as show in Fig. 5**Errore. L'origine riferimento non è stata trovata.**.

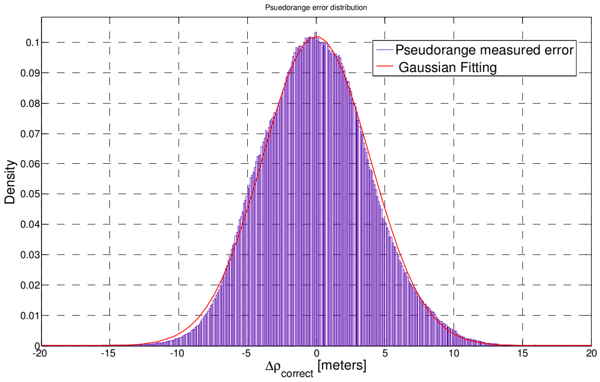

Fig. 7: Pseudorange error distribution in case of iono-tropo -corrected data

RESULTS WITH REAL DATA

The hardware platform was placed on the rooftop of T.R.S. labs for the data campaign acquisition. A set of sampled GNSS signals has been collected. Each element of the set has a quite short time period of acquisition (720 seconds) due to the hugeness of the data to be stored. Data has been processed by the SW Section of the GANIMEDE SDR using with different set up in order to simulate several scenarios and to compare the obtained results. The relevant plots of the analysis conducted on the data processed are shown as follows.

Fig. 8, show an example of tracking results for one GLONASS satellite. The small plot located in the top left corner of the figures shows the in-phase(I)/quadrature(Q) scatter plot. The middle right subplot shows the fluctuation of the magnitude of early, prompt and late correlator outputs and the fact that the prompt correlator energy is above the early and late correlator ones.

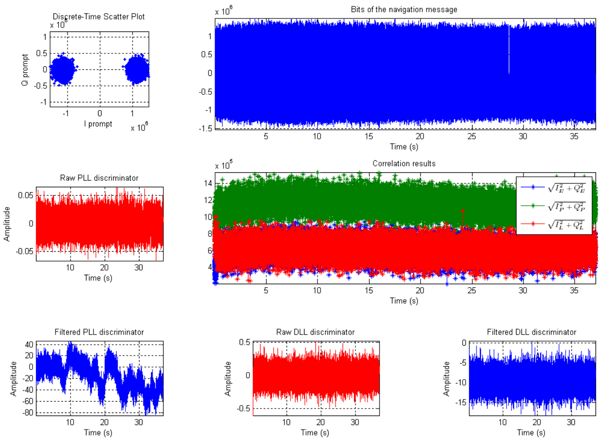

Fig. 8: Example of plotted tracking results for one GLONASS satellite

The tracking function provides also the signal to noise ratio estimation, computed with the SNV (signal to noise variance) method, whose values are shown in Table 2: Signal to noise ratio for GPS and SBAS satellites

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Table 2: Signal to noise ratio for GPS and SBAS satellites

GPS + SBAS Satellite		
Channel	**PRN**	**Average C/N0 (dB)**
1	30	51.61
2	31	53.32
3	29	48.22
4	21	49.83
5	6	47.18
6	25	47.64
7	126	32.11
8	16	29.78
9	120	49.02
GLONASS Satellite		
Channel	**PRN**	**Average C/N0 (dB)**
1	39	58.02
2	37	49.55
3	38	53.95

Concerning PVT some results are shown in the following pictures. The first example concerns a GPS monoconstellation then the some results from the GPS+GLONASS multiconstellation are shown. Finally some results of the NIORAIM performances are described.

Fig. 9 shows position accuracy computed with the GPS mono constellation, eventually SBAS augmented, while a comparison of CEPs, at different sampling frequencies, are shown in Table 3.

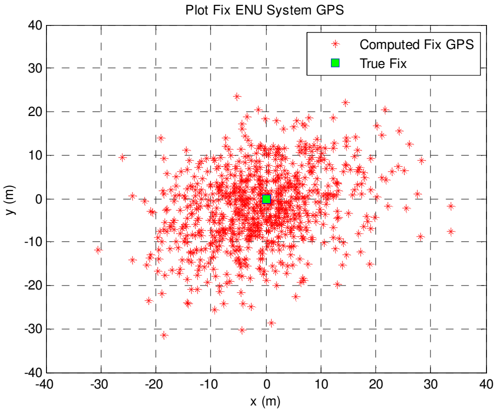

Fig. 9: Fix computed with the Weighted RAIM algorithm applied to a GPS only constellation (sampling frequency 16 MSps)

Table 3: Comparison of the CEP of a GPS only and a GPS + SBAS constellation obtained with different sampling frequency

Satellite Constellation	Sampling Frequency	Algorithm Type	CEP 50 (m)
GPS only	4 MSps	Weighted RAIM	23.63
GPS with EGNOS augmentation	4 MSps	Weighted RAIM	22.65
GPS only	16 MSps	Weighted RAIM	10.55
GPS with EGNOS augmentation	16 MSps	Weighted RAIM	10.12

It is then worth showing results of the CEP values obtained with a GPS only constellation and with a GPS+GLONASS multiconstellation; **Errore. L'origine riferimento non è stata trovata.** lists those values.

