SISE Prediction and Iono/Tropo Corrections in a Local Element Augmentation System

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BIOGRAPHY

Riccardo Di Corato received a Master Degree in Space Engineering from the University of Rome “La Sapienza” in March 2006. He is currently involved in the GALILEA project for GJU and in lunar mission studies for the Italian Space Agency.

Stefano Falzini is a technical manager at Space Engineering. In 1990 he received a diploma in Aeronautical Engineering. His background ranges from Earth Observation mission studies and products to the satellite navigation studies and algorithms definition, passing through mission analysis and AOCS S/W. Recently, in the GNSS field, he has been involved in “Galileo System Test Bed” (GSTB) development activities and GJU research contracts.

Andrea Beccarini received a Master Degree in Electronic Engineering from the University of Rome "Tor Vergata" in January 1997. He is currently involved in the GALILEA project for GJU, and worked for CosmoSkymed Ground Segment.

Alessandro Caporali holds a Master in Physics from the University of Padova in 1975 and a PhD in Physics from the University of Munich in 1979. He currently serves as professor of Solid Earth Physics at the University of Padova, specializing in precision positioning by GPS, and development of specific hardware/software based on GPS/GNSS interferometry.

Carlotta Morini received a Master Degree in Telecommunication Engineering from the University of Padova in June 2005. She is a PhD student in Space Sciences and Technology at CISAS (University of Padova). She is currently involved in the GALILEA project for GJU and in the analysis and dissemination of GNSS data via Internet in real time.

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ABSTRACT

This paper describes principles and algorithms to predict the Signal in Space Error (SISE) in a local scenario, and to compute user position dependent ionospheric and tropospheric corrections. This work has been performed under the GALILEA (Galileo Local Elements Augmentation) project, co-funded by GJU (Galileo Joint Undertaking).

SISE prediction and iono/tropo corrections can be considered as additional features, with respect to the baseline services presently planned for Galileo local elements. We assume an application scenario where a user integrates the Signal in Space (SIS) with data generated locally. The basic concept is to provide, to the users in the proximity of reference stations, additional information to improve both the accuracy and the safety of the navigation. This approach may lead to a Galileo generated business application, in the sense of local providers of integrity data, system performance and differential corrections.

We address here the question on whether the SISE for each satellite in view can be predicted in the near future. The practical relevance of this problem rents on the opportunity for users to be alerted with some time in advance about a change of the integrity flag for each satellite in view. To overcome the lack of globality that could affect the SISE estimation accuracy and that is inherent to an approach based on few local stations, we opted for the use of the IGS orbital and clock high accuracy predictions. The selected data fusion approach consists in correcting the IGS SISE prediction with real-time error measurements (SISE corrections) in order to take in account effects not included in the IGS prediction (e.g. unpredicted failure). SISE corrections are computed applying a recursive digital filter to the pseudorange residuals fitted with an RBTB model and averaged on a number of reference stations located in the local area.

Concerning the ionospheric and tropospheric corrections, algorithms have been developed after a trade-off between different models, taking in account the specific Galileo features and the local architecture. The ionospheric correction module is based on an analytical three-frequency algorithm, which allows the second order terms of the ionospheric error to be taken into account. The tropospheric correction module makes use of local measures of temperature, pressure and humidity collected by a network of meteorological stations; this can be considered as an important additional service for a local user, since the tropospheric effects tend to rapidly change with space and time.

Ionospheric and tropospheric corrections are output in the form of coefficients: in this way, the corrections are dependent on the user position. The coefficients are computed interpolating the iono/tropo delays resulting by the network of local stations.

INTRODUCTION

It is well known that Galileo will provide integrity service at global and regional levels. At global level, the integrity flag information will be disseminated by the GNSS constellation itself, while, at regional level, the auxiliary data will be broadcast by additional geostationary satellites (e.g. EGNOS). The integrity information contained in the Galileo SIS is composed by the following parameters:

- SISA (Signal in Space Accuracy): it is a bound with a certain confidence level of the SISE standard deviation, where SISE is a residual error composed of Satellite Orbit Parameters (Ephemeris) errors and Satellite Clock errors (after application of the clock corrections). SISA will be estimated by the Galileo OSPF (Orbitography and Synchronization Processing Facility), and updated each 100 minutes.
- SISMA (Signal in Space Monitoring Accuracy): this parameter represents the accuracy (in statistical sense) of the SISE estimation.
- IF (Integrity Flag): it is a state parameter which informs about the validity of SISA. In case of system failure, the user has to be alerted within a 6 seconds Time to Alert (TTA).

There exist several applications imposing user requirements which in some cases necessitate an additional (to Galileo) system to be fulfilled. Such user classes include applications in road, aviation, rail (train control) and maritime (harbour navigation). User requirements are generally expressed in terms of accuracy, time to alarm, integrity risk, continuity, availability. For SoL (Safety of Life) users, the SISE prediction in near real time is an essential information to enhance the continuity of the service, whenever the user is involved in critical operations. Further, for open service users, relaying on low cost single frequency terminals, atmospheric corrections, in addition to differential corrections, could provide a significant added value to the standard service.

A local augmentation system aims to provide additional data to users located in the proximity of a set of reference stations. The local concept at the same time limits the number of possible users but enhances the quality of the service to be provided. Hence, the development of a local augmentation system will be economically advantageous in a location characterized by:

- A high concentration of potential users. A city, where the system could serve both private and public transport; a high traffic commercial harbour, where a certain accuracy is needed for maritime docking; a train station.
- The need for a high accuracy and safety service. Civil and military airports.

A number of considerations make the local architecture an attractive option:

- Autonomy with respect to the Global System. It implies that the economic potential of the service will be independent on the Galileo System, but also that the service guarantee associated with the local integrity message is completely responsibility of the local provider.
- No need for a communication link with the Global Facility, reducing complications and costs.
- Better performances respect to a global-based system, due to:
  - A reduced processing time, because all processing is typically carried out at a single site, thereby minimizing any data transmission latency, and there are physically less data to process respect to a global-based system;
  - A high accuracy modelling of ionospheric and tropospheric effects based on the fact that they are very dependent on geographic location and time evolution.

OPERATIONAL SCENARIO

The proposed application for the GALILEA project can be considered as a Galileo Local Element which augments the global Galileo service in a local area. A network of local stations produces observation data with high rate. Data are collected, merged with global (slower) information (e.g. IGS satellite ephemeris) and processed. Outputs are broadcast to local users via radio frequency; they are composed by integrity information, as SISE prediction, and ionospheric-tropospheric correction data.

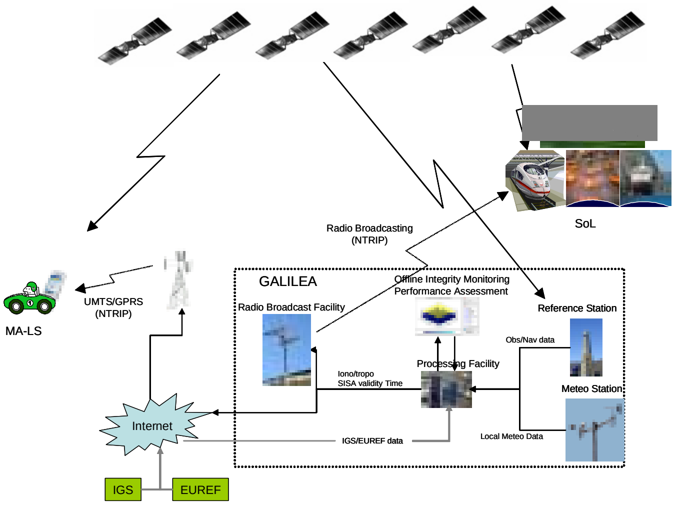

Figure 1: Operational scenario

The following elements constitute the operational scenario represented in Figure 1:

- Reference Stations. Each station has to produce observation and navigation files (in RINEX format) with high rate, and transmit them in real time to the processing facility. The necessity of more than one station is due to the following reasons:
  - The transmitted iono and tropo corrections can be user location dependent only if a grid in space is defined:
  - A SISE prediction can be independent on signal errors relative to a specific station only if a multiple station approach is selected.
- Processing Facility. The facility has to collect data from different sources and elaborate them.
- Offline Integrity Monitoring. The Offline Integrity Monitoring computes the Integrity Risk and/or the User Protection Level in the local service area.
- Meteo Stations. Local meteorological information (pressure, temperature, humidity) can significantly improve the tropospheric modeling accuracy.
- Radio Broadcast Facility. Direct radio transmission to SoL users is accounted to a dedicated broadcast facility, while communication with MA-LS users is performed using the Internet.

The 7 GNSS stations used for the validation campaign belong to the Hungarian Active GPS Network. A set of meteorological stations as closer as possible to the GNSS stations has been selected (see Figure 2).

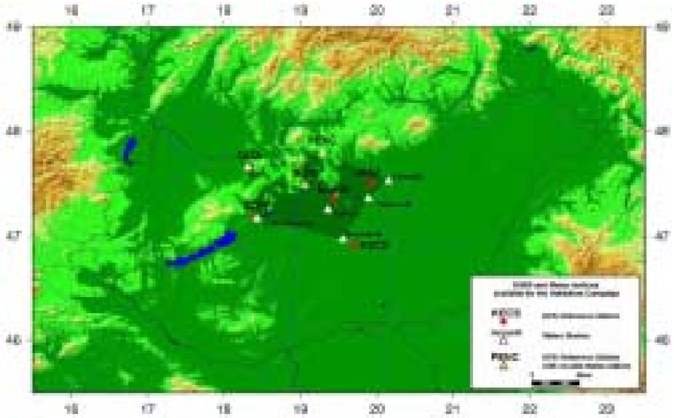

Figure 2: The location of GNSS and meteo stations

The validation campaign is planned and performed in collaboration with BUTE (Budapest University of Technology and Economics). The validation tests are executed both with real (GPS) observation data and with simulated (Galileo) data, using the ESA tool GSSF (Galileo System Simulation Facility). Simulated data allow the software to be tested in presence of a modeled satellite failure.

THE EPCM TOOL

In order to achieve the GALILEA project objectives, Space Engineering and CISAS have developed a software tool called Error Prediction and Correction Module. This tool acquires as input observation and navigation files in RINEX format from a set of GNSS stations, IGS orbital and clock prediction files in sp3 format, meteo files containing local atmospheric values, precise station coordinate files in SINEX format (if available), SISA files (if available).

EPCM outputs are SISE prediction files for each satellite in view and ionospheric/tropospheric correction coefficients to be implemented by the user knowing his position in the operational area.

Figure 3 represents the Error Prediction and Correction Module block scheme. One can observe that the tool is composed by four main submodules:

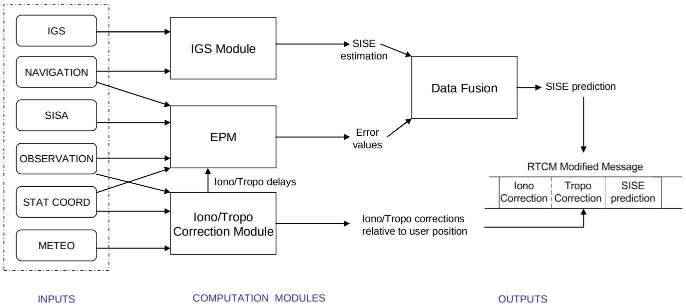

Figure 3: EPCM block scheme

- IGS Module: this module computes the OCE (Orbital and Clock Error) processing IGS predicted orbital files and navigation files.
- Error Prediction Module: this module computes the pseudorange residuals at each time and for each satellite-station combination, fits them with a modified RBTB model and computes the instantaneous error value at satellite level with a multiple station approach. A detailed block scheme of the EPM is represented in Figure 4.

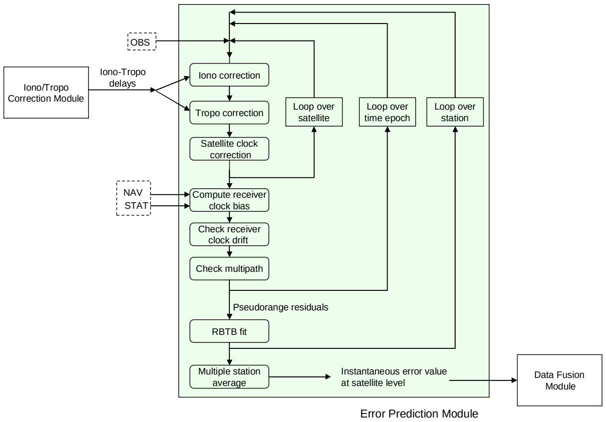

Figure 4: EPM block scheme

- Iono/Tropo Correction Module: this module computes the ionospheric and tropospheric delays at each time epoch and satellite-station combination, interpolates them and outputs the correction coefficients.
- Data Fusion Module: this module merges the outputs of the IGS Module and the EPM in order to compute the SISE prediction.

The EPCM tool has successfully passed the integration tests in December 2006: these tests principally aimed at verifying the main functions of the software. The following sections describe the algorithms and models implemented in the EPCM.

IONOSPHERIC MODEL

The aim is the calibration of the pseudorange for a modellable systematic effect due to the transit of the signal through the charged component of the atmosphere. It computes, for each reference station and satellite, the iono-free pseudoranges and the coefficients to correct the first and second (only if three frequencies are available) order refraction effects, both in the two (GPS) and three (Galileo) frequencies case. Such computation is done for every set of observables contained into the RINEX observation files of each station, whose number is strictly dependent on the sampling time of the RINEX files themselves.

Using a dual/triple frequency technique it's possible to correct the ionospheric refraction effect. We propose two procedures, the first applicable when two frequencies are available (as, for instance, using GPS data) and the second when, on the other hand, the signal is carried out by three frequencies (Galileo data).
Using two frequencies it's possible to remove only the first order ionospheric refraction terms (up to the 99% of the total refractive effect) using their dependence on frequency:

$$d\rho_i = \int_s \frac{a_1}{f_i^2} ds = \frac{A_1}{f_i^2}, \; i=1,2 \qquad \text{Eq. 1}$$

It's possible, then, to eliminate the delays due to the ionosphere from the measured dual-frequency pseudoranges obtaining the well known equation:

$$\rho_{iono-free} = \frac{\rho_{L2} - \gamma\rho_{L1}}{1-\gamma} \qquad \text{Eq. 2}$$

where ρ_{L1} and ρ_{L2} are the pseudorange measured on L1 and L2 channel respectively and $\gamma = \left(\frac{f_{L1}}{f_{L2}}\right)^2$, with f_{L1} = 1575.42 MHz and f_{L2} = 1227.60 MHz.

When three frequencies are available (Galileo real and simulated data) two different approaches are possible. The first is a least square model based on the search of the optimal values of the unknown parameters (A_1 and the ionofree pseudorange) while the second is an analytical approach analogous the one developed for the two frequencies. Thanks to the third frequency it becomes possible to correct also the second order refractive effect achieving a precision better than a centimeter level. We have decided to choose the last approach because it merges optimally the simplicity of the algorithm with a high degree of precision. Eq. 1 becomes so:

$$d\rho_I = \int_s \frac{a_1}{f_I^2} ds + \int_s \frac{a_2}{f_I^3} ds = \frac{A_1}{f_i^2} + \frac{A_2}{f_i^3} \qquad \text{Eq. 3}$$

where f_i (i=1,2,3) represents the generic Galileo frequency. The first order ionospheric refraction removed combinations can be obtained from Eq. 3:

$$d\rho_1 \cdot f_1^2 - d\rho_2 \cdot f_2^2 = \frac{A_2}{f_1} - \frac{A_2}{f_2} = \frac{f_2 - f_1}{f_1 f_2} \cdot A_2 \qquad \text{Eq. 4}$$

$$d\rho_1 \cdot f_1^2 - d\rho_3 \cdot f_3^2 = \frac{A_2}{f_1} - \frac{A_2}{f_3} = \frac{f_3 - f_1}{f_1 f_3} \cdot A_2$$

From these equations it results:

$$A_1 = \frac{\rho_{12} f_1^3 (f_3^3 - f_2^3) - \rho_{23} f_3^3 (f_2^3 - f_1^3)}{f_1^3 (f_2 - f_3) + f_2^3 (f_3 - f_1) + f_3^3 (f_1 - f_2)} \qquad \text{Eq. 5}$$

$$A_2 = -\frac{\rho_{12} f_1^3 f_2 f_3 (f_3^2 - f_2^2) - \rho_{23} f_1 f_2 f_3^3 (f_2^2 - f_1^2)}{f_1^3 (f_2 - f_3) + f_2^3 (f_3 - f_1) + f_3^3 (f_1 - f_2)}$$

where $\rho_{ij} = \rho_i - \rho_j$.

Assuming f_3 equal to zero this equation becomes exactly the expression well known for the two frequencies case.

TROPOSPHERIC MODEL

To evaluate the tropospheric correction it's necessary to compute a model, as accurate and complete as possible, of the troposphere, and its effects on the electromagnetic waves crossing it.

About the 90% of the tropospheric refraction arises from the dry part of the atmosphere and only the 10% from the wet part of it.

The wet and dry refractivity at a specific location can be evaluated using several models. The simplest consists in computing the dry and wet component on the basis of average values. In this work it has been chosen to take into account the data provided by a network of meteorological stations located in proximity of the reference stations (RINEX MET data). The usage of local data represents an additional service for local applications, being the tropospheric effects greatly dependent on the temporal and spatial changes.

After a trade off analysis we have concluded that the model which best suits the requirements addressed in our work, in terms of precision and accuracy, is the Langley and Collins model. It provides a different pattern for the wet and dry part of the atmosphere, going over what was the limit of other models (for instance the Hopfield one), and, at the same time, it doesn't lack in precision for reduced elevation angles (Saastamoinen model).

The Langley and Collins model is based on the classical Davies expression:

$$\Delta t_{tropo} = \left(\frac{-(d_{dry} + d_{wet}) \cdot m(El_i)}{c} \right) \qquad \text{Eq. 6}$$

where $m(El_i)$ is a mapping function depending on the satellite elevation and c the speed of light. The Langley and Collins model rewrites the tropospheric delays of Eq. 6 as:

$$d_{dry} = \left(1 - \frac{\beta H}{T}\right)^{g / R_d \beta} z_{dry} \qquad \text{Eq. 7}$$

$$d_{wet} = \left(1 - \frac{\beta H}{T}\right)^{\frac{(\lambda+1) g}{R_d \beta} - 1} z_{wet} \qquad \text{Eq. 8}$$

where g is the acceleration of gravity, R_d is the gas constant for the dry air, h is the geodetic height of the receiver in meters, T is the temperature in K at the sea level, β is the temperature lapse rate in K/m, λ is the lapse rate of the water vapour, z_{dry} and z_{wet} are the delays due respectively to the dry and wet part of the atmosphere computed in correspondence of the zenith ($E = \pi/2$). At the sea level (h=0) the expressions for the delays become:

$$z_{dry} = \frac{10^{-6} k_1 R_d P}{g_m} \qquad \text{Eq. 9}$$

$$z_{wet} = \frac{10^{-6} k_2 R_d}{g_m (\lambda + 1) - \beta R_d} \cdot \frac{e}{T} \qquad \text{Eq. 10}$$

where k_1 and k_2 are the refractivity constants.

To compute the tropospheric delays for all the elevation angles and not only delays at the zenith, it's necessary to introduce a mapping function. Our aim was to find a model for the mapping function capable to provide good performances being suitable for the majority of the elevation angles, and, at the same time, being as simple as possible according with real time implementations on computation limited receivers. For these reasons, and also in conformity with the model adopted by ESA, we have decided to use the Black and Eisner mapping function:

$$m(El_i) = \frac{1.001}{\sqrt{0.002001 + \sin^2(El_i)}} \qquad \text{Eq. 11}$$

valid for $El_i > 5°$.

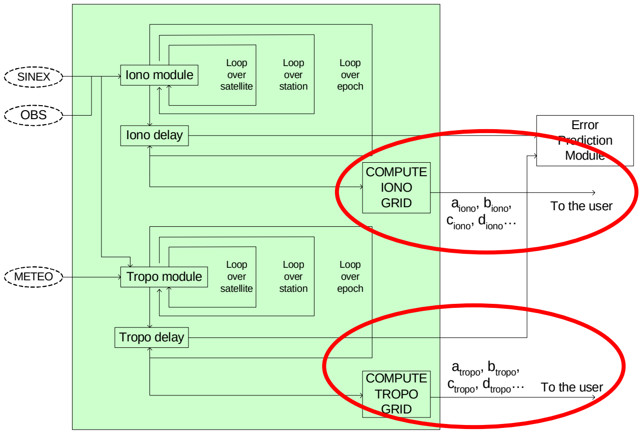

Figure 5: Iono/tropo module block scheme in EPCM

The modules outlined in Figure 5 will be explained in detail further in this paper.

ORBITAL AND CLOCK ERROR

The task of the IGS module is the comparison between IGS ephemeris (contained in sp3 files) and the ephemeris computed from the sets of orbital parameters included in each navigation message. The satellites coordinates, computed from the IGS ephemeris (considered more reliable, from our point of view, than the navigation data) are compared with the ones calculated from the RINEX NAV files in order to estimate the Signal in Space Error due to Orbit and Clock Errors, called OCE. This error, computed as the projection of the difference vector onto the line of sight satellite-station, is the effective magnitude which will be compared with the SISE estimation.

It's possible to visualize the procedure which leads to the computation of OCE in Figure 6.

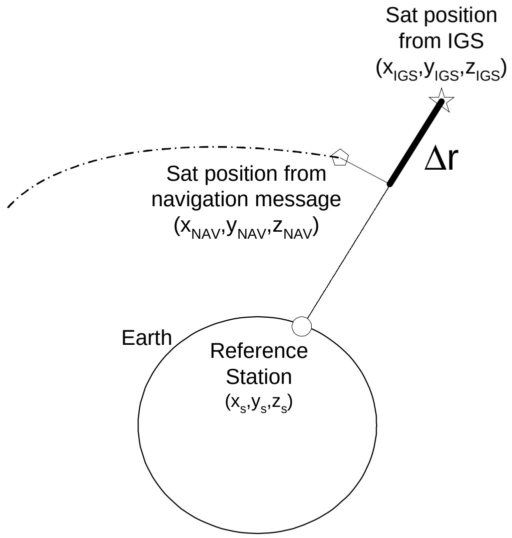

Figure 6: Orbital and Clock Error

Δr is the projection of the vector connecting the two positions of the satellite computed using ephemeris and IGS data respectively. Ideally the absolute value of such vector should be zero, which means that the relative error is zero. Now it's sufficient to add the clock correction, multiplied with the light speed, to Δr, to obtain the OCE value (see Eq. 13).

The first step, so, is to calculate, for a certain instant, the vectors connecting the satellite with the user location for both the determinations, IGS and navigation message ones, and to compute the projection of the vector $\bar{r}(\bar{r}_{IGS} - \bar{r}_{NAV})$ onto $\bar{r}_{IGS}$:

$$\Delta r = r_{IGS} - \frac{\bar{r}_{IGS} \cdot \bar{r}_{NAV}}{r_{IGS}} = r_{IGS} - r_{NAV} \cos\theta \qquad \text{Eq. 12}$$

where θ is the angle between the two vectors r_{NAV} and r_{IGS}. The OCE value results adding to such quantity the time delay due to clock errors multiplied with the light speed:

$$OCE = \left|\Delta r\right| + \left|(\Delta t)_{IGS} - (\Delta t)_{NAV}\right| \cdot c \qquad \text{Eq. 13}$$

IGS ephemerides are available only every 15 minutes, thus the OCE can not be computed for shorter time intervals without introducing an approximation. On the other hand, the SISE computed with the RBTB model presents a sampling time of few seconds. Thus it becomes necessary to interpolate the OCE data, in order to compare the two magnitudes, to achieve an index of the real Signal In Space Error as reliable as possible. After a trade off analysis we have chosen a cubic spline interpolator because it best addresses the requirements of our work.

It's possible to plot the OCE, relative to a window of only one day, in order to analyze the OCE trend (see Figure 7).

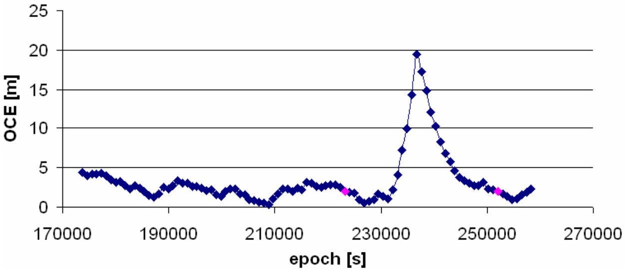

Figure 7: OCE trend for SV 1.

We have verified that the peak in the figure was in fact caused by a lack of valid ephemeris in the navigation files for that specific epoch. The old ephemeris set (first pink dot in Figure 7) was propagated until a new one (second pink dot in the figure) was available causing an increase in the differences between the two set of coordinates, and so higher values of OCE.

RBTB PSEUDORANGE RESIDUALS FIT

The main drawback of a SISE prediction only based on IGS data is that it cannot take in account real time effects on SISE, as a satellite clock failure. On the other hand, pseudorange measurements collected by a set of stations can detect in real time an unexpected drift of the error and provide correction data for the SISE prediction.

Pseudorange residuals are obtained applying the error corrections to the pseudorange measurements and subtracting the satellite-station distance based on the navigation message. Ionospheric and tropospheric errors are acquired from the Iono/Tropo Correction Module, satellite clock bias is calculated using the parameters contained in the navigation message, station clock bias is computed performing a single point solution at each time step. Earth rotation and relativity theory effects are also modeled.

Even after corrections have been applied, pseudorange residuals are still far from showing a regular trend describing the SISE. A residual error due to ionosphere, troposphere and clock remains after the corrections; receiver noise and some components of the multipath error – which typically behave as a random function – cannot be corrected. In order to cancel the random effects on the pseudorange residuals and to identify the correct trend of the error, a least square fit on a specified data interval is necessary. The modified RBTB model has resulted from the model tradeoff analysis to be the best option for the pseudorange residuals least square fit. It allows to cancel the random effects on the pseudorange residuals and to fit rapid error variations thanks to the third equation term time dependence. The modified RBTB model equation has the following form:

$$\Delta\rho = RB + \frac{DRB}{\sin(El)} + TB(t) \qquad \text{Eq. 14}$$

The difference respect to the RBTB model is in the third term, where radial velocity has been substituted with time. This choice is due to some considerations about the SISE behavior: typically, ephemeris and clock errors tend to linearly grow with time since the last navigation message update time. This is due to the fact that orbital parameters and clock correction data contained in the navigation message represent a sort of prediction which becomes more and more inaccurate as time increases. Figure 8 represents the result of a modified RBTB fit applied to a pseudorange residuals interval, where the tropospheric effect is decreasing with time. Pseudorange data have been generated using the ESA simulation tool GRANADA at satellite-station level.

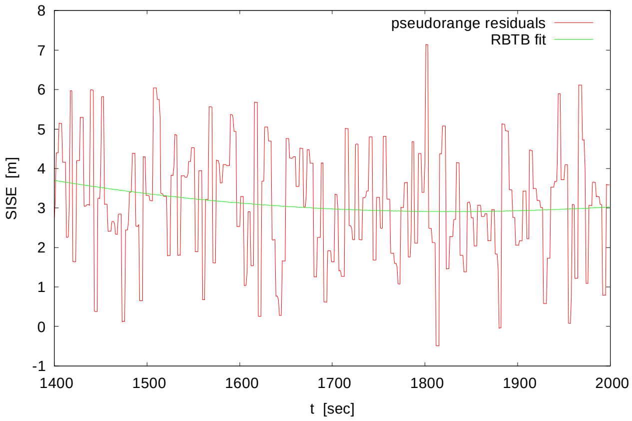

Figure 8: Modified RBTB model fit

Moving the data fit window (600 sec) further with a sample time of 6 seconds, it is possible to reconstruct the instantaneous error trend in a certain time interval (see Figure 9):

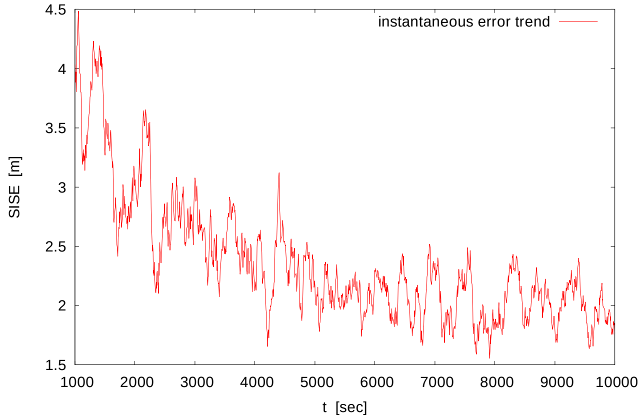

Figure 9: Instantaneous error trend

The effect of the rapid oscillations in the error trend will be attenuated as the error is averaged within a number of reference stations, since this effect does not depend on the satellite error components.

Figure 10 represents the error trend when a satellite failure starting from a certain instant is introduced. The plot shows that the model is able to fit rapid variations of the SISE with a short reaction time.

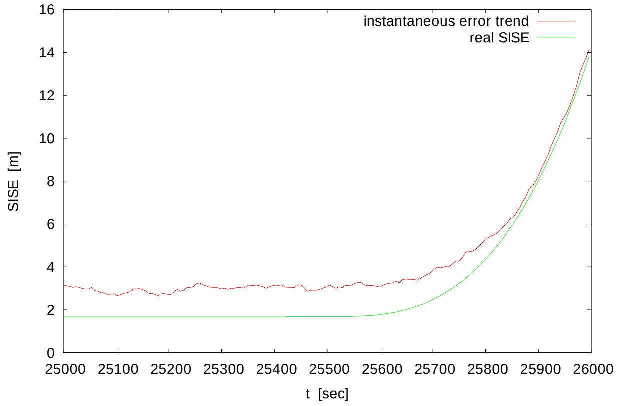

Figure 10: Instantaneous error trend in case of satellite failure

DATA FUSION

The IGS SISE estimation has to be corrected with real-time error measurements (SISE corrections) in order to take in account effects not included in the IGS prediction (e.g. unpredicted failure).

In the instantaneous error trend (see Figure 9), a residual error correlating with the elevation angle variations (due to the tropospheric model uncertainty and to the multipath constant term) is still present. Furthermore, high frequency variations due to the random multipath distribution can be observed. According to this analysis, SISE corrections have to be generated respecting the following conditions:

- Since a SISE correction has to be applied to the IGS SISE estimation, it does not have to take in account SISE variations already described by the IGS estimation.
- High frequency variations of the instantaneous error trend caused by the random multipath distribution have to be reduced.
- Low frequency variations of the instantaneous error trend caused by the elevation angle dependency have to be ignored.

The first task is very easy to perform: the IGS SISE prediction has to be subtracted to the Instantaneous Error Trend. In this way, the remaining error can be considered as a correction to the IGS SISE. The second and third tasks can be performed using a properly designed filter, which generates SISE corrections different by zero only in case the SISE is really varying respect to the IGS module prediction. Between the two conditions, the third has to be considered the most important in the filter design: indeed, high frequency random variations of the error tend to cancel out as the number of reference stations increases.

A recursive (or Infinite Impulse Response) digital filter has been selected in order to perform the high and low pass operation on the signal. Recursive filters use all the previous signal samples to generate the filtered signal at the present time. They show a very good behaviour in the time domain and are easy to implement. High performances in the frequency domain are not necessary for this application: therefore, a single pole recursive filter has been selected.

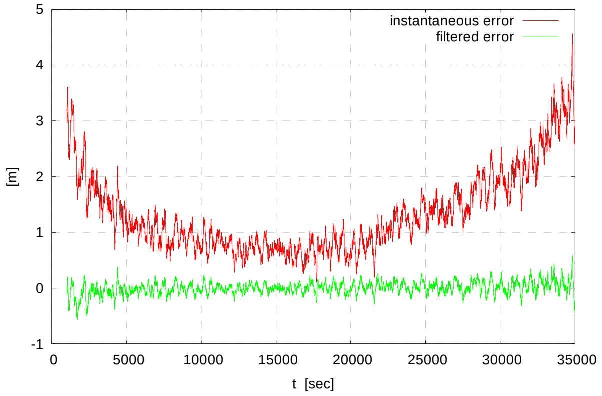

Figure 11: Filtered error trend

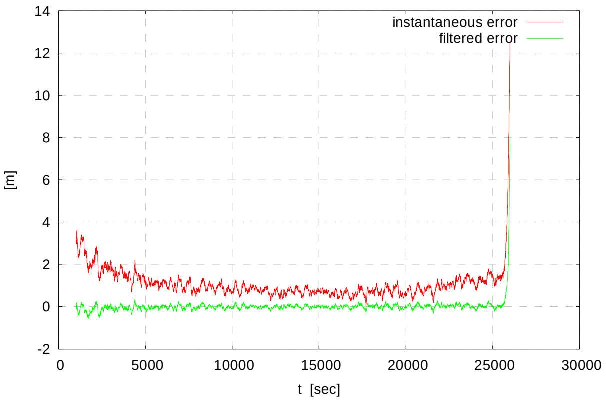

Figure 12: Filtered error trend in presence of a satellite failure

Figure 11 shows the filter output, considering an error trend generated by a single station. High frequency variations can be further attenuated decreasing the low pass cutoff frequency: however, this will also introduce attenuation when real SISE variations occur. Figure 12 shows the same error trend when a satellite failure – here modeled as a cubic function – occurs. The filtered error trend shows the following features, which make it suitable to constitute a SISE correction term:

- Its value is around zero when no unpredicted SISE variations occur.
- It rapidly increases when unpredicted SISE variations occur.

In order to compute the SISE correction value at the present time and to predict its trend, a second order polynomial fit has to be applied to a specified time interval of the filtered error. When no unexpected SISE variation occurs, the correction term will be close to zero, thus the SISE prediction will be close to the IGS prediction. A long fit time interval will increase the prediction accuracy, but will also make it slower to predict fast SISE variations due to a satellite failure.

IONO/TROPO COEFFICIENTS COMPUTATION

As said above, the working area is characterized by seven Hungarian reference stations: BUTE, TATA, SZVF, MONO, PENC, JASZ and KECS which coordinates are provided by SINEX files. The basic idea is to interpolate, with a surface, the values of the ionospheric (tropospheric) delays obtained from such reference stations, for each satellite and epoch. The geodetic coordinates of the stations are projected onto a plane after computing the barycenter of the stations network. The new reference system, centered onto the network barycenter, is given by the following expression:

$$n_i = (\varphi_i - \varphi_0) R_E \qquad \text{Eq. 15}$$
$$e_i = (\lambda_i - \lambda_0) R_E \cos(\varphi_0)$$

where φ_0 and λ_0 are the coordinates of the barycentre, φ_i and λ_i are the coordinates of the i-th station, and R_E is the Earth radium in km.

The ionospheric (tropospheric) delays relative to a generic point of the plane can be calculated computing the coefficients of the polynomial interpolation:

$$h_i = a_0 + a_1 n_i + a_2 e_i + a_3 n_i^2 + a_4 n_i e_i + a_5 e_i^2 \qquad \text{Eq. 16}$$

where h_i is the ionospheric (tropospheric) delay relative to the i-th station. It has been chosen to utilize two different polynomials to represent the ionospheric and tropospheric delays to best suit the peculiar characteristics of the two atmospheric layers. The choice of the polynomial order has resulted from a compromise between the optimization of the results and the computational complexity. The resulting system is solved through the Cholesky decomposition.

Figure 13 and Figure 14 show respectively the trends of the ionospheric and tropospheric delays patterns computed at the same epoch considering the same satellite.

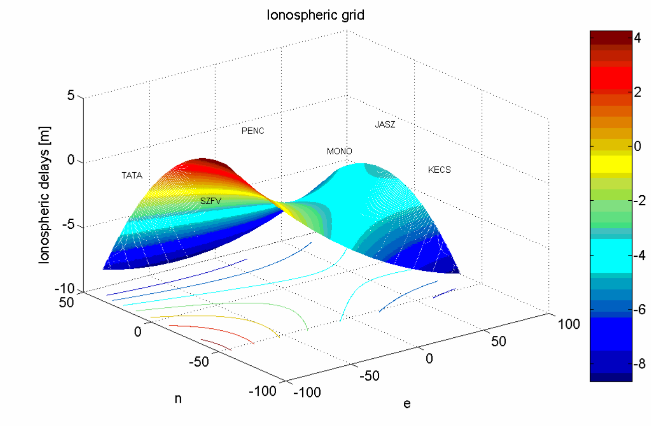

Figure 13: Ionospheric delays pattern

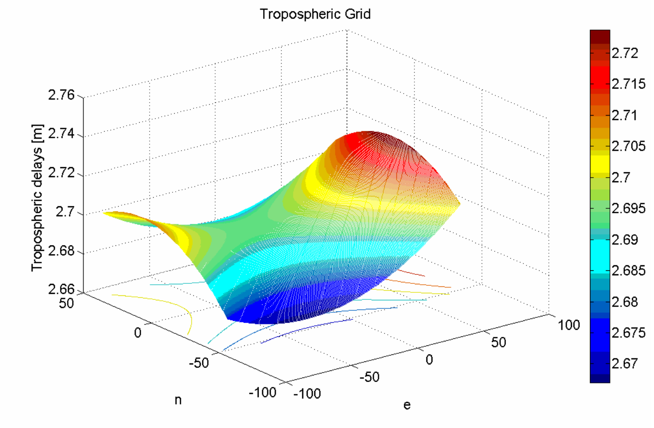

Figure 14: Tropospheric delays pattern

The above figures show the contour lines in 3D, the same lines projected onto the *n-e* plane, and the positions of the reference stations. It's possible to observe that the highest values of the ionospheric (tropospheric) delays are achieved in correspondence of the boundary zones, regions where the accuracy of the coefficients obviously degrades.

In Figure 15 it is represented the general approach followed in implementing the ionospheric and tropospheric delays interpolation. A future step of our work could be the merger of the data relative to different satellites computed at zenith in order to provide a general index of the ionospheric (tropospheric) activity in the local area.

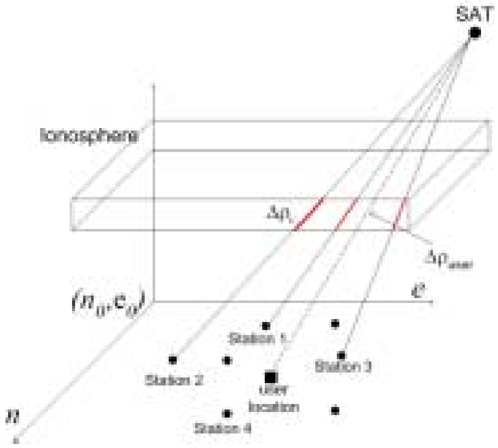

Figure 15: Scheme of the approach

SISE PREDICTION TEST RESULTS

The GALILEA validation plan for the EPCM tool envisages 5 validation test cases with real observation data and 3 tests with simulated data. At the time of the present paper issue, the simulated data results are available from the validation campaign.

The EPCM SISE prediction feature can be tested with simulated data introducing an orbital/clock error (failure case). One of the SISE prediction test cases has been performed introducing in the GSSF raw data generator a satellite clock drift of 5.55E-11 s/s for a certain Galileo satellite.

The plot in Figure 16 represents the filtered error (as output by the data fusion module) and the SISE prediction computed at a time epoch preceding the satellite failure. The data fit time has been set to 300 s. It can be observed that the SISE predicted values reflect the trend of the filtered error, and remain very close to zero.

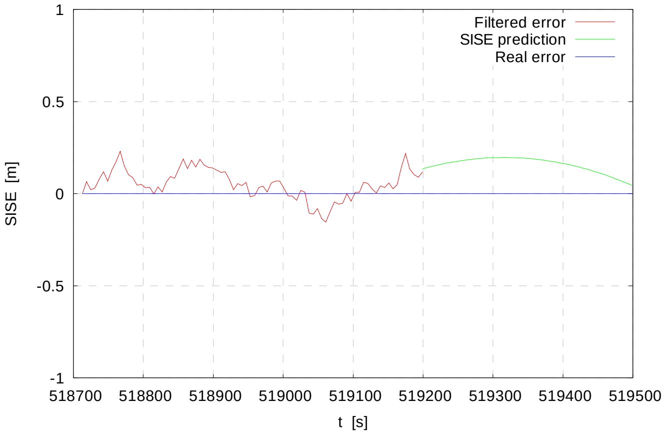

Figure 16: SISE prediction before the failure occurrence

The plot in Figure 17 represents the SISE prediction computed after the satellite failure occurrence, keeping the same data fit time as in the previous plot. The SISE predicted values react to the additional error with a short delay. In this case, a user can be alerted in advance on a change of the integrity flag for a certain satellite, occurring when the SISE exceeds a defined threshold.

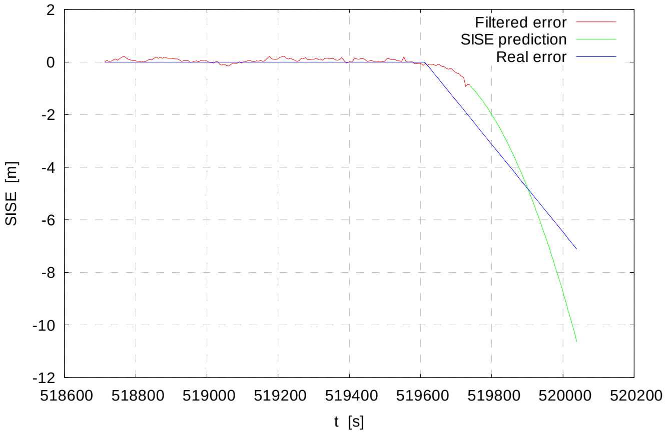

Figure 17: SISE prediction in failure case

The SISE prediction reaction time can be shortened by reducing the data fit time. In this way, however, an increasing SISE could be erroneously predicted by EPCM when no failure is occurring.

An increase of the filtered error for the other satellites in view (not affected by failure) has been observed for the described test case. This effect has to be attenuated, in order to avoid misleading integrity information for the user. A feasible approach could be to remove the satellite affected by failure from the EPCM single point solution computation as soon as it is recognized.

CONCLUSIONS

The proposed local architecture for the GALILEA project has resulted to be capable to provide an added value to the baseline Galileo service, in terms of integrity and continuity. Galileo standard integrity parameters, as SISA and Integrity Flag, can be complemented by additional information, as SISE prediction, for users operating in a local area.

During the models development phase, a tradeoff analysis has been performed for the ionospheric and the tropospheric correction models, taking in account the availability of local meteorological measures and the Galileo three frequencies.
The RBTB fit model has been modified introducing a time dependent third term, which makes it more efficient to fit rapid error variations.
A new model has been developed to compute the Orbital and Clock Error (OCE) from the comparison between IGS predicted satellite position/clock data and navigation message ephemeredes.
The design and implementation of a digital recursive (IIR) filter has solved the data fusion problem, where range measurements affected by a number of error sources has to be used to correct the accurate, but slow, IGS-based error prediction.

A software tool, called Error Prediction and Correction Module (EPCM), has been developed in a short time following the project objectives by means of the described models.
From the EPCM validation test cases with simulated data, the SISE prediction algorithm has resulted to be well suited to failure cases where the error increases with time, starting from a low level. The validation campaign with real data will assess the influence of the number and the position of the reference stations on the EPCM outputs.

Nowadays the results of the tests relative to the iono/tropospheric delays computation are not yet available, but they are supposed to confirm the validity and the efficacy of the chosen models. The same considerations can be applied to the iono/tropospheric coefficients computation, which, anyway, from the preliminary tests seems to be consistent with the expectations. The merger of the data relative to different satellites computed at zenith can be a starting point for the future development of the research.

ACKNOWLEDGMENTS

The GALILEA project is co-fundend by the Galileo Joint Undertaking under the contract number:
GJU/05/2423/CTR/GALILEA

The GALILEA consortium is composed by Space Engineering S.p.A. (Italy), Center of Studies and Activities for Space “G. Colombo” (Italy), NavPos System GmbH (Germany), Budapest University of Technology and Economics (Hungary) and Federal Agency for Cartography and Geodesy (Germany).

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