GNSS Performance Monitoring Services with GalTeC

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BIOGRAPHY

Walter Ehret
graduated as an Aeronautical and Space Engineer from the Technical University (TU) of Braunschweig, Germany in 1996. Since 1996 has been involved in continuous research and engineering activities related with Satellite Navigation and its applications. Currently he is active as Senior Systems Engineer at THALES ATM in Stuttgart where he was and is involved in Galileo related programs and studies. His expertise is dedicated particularly to Integrity related aspects of GNSS.

Dr. Hua Su

Currently the Senior GNSS Systems Engineer at THALES ATM GmbH, Germany. He obtained his Dr. – Ing. from the University FAF Munich, Germany in 2000. Over the last 20 years he has been responsible for many projects related to development of precise satellite orbit determination, differential GPS positioning, satellite navigation and GPS receiver software. In the period 2001 to 2005, he was responsible for systems engineering for EGNOS System AIV (Assemble, Integration and Validation) project dealing with EGNOS subsystems RIMS A/B/C and TUE performance, system monitoring and performance analysis. Since May 2005 he has been involved in the Galileo project and in particular the Galileo services performance monitoring and analysis.

Oswald Glaser
is currently working as Senior Systems Engineer at Thales ATM in Stuttgart and holds a diploma degree in electrical engineering of the Technical University of Graz in Austria of 1982. Since 1985 he has been working in the aeronautical industry, mainly in projects that are closely related to satellite navigation. Initially concerned with the combination of satellite navigation with inertial navigation, and later working on the application of GNSS in Airport Surface Movement and Control. Recently his work focused on the application of the future Galileo system for Ground Based Augmentation Systems in aeronautics.

Alexander Wahl
graduated in information economics at the Hochschule der Medien, University of Applied Sciences, in Stuttgart in 2006. Since 2007 he has been responsible for the web application of GalTeC, where the results of his research will be presented to the interested audience.

Eduarda Blomenhofer is Managing Director of NavPos Systems GmbH (In Oberwiesen 16, 88682 Salem), a German SME which specialized in satellite navigation related systems engineering and software development. She has an Engineer Degree in Surveying/Geodesy from the Porto University, Portugal. She has been working in satellite navigation disciplines since 1990, with activities on high precision differential GPS algorithms and software for real time applications, data processing and service volume simulation for GPS, GLONASS, GBAS, SBAS and Galileo.

ABSTRACT

This paper presents a concept of integrating different GNSS information sources in one single GNSS Service Centre which provides comparable and understandable information for different user groups and their needs.
The first part of the paper will introduce the architecture and concept of GalTeC which is to be understood as a GNSS Service Centre for the Satellite Navigation Systems Galileo, GPS, and EGNOS as a first implementation.
GalTeC is based on four corner stones. The first of them is the Satellites Reference Orbit & Clock reconstitution, which serves as the basis of analysis in Signal In Space(SIS) domain. First results of this capability is presented upon the SIS related behaviour of each GPS satellite for a representative time period.
The second cornerstone of GalTeC will be the analysis capability in the user domain, accounting raw measurements with all errors along the path. They serve for determination of positions, protection levels (SBAS, RAIM), integrity risks (Galileo).
The third cornerstone of GalTeC is its powerful service volume simulation capability for different kinds of constellations and different integrity methods (RAIM,

SBAS, GBAS, Galileo Integrity). Within this paper, results will be presented using the new AVIGA Service Availability Module. The module results are the Availabilities of Accuracy, Integrity Risk, Continuity Risk and Availability of Service.
The fourth cornerstone of GalTeC is the collection and structured handling and archiving of GNSS monitor station observations and computed data. For the results obtained in this paper the IGS provided observations are used on the one hand and one EGNOS/GPS receiver on the other hand.
Finally an outlook on the Services Provision methodology and architecture is given and the offered products are presented showing an example of the internet browser based functionality and styles for condensing the GPS and EGNOS/GPS analysis at staged levels of information depth.

INTRODUCTION

The future Satellite Navigation environment will comprise multiple GNSS constellations and multiple augmentation systems, ground based, space based and autonomous. For interested users, i.e. for downstream service providers as well as for the scientific community, an harmonised view on the status and performance of the different systems will be of great advantage. Up to now each GNSS System provides information on the operational status, notices and coarse predicted performance.. This is related to the method to distribution of information via WWW, FTP and E-Mail services, and content and format.

Within the near future the European GNSS Galileo system will be in place that will provide it's own means of performance status and announcement services, via the Galileo Service Centre.

The GalTeC (Galileo Technology Centre) has been developed to accommodate user interest concentrating on the need for easy to read information of all available GNSS systems i.e. status and performance in user understandable formats.

On the other hand professional and scientific users construct networks of information exchange, e.g. for GNSS measurement raw data where GalTeC can be one of the nodes of such networking, hence contributing to the broadening of independent system performance or augmentation capabilities. GalTeC Monitoring Station(s) can add observation data for Giove or Galileo in an initial operation phase to a joint network when only few Galileo monitors will exist. Due to the installation costs, interested application planners will need to approach such networks to evaluate the possibilities of their planned services based on pure Galileo services or integrated (GPS/GALILEO) solutions.

Finally, to dimension the application related services for innovative service providers, interested in employing the various Galileo service levels – particularly, the guaranteed Safety of Life, and Commercial Services, a dedicated simulation capability would be desirable as part of a sophisticated GNSS Centre.

Currently GalTeC is at level Version 1, and is effectively usable for offline GPS and EGNOS analysis. Some isolated Analysis has already been performed on GPS and GPS/EGNOS performance, further, simulations of the main Galileo Safety of Life key performance parameters, based on the specific Galileo Integrity concept and its application have been performed.. Continuous monitoring of GNSS systems and online information to users via internet will be provided with Version 2.

GALTEC CONCEPT

The application concept of GalTeC is to provide value added services related to the provision of Galileo satellite-only services. However, it will also provide services linked to the other GNSS systems - GPS, GLONASS as well as SBAS facilities. The services will comprise past GNSS functional and performance monitoring. and prediction capability about the future situation in GNSS services and planning, for downstream commercial services.