Table 4: Comparison of CEP of a GPS only and GPS + GLONASS multiconstellation results

Satellite Constellation	Sampling Frequency	Algorithm Type	CEP 50 (m)
GPS only	4 MSps	Weighted RAIM	28.72
GPS + GLONASS	4 MSps	Weighted RAIM	25.58

Then the CEP of the position solution obtained by exploiting a weighted least square method where the weighting matrix comes by the NIORAIM algorithm is shown for both a mono GPS constellation and a GPS+GLONASS multiconstellation; results are shown in Table **5**.

Table 5: Comparison of CEP between the GPS only and GPS + GLONASS multiconstellation results using NIORAIM

Satellite Constellation	Sampling Frequency	Algorithm Type	CEP 50 (m)
GPS only	4 MSps	NIORAIM	27.98
GPS + GLONASS	4 MSps	NIORAIM	23.22

Concerning the results obtained by the analysis of the NIORAIM FDE algorithms, some additional discussion is here needed. In order to perform a first evaluation of the performances of the implemented NIORAIM FDE algorithm, signals has been acquired on different times of the days and then a two step method has been followed on each of the collected data.

In a first step the data has been processed by the GANIMEDE SDR in order to compute the couple of satellites, among all the ones in view, giving the $slope_{MaxMax}$ ([11], [12]), i.e. the maximum value of $slope_{Max}$. This parameter provides a measure of the difficulty to accurately detect a two-fault in presence of noise: the higher the $slope_{Max}$, the more difficult it is to detect the fault on the pair. For this reason the couple of satellites producing the maximum $slope_{Max}$ was computed and used as input information to evaluate the performances of the NIORAIM FDE algorithm implemented in the GANIMEDE SDR.
In the second step an increasing bias has been applied on the two identified satellites. Data were processed by the GANIMEDE SDR, with the NIORAIM FDE function enabled, and the right exclusion of the failed satellites from the navigation solution was checked.

Fig. 10 show the plot of root of WSSE before and after the exclusion of the biased satellites for one of the data set acquired.

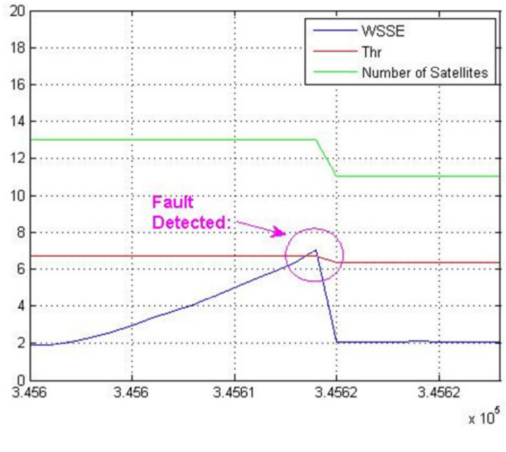

Fig. 10: WSSE and RAIM threshold in presence of bias on a couple of satellites and exclusion is performed

It is possible to note that the increasing bias produces an increase of the WSSE. Starting from a certain detection time the decision variable exceeds the threshold, so the FD function detects a failure and then the FE function excludes the faulty satellites from the position solution, allowing the GNSS monitoring system to continue its normal operations without service interruptions.
Such a behaviour has been exhibited by all the data acquired.

CONCLUSION

Many technical challenges have been described in this work to develop a GNSS SDR able to compute PVT either by combining GPS and GLONASS constellations or GPS augmented by SBAS. A relevant contribution to reach such objective has been the availability of an appropriate noise model to characterize the GLONASS satellites. The GANIMEDE SDR has shown its capabilities in performing integrity monitoring for both mono and multiconstellation mode. The possibility to develop an efficient NIORAIM integrity algorithm which is able to perform both Fault Detection and Exclusion services has been successfully explored with promising results.
The GANIMEDE SDR has shown all its flexibility as allowed the team to manage heterogeneous satellite navigation constellations with a moderate effort, as expected.
The results obtained open to other important achievements as the introduction of the Galileo constellation along with the GLONASS and GPS and the development of a real-time SW Section of the GANIMEDE SDR. At the moment, works are currently under way in TRS for the design and development of a new fully-integrated custom RF-Front End which will be equipped with an high performance ADC section, to fully manage the whole L-Band at the same time and to produce samples at very high resolution.

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