The GalTeC is understood to be a source for the provision of bundled GNSS information. Logically GalTeC can be found between the GNSS systems (particularly Galileo) and the End Users and between the Galileo System and down-stream Commercial Service providers etc. The inputs for GalTeC are GNSS raw measurements obtained from various sources and the messages broadcast by the GNSS Satellites. These sources are in-house and/or 3rd party GNSS monitoring networks, like those associated with the IGS. Further, GalTeC will take publicly available information directly from GNSS System Operators, and in particular from the planned Galileo Service Centre.

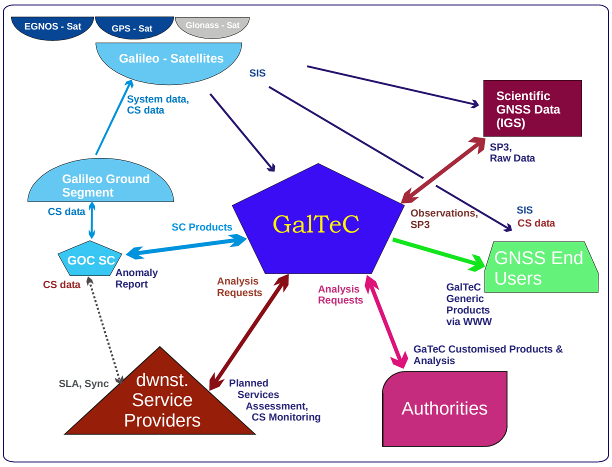

Figure 1: GalTeC Context

GalTeC will be composed of five functional blocks:

Measurements & Data:

- Monitoring Galileo and other GNSS system performance from an "in-house" monitoring receiver, partner monitor receiver networks and potentially system monitoring network (e.g. Galileo/GSS)
- Interface to international GNSS service, i.e. IGS or others for the exchange of data and information

Reference Determination

- Provision of highly precise satellite ephemeris (orbit and clock parameters) - for a posteriorly assessment of GNSS system performance
- Independent SIS performance evaluation service covering the past and current time periods for the systems Galileo, SBAS, GPS and eventually GLONASS.
- User Position and Time Calculation independent from receiver computed output.

Simulation

- Performance analysis of past, current or future constellation geometry, using service volume simulation based on constellation parameters like Almanacs
- Consultancy for commercial service providers for their access to the system, dimensioning of their service and prediction of the service performance

Analysis and Services

- Analysis of GNSS system status and performance in terms of Accuracy, Integrity, Availability and Continuity based on the measurements and reference orbit determination.
- Generation and Composition of GalTeC products (reports etc.)
- Provision of access means to for external and internal users to GalTeC.

Data Base and Data Handling

- Central data storage and data handling.
- Data archiving and retrieval.

HW Architecture

The GalTeC architecture basically consists of a scalable server/client architecture with several computer systems on which the different software-based functions will be realized.

The basic HW mounted in a single 19' rack consists of the three GalTeC servers with integrated mass storage. The various analysis and evaluation software on the GalTeC servers need access to the Internet in order to download actual data from various sources delivering GNSS measurements and evaluated data. The external access to GalTeC is given also through Internet. For security reasons the GalTeC Internet services are actually not directly provided by the GalTeC main server itself but via an external service provider.

The GalTeC servers will be connected internally to local users with their own working stations for performing individual computations. There will also be one operator workstation (GalTeC Client) directly connected to the servers and located in the lab room. Finally it is planned to foresee a connection to the Galileo Ground Segment via Galileo’s Service Centre Interface, or to a dedicated Central Galileo Service Centre.

Figure 3 shows left hand the content of the GalTeC rack. We can see the integrated GNSS receiver on top, a network interface, the Simulation Server (yellow), the server for the reference orbit determination (red) an the server for the analysis function an the provision of services to the users. This is complemented by an uninterruptible power supply to ensure continuous operation.

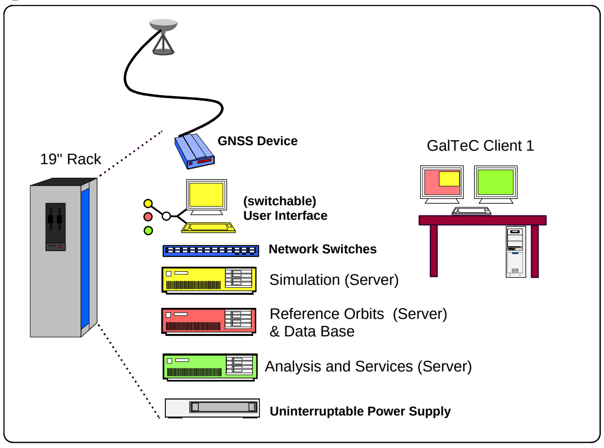

Figure 3: GalTeC Components

Right hand in the figure we can see the GalTeC Client workstation giving access to the different GalTeC functions on two screen via different windows (shown in the picture by different colour of the sub-windows).

GALTEC REFERENCE MODULE: GPS ANALYSIS

The Reference Orbit Determination and Time Synchronisation (OD&TS) is a very important component for GalTeC. It provides the precise reference orbit for further data analysis and processing.

The reference orbit determination is performed in GalTeC using raw measurements from Galileo GSS stations and monitoring station networks like IGS (International GNSS Service). Also GalTeC own ground stations will collect pseudo-range and carrier phase measurements and provide them offline for further data processing.

The major processing steps of reference orbit determination are drawn in **Figure 5**.

The Galileo or generally GNSS satellite orbits are implemented in GalTeC using the dynamic method in batch processing mode. Assuming the satellite movement equation is

$$\ddot{\vec{x}} = -\mu \frac{\vec{x}}{|x|^3} + \frac{\partial R}{\partial t} = f(\vec{x}, t) \qquad \textbf{(Eq. 1)}$$

where:

$\ddot{\vec{x}}$ satellite acceleration vector,
$\vec{x}$ satellite position vector,
μ earth's gravitational constant,
R sum of various perturbation sources, i.e. $R = R_e + R_s + R_m + R_l + R_\Sigma$ ·
R_e geopotential model,
R_s, R_m solar and lunar attraction models,
R_l solar radiation pressure model,
R_Σ other small perturbation models

Then the batch processing mode can be expressed as

$$\vec{x}_k = \Phi_{k,k-1}\vec{x}_{k-1} + \Gamma_{k,k-1}\vec{w}_{k-1} \qquad \textbf{(Eq. 2)}$$

with the observation equation

$$\vec{y}_k = H_k \vec{x}_k + \vec{\varepsilon}_k \qquad \textbf{(Eq. 3)}$$

where

$\vec{x}_k$ n dimensional satellite orbit and dynamic parameters,
$\vec{y}_k$ m dimensional observation vector,
$\Phi_{k,k-1}$ $n \times n$ dimensional state transition matrix,
$\vec{w}_k$ dynamic system noise vector,
$\vec{\varepsilon}_k$ observation noise vector,
$\Gamma_{k,k-1}$ coefficient matrix of dynamic system noise vector,
H_k $m \times n$ dimensional observation coefficient matrix

The equations above can be solved together with numerical integration, i.e.

$$\left.\begin{aligned} &\ddot{\vec{x}}'_k = f(\vec{x}'_k, t) \\ &P'_k = \Phi_{k,k-1}P_{k-1}\Phi^T_{k,k-1} + \Gamma_{k,k-1}Q_{k-1}\Gamma^T_{k,k-1} \\ &K_k = P'_k H^T_k (H_k P'_k H^T_k + R_k)^{-1} \\ &\tilde{\vec{x}}_k = \vec{x}'_k + K_k(y_k - H_k \vec{x}'_k) \\ &P_k = (I - K_k H_k) P'_k \end{aligned}\right\} \qquad \textbf{(Eq. 4)}$$

where P_k is the weight matrix of parameters.

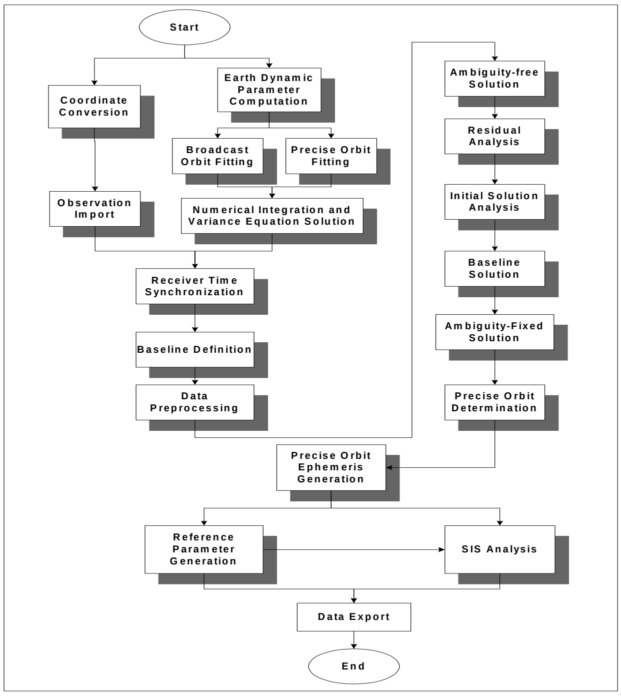

Figure 5: Processing Steps of Reference Orbit Determination

GalTeC will be able to compute (estimate) the so-called *SISE* (Signal-in-Space Errors, according to

$$SISE = R_{srew,k}(\vec{y}_k - H_k \tilde{\vec{x}}_k) \qquad \textbf{(Eq. 5)}$$

where $R_{srew,k}$ is the conversion matrix to the worst user location. This estimation will come of the ODTS prediction process quite similar as done by OSPF of Galileo GMS.

On the other hand, assuming $\vec{x}^b_k$ computed from Galileo broadcast ephemeris and the precise orbit, *SISRE* (Signal-In-Space Reference Errors) can be computed by

$$SISRE = H_{srew,k}(\tilde{\vec{x}}_k - \vec{x}^b_k) \qquad \textbf{(Eq. 6)}$$

where, $H_{srew,k}$ is the mapping matrix to observation domain at the direction to the worst user location.

The *SISRE* reflects the actual accuracy of Galileo or any GNSS broadcast ephemeris. *SISRE* is a key performance parameter which can be used for monitoring and validation of the performance of the Galileo broadcast orbit. Currently *SISRE* for GPS can be computed.

Based on *SISRE*, another key performance parameter, *SISRA* (Signal-in-Space Reference Accuracy) can also be computed. *SISRA* is a minimum standard deviation of the unbiased Gaussian distribution over-bounding *SISRE*. *SISRA* can be directly compared with Galileo broadcast *SISA* and *SISMA*.

GALTEC ANALYSIS MODULE

The GalTeC Analysis module is the last processing and graphical tool set in the chain before the Service provision. The structure of Analysis will be subdivided in following examination areas:

- Direct Signal domain
- User Range domain
- User Position domain

for the GNSS systems Galileo, GPS, GPS/EGNOS and potentially GLONASS. Further details can be found in [1]. Currently some functions are realised in the GalTeC Version 1 which are Signal in Space (SIS) analysis and user position domain analysis for GPS and GPS/EGNOS.

This chapter will present the preliminary results obtained through use of GalTeC V1 capabilities.

SIS/Range Domain

The analysis in the SIS domain uses the outputs of the GalTeC module described in the previous chapter. The SIS Analysis modules take this data, plots it partly straight forward and partly after applying some statistical functions. Currently the module is adapted to GPS-only analysis.

The following figures show the analysis per satellite with the example of PRN 3. PRN 3 (SVN 33) is a relative old satellite. It is a Block IIA satellite, in service since 1996 and running on a Caesium clock.

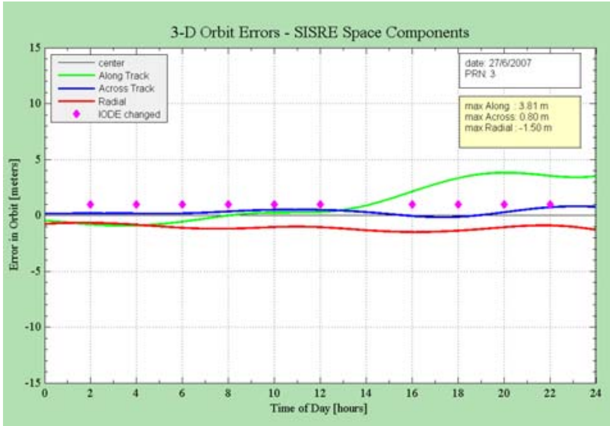

Figure 7: Ephemeris Orbit Errors plot

Figure 7 is an Orbit Error plot showing the typical deviations in the vector components: along-track, across-track and radial. The plot is also draped with event markers which show when a new Ephemeris set was broadcast from the satellite (identified by a changing IODE value, typically each 2 hours).

Figure 8 shows a typical behaviour of the clock with an error of up to 3 meters (i.e. 9-10 nanoseconds). Some jumps can be recognised when Clock parameters is updated in a new Navigation Message set. It is interesting to observe that the updates seem sometimes to add errors (e.g. at 16:00 GPS Time).

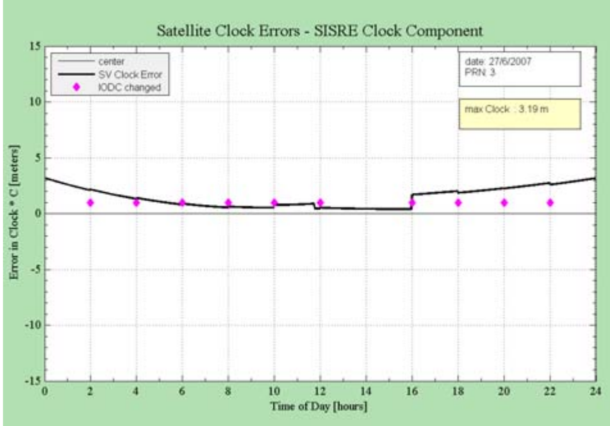

Figure 8: Ephemeris SV Clock Errors plot

Generally it can be said that the Clock performance is mostly smooth with Rubidium clocks on Block IIR & IIR-M satellites with some good-performance exceptions on Block IIA satellites (mostly running on Rubidium clocks). Nevertheless there is often a quasi constant offset of 1-2 meters over the 24 hours.

PRN3 in **Figure 8** using a Caesium clock shows medium performance. However PRN 3 (SVN33) is now over 11y in service - beyond its 7.5y design life.

The intrinsically interesting information however is the total SIS Error in the Pseudorange domain. Therefore a direction vector to a user must be found. This can be either a real user position or an automatic search to a worst user location. Worst User means a location where the projection of all above components is maximised. This task is already performed by the GalTeC ODTS module described in the chapter above (see *SISRE*).

Figure 9: SISRE time plot

In GalTeC context it has been named SISRE (Signal In Space Reference Error) in the style of Galileo SISE understanding, i.e. it is not a statistical parameter.

In GPS terminology it would be the instantaneous SPS SIS URE [User Range Error] as defined in [4] - but only with Orbit and Clock Errors components to be precise.

The SISRE in the above example ranges below 4 meters on the 27th of June and is such well in the specifications [4] (< 6 meters RMS and 30 meters not to exceed).

GPS Navigation messages contain also the URA (User Range Accuracy) parameter which is the prediction of the above monitored errors. The URA is plotted in **Figure 9** as dashed magenta line. To check whether URA was broadcast correctly the Analysis tool makes, currently, a small check over the day where samples are accumulated with the condition: SISRE < URA. If it arrives at < 68.27% of all samples (in 24h) a URA failure can be considered.

In future this test may be sequenced in time epochs of constant URA instead of whole day reference. An analogue test will be performed over Galileo once it will transmit the integrity parameter SISA.

In the above case the percentage is well above 68.27% and so all URA broadcasts meet the goal of representing a 1-sigma coverage of Navigation broadcast errors (see definition of URA in [3].

An additional, more natural means of URA (and SISA) check within GalTeC is the histogram representation shown below.

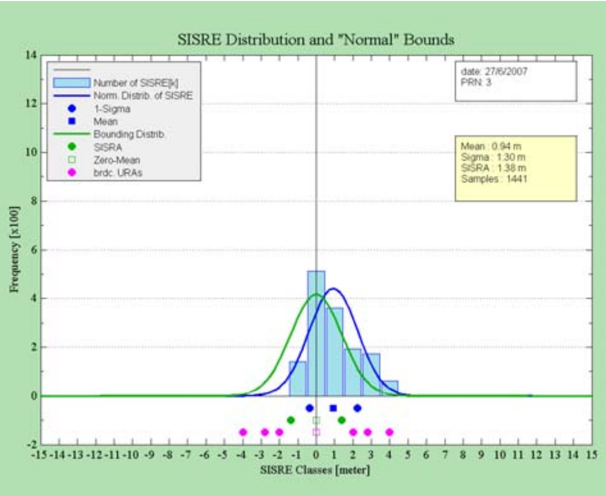

Figure 10: SISRE histogram plot

Figure 10 tries to summarize the whole range domain analysis above. SISRE samples of the day are put in classes or bins of (currently) 1 meter width and the central bin from -0.5m to +0.5meter. The related plot allows a quick understanding whether the errors are really normally distributed and zero-centred as often assumed. Simple statistical computations determine the mean and the corresponding standard deviation of the real distribution. The results are displayed as numbers and graphically - below the zero-line as blue markers and above as blue gaussian curve.

URA in the GPS case or SISA in the Galileo case do consider a zero centred distribution which shall bound also the displaced real distribution. The GalTeC algorithm implemented to find this overbound is currently quite simple by searching symmetrically to 0 the 68.27% percentile of the samples. The found value is displayed numerically in the yellow box as well as graphically by green markers and a green gaussian curve. In **Figure 10** SISRA is 1.38 meters and built with data of the whole 24 hours of the day (meaning 1441 samples out of 5min steps).

The magenta markers are the URA values of the day. Normally the green markers shall be between the magenta markers. In future a better representation will be searched to reflect the shorter validity time of each individual URA (sometimes 2 hours only).

Finally the results for all GPS is summed up:

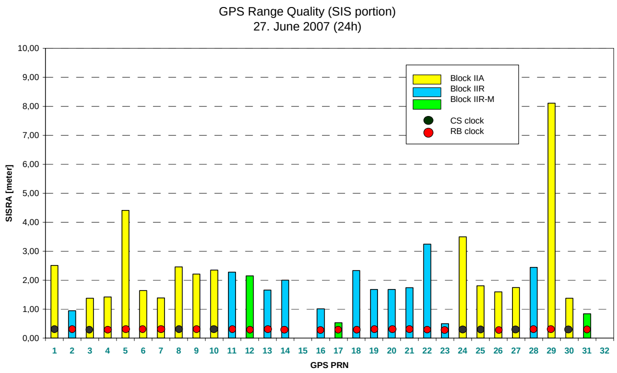

Figure 11: SIS Errors per GPS PRN, 27.6.07

In **Figure 11** shown is the SISRA out of **Figure 10** for each GPS PRN. The columns are marked according to satellite generation (Block IIA, IIR, IIR-M). Also the operational clock type is marked (red/black dots). As can be seen there is no direct dependence of the SIS quality and the model/generation of GPS vehicle. This is more evident while looking on a further day analysed:

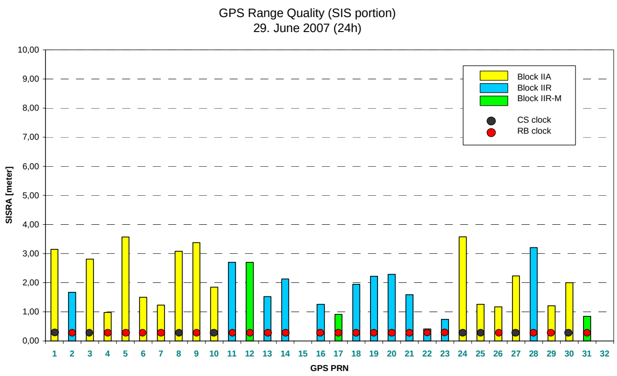

Figure 12: SIS Errors per GPS PRN, 29.6.07

Comparing with other sources, the SISRA figure is maybe not direct comparable to the GPS SPS [4] or the FAA Performance Report [5] since the RMS statistic is used there. However our results lie in the same range of below 2 meters in average. However some outliers exist in our analysis. As the SISRA is per definition > RMS URE and SISRA was with one exception generally below 6 meters the specification in [5] could be considered as met. Also the URE Not-To-Exceed of 30 meter requirement can be considered as met (worst SISRE for PRN29 is 15.7 meters).

The quality of the range seems not to depend on the generation (block) of satellites, but more on the individual satellites. As a tendency - outliers like in the case of PRN29 on 27. June are however allocated to older Block IIA satellites. On the other hand there are Block IIA satellites which seem to be better in performance than even Block-IIR-M satellites. This finding is unexpected to the authors. Also there seems to be no correlation of total range error sizes to the clocks. The day to day performance of satellites seems to be constant in some cases (e.g. PRN 4) and quite different in other cases (e.g. PRN22).

Position and Position/Integrity Domain

The analysis in the user position domain uses in the moment the GalTeC receiver output (computed data), i.e. from the GalTeC Measurement Collection function. The receiver is a dual frequency GPS receiver with EGNOS capability: Septentrio PolaRx2. Its antenna has a clear view of sky on the roof of the Thales building.

The following data is used currently:

- Receiver (Antenna) Position/Height (Single GPS or EGNOS/GPS)
- EGNOS Protection Level (HPL,VPL)
- Number of Satellites and DOP factors

In the final Version GalTeC will be prepared to include Galileo Position/Integrity. However the project will end before the four IOV satellites are launched.

This sub-chapter presents the results of two weeks observation, one week in EGNOS/GPS mode and one week in GPS only mode. This functions are designed for day to day monitoring of the Positioning performance and its Integrity.

The results presented shall compare the GPS only performance with respect to EGNOS/GPS performance as would be seen by a user in the core region of EGNOS service area.

- EGNOS/GPS: 18.6. - 24.6.2007
- GPS (L1/L2) only: 26.6. - 2.7.2007

The first level of plots generated by the analysis functions are the typical time series of the data and some simple statistics of accuracy. The typical aviation figures are used - "95% accuracy". In the horizontal case it would represent a R95 circle.

The following graphs represent the 19th June 2007 data, where the receiver was configured in EGNOS mode.

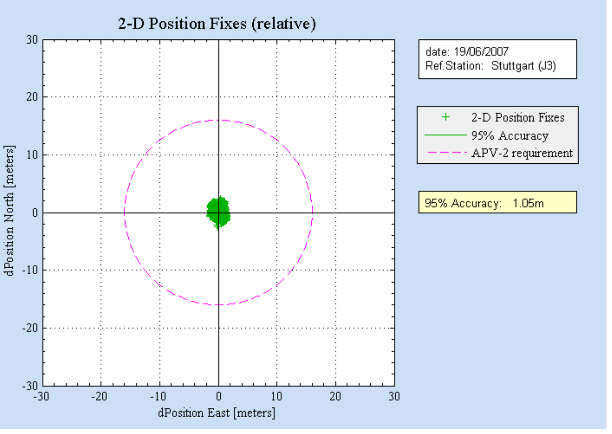

Figure 13: GPS/EGNOS hor. accuracy

The time plot is omitted here for the horizontal case, but is similar as the plots hown here for the vertical case.

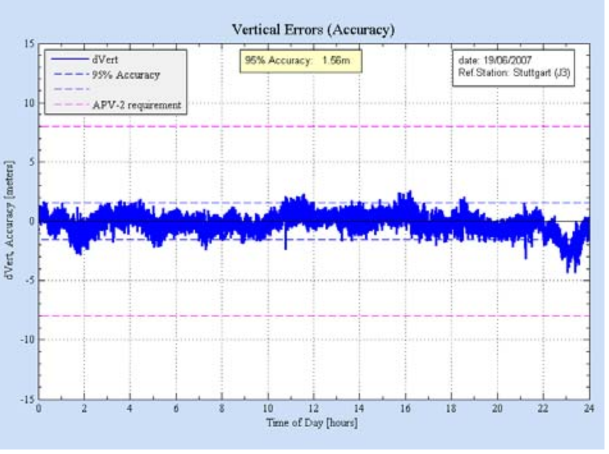

Figure 14: GPS/EGNOS vert. accuracy

In GalTeC also position error histograms are built for the three directions North, East and Vertical.

As seen from the two plots above the 95% accuracy in 24 hours period are 1.05 m in horizontal and 1.56 m in vertical direction. This is a typical value for the Stuttgart region if EGNOS operates nominally.

The Integrity (SBAS protection Levels) can be displayed in two ways. First the time plots - e.g. vertically (**Figure 15**). The very good vertical accuracy is well protected by the VPL.

It may seem that the protection is quite conservative. However during some days there have been position outliers beyond the Alarm Limit of 20 m. In these cases the VPL was also far above the VAL and protected such the potential navigation system of using this position (e.g. on 20.6.07, not shown here).

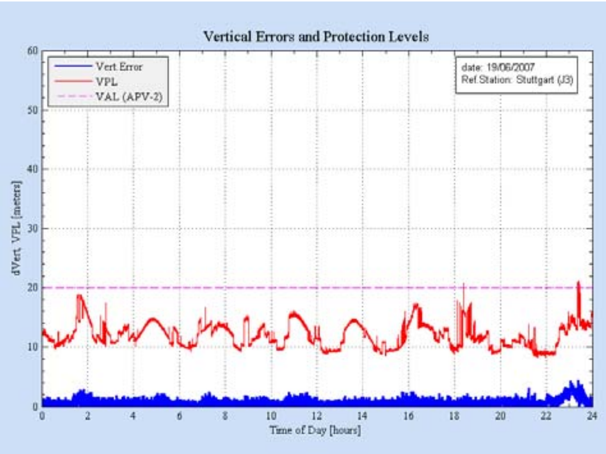

Figure 15: EGNOS VPL and VNE

Finally the analysis is performed in a statistical way to generate Stanford plots and availability figures. Again the vertical dimension is represented:

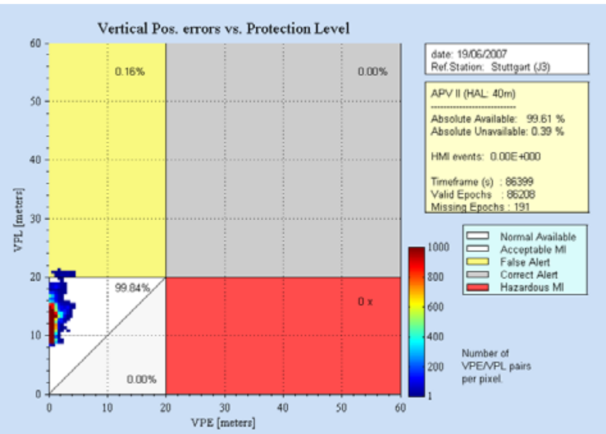

Figure 16: Stanford Plot, Vertical

The division of the sectors is adapted to aviation precision approach requirements APV-II defined by ICAO (i.e. vertical alarm limit 20 meters. The sectors are modified a little bit from the usually published ones in a more pragmatic way. It is noted here that the percentages in the plot itself are related to the total number of samples.

In the yellow result field at the right side, the more relevant percentage related to 24 hours (86400 seconds) is displayed. Here e.g. for unknown reasons in accumulated 191 seconds no VPL/HPL data was output by the receiver, which adds to the "system unavailability" time.

The total availability has been vertically 99.61%. Horizontally it is 99.78% and both together 99.61%.

The final analysis of the observed period is summarized in:

Table 1: EGNOS/GPS performance (18.-24.6.07)

Date	95% accuracy		System availability
	horizontal	vertical	
18.6.2007	0.85 m	1.50 m	99.78 %
19.6.2007	1.05 m	1.56 m	99.61 %
20.6.2007	0.98 m	1.49 m	99.43 %
21.6.2007	0.83 m	1.20 m	99.97 %
22.6.2007	0.90 m	1.30 m	99.98 %
23.6.2007	0.85 m	1.36 m	99.38 %
24.6.2007	1.01 m	1.40 m	98.31 %

GALTEC SIMULATION AND PREDICTION TOOL

For the prediction of the system performance and also for the design and dimensioning of the GNSS Services a simulation function is needed. For this purpose, the NavPos Systems Service Volume Simulator AVIGA® will be used and further developed to a GalTeC Prediction tool in the frame of the GalTeC project. The prediction tool offers the means to predict, analyse and evaluate Galileo Services.
A main AVIGA Objective shall be the analysis of the GNSS user performance of past, current or future constellations using simulation.

AVIGA offers to run simulations at point, over area and along routes in terms to analyse

- Accuracy,
- Continuity of Service,
- Integrity and
- Availability.

In addition, AVIGA supports the analysis of GNSS constellation performances in terms of

- Visibility and
- Geometry.

The AVIGA tool is composed of modules, which will fulfil the following tasks:

Space Segment Module: predicts satellites trajectories from standard almanacs, e.g. Almanac YUMA files, computes satellite trajectories from user – defined Keplerian elements; Broadcast Ephemeris or SP3 Precise Ephemeris.

Visibility Module: evaluates visibility characteristics of satellite coverage accounting for mask skyline angles;

DOP (or Geometry) Module: evaluates DOP and Position Error characteristics of satellite coverage, position accuracy is estimated from the position errors covariance matrix.

Availability Module: evaluates availability of DOP and position accuracy. Models of satellite outages and navigation solution errors are used in this model.

Integrity/Continuity Modules:

- RAIM: evaluates availability of the snapshot RAIM FD/FDE methods.
- SBAS: evaluates availability of the SBAS Protection Levels.
- Galileo: evaluates availability of protection level according to concept proposed for Galileo system, calculates the pertaining Integrity Risk.

Service Availability module: analyses availability of Accuracy, Continuity and Integrity Risk according to the proposed Galileo concept. It also allows to analyse critical satellites.

GBAS / Galileo LE: analyses performance of GPS, Galileo based local area augmentation systems.

Route Module: analyses the performance along a specified route

SISE Analysis Module: assesses satellite orbital and clock errors from SP3 precision orbits and RINEX Navigation files.

Data Dissemination Module: simulates disseminating of Galileo Messages from Ground Mission Segment via ULS network to world-wide or regional users (under development).

Some of the AVIGA Service Volume Simulation modules include error components simulation to analyse the Galileo Service performance and the impact of various errors sources.

The prediction of the Galileo Services according to their specification, and also with further parameter settings, shall be done with the GalTeC Prediction Tool. The tool shall also allow the simulation of seldom failures of the system such as erroneous behaviour and outages.

Galileo Integrity Risk (User Concept)

According to approach [8], [9], the user receives direct information about the estimated performance of each satellite (SISA, SISMA, IF) . Processing this information per satellite in the navigation solution the user can evaluate the integrity risk and decide whether it is possible to start the operation or not. The overall or combined user integrity risk is defined from the equation [7]:

$$P_{HMI} = \overbrace{(1 - erf(\frac{VAL}{\sqrt{2} \cdot \sigma_{u,v}})}^{term\_1} + \overbrace{\sum_{io=1}^{n} p_{fail} \cdot \frac{1}{2} \cdot (1 - erf(\frac{VAL - \left| M_u[3,i_0] \cdot B_{0,i_0} \right|}{\sqrt{2} \cdot \sigma'_{u,v}(i_0)})}^{term\_2\_0}$$

$$+ \overbrace{\sum_{io=1}^{n} p_{fail} \cdot \frac{1}{2} \cdot (1 - erf(\frac{VAL + \left| M_u[3,i_0] \cdot B_{0,i_0} \right|}{\sqrt{2} \cdot \sigma'_{u,v}(i_0)})}^{term\_2\_1} +$$

$$+ \overbrace{\chi^2_{f=2}(\frac{HAL^2}{\xi^2})}^{term\_3} + \overbrace{\sum_{i_0=1}^{n} p_{fail} \cdot \chi^2_{nc,f=2}\left((\frac{HAL^2}{(\xi'(i_0))^2}), (\frac{(M_u[1,i_0] \cdot B_{0,i_0})^2 + (M_u[2,i_0] \cdot B_{0,i_0})^2}{(\xi'(i_0))^2}) \right)}^{term\_4}$$

(Eq. 7)

where [7]:

- VAL is the specified Vertical Alert Limit
- HAL is the specified Horizontal Alert Limit
- $\sigma_{u,v}$ is the standard deviation of the model CDF that overbounds the vertical position error in fault free state. defined in [7]
- $\chi^2_{f=2}(*)$ is the central chi-squared distribution with 2 degree of freedom (DOF), for DOF = 2 simple exponent
- ξ^2 is the variance of the model CDF that overbounds the fault free position uncertainty along the semi-major axis of the error ellipse in the xy plane
- n is the number of valid measurements
- i_0 denotes the index of a satellite with failed signal
- Pfail is the probability in any 150 s that one and only one of the received signals is outside the specification and flagged by the IF as "OK"
- $\sigma_{u,v}'$ (i_0) is the standard deviation of the model CDF that overbounds the vertical position error, when the satellite i_0 is failed
- B_0,i_0 is the (undetected) bias error affecting signal i_0
- $\chi^2_{nc,f=2}(*, p)$ is the non-central chi-squared distribution with DOF = 2 and parameter p
- $(\xi'(i_0))^2$ is the variance of the model CDF that overbounds the position uncertainty (for signal i_0) along the semi-major axis of the error ellipse in the xy plane when the signal i_0 is failed

An important parameter for the performance assessment of the Galileo Safety of Life Service is the Signal in Space Error (SISE). For the provision of Galileo integrity, the main role is assigned to the integrity flags which are generated in the Integrity Processing Facility.
The generation of integrity flags is based on the determination of SISE in real time. The value of SISE and its quality SISMA depends on the number of ground sensor stations (GSS) and the satellite to GSS errors. A sensitivity analysis was presented in [9]. **Figure 17** shows the SISMA map for 30 GSS and a GSS mask angle of 15°.

Using a 30 GSS network, a nominal SISMA of better than 70cm was mostly achieved and in case of GSS outages a degraded SISMA of 130cm could be assumed. **Figure 18** shows the Availabilities of accuracy, continuity and integrity and also their service availability. The Availability of Service is the combination of the Availabilities of Accuracy, Continuity and Integrity. The average availability of service is 99.06% with a minimum of 95.74% as compared with the Galileo availability requirement of 99.5%.

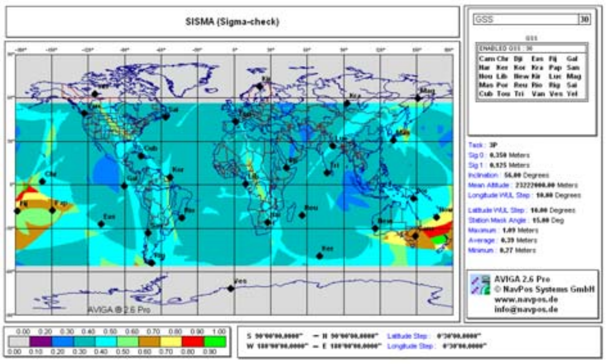

Figure 17: SISMA map for 30 GSS network

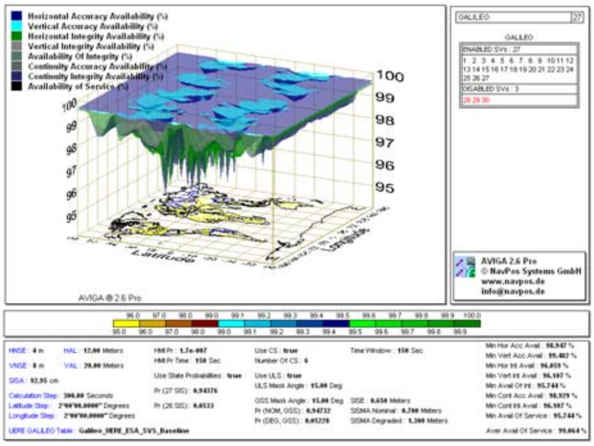

Figure 18: Galileo Service Availability assuming 30 GSS

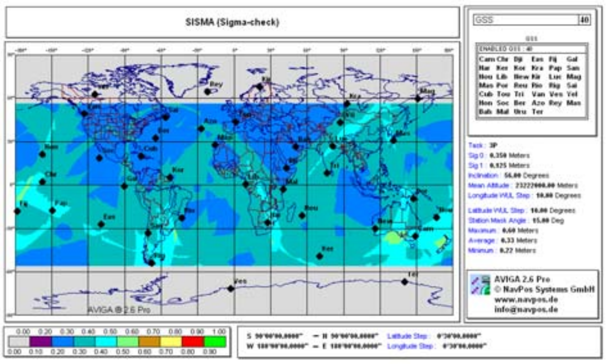

Figure 19: SISMA map for 40 GSS network

The sensitivity analysis in [9] also used an arbitrary set of 40 GSS (30 GSS as specified plus additional 10GSS). The simulations showed a good robustness against GSS outages. Furthermore, it could be concluded that a nominal SISMA of 50cm and a degraded SISMA of 100cm seem to be achievable.

Figure 20 shows the service availability assuming such a 40 GSS network. The average availability of service is 99.45% with a minimum of 96.09%.

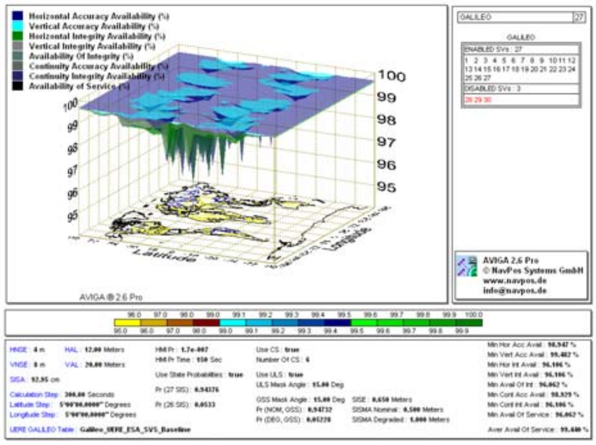

Figure 20: Galileo Service Availability assuming 40 GSS

Critical Satellites

For the allocation of continuity requirements in the LAAS MASPS [10] the possibility is outlined that the protection level during a 15 seconds period could jump over the specified alarm limit due to loss of signals to one or more satellites (PL>AL risk).

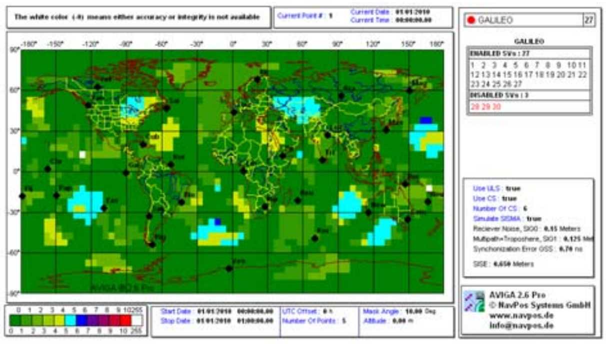

Figure 21: Number of Critical Satellites Snapshot

For the reduction of the approach continuity risk it is reasonable to analyse the available constellation for the number of so called "critical satellites". The introduction of the number of critical satellites will have also an effect on the availability of PL< AL. With a low allowed number of critical satellites the availability will be lower but the continuity will be higher.

The consideration of critical satellites is also part of the Galileo baseline. In the frame of this paper simulations have been performed showing the availability of protection levels taking into account a number of 6 allowable critical satellites.

AVIGA Service Dimensioning

In the course of the further development of the AVIGA® Prediction Tool, new features e.g. for the dimensioning of services and for the performance assessment in relation to the needed signal bandwidth will be implemented (see **Figure 22**). The design and dimensioning is needed for the feasibility and cost estimation of a service. An application example for GalTeC will be to offer Service Providers the possibility to estimate the needed data volume and to develop distribution strategies for their planed Services.

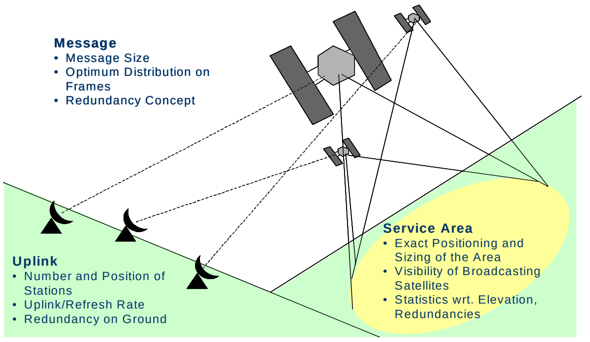

Figure 22: GNSS new Services Dimensioning for GALILEO

GALTEC SERVICES

The GalTeC Service module is responsible for combining information from the modules responsible for Measurement, Simulation, Reference Orbit and Time Determination and Analysis and for presenting the essential conclusions in a distinctive and evident way via web services to the user.

Therefore one objective of the service module is to serve the results in graphical and textual representation together with their underlying data produced on different machines and applications through one single point of access. This concept ensures easy access to all results of GalTeC without the need of special knowledge by the end user.

Furthermore it is very important to provide pre-defined products showing the key performance parameters that are of main interest in an obvious and evident way that can easily be interpreted by the users. It is planned to analyse data that are available today for GPS and GLONASS as well as for EGNOS. As soon as they are available, Galileo data will be included. The main task is to provide the key performance parameters in concise form as it is presented in the description of the analysis module. In addition also supplementary products that are standardised to a certain level like e.g. SP3 and RINEX data file are provided in order to permit independent verification.

At the moment the data products and reports can be characterised by the following attributes :

- Update Rate and observation frame (hourly, daily, weekly)
- Actuality (minutes, hours, days)
- Data and File Formats (RINEX, SP3, XML, HTML, TXT, PDF, PNG/JPG)
- Access (Public, Restricted, Individual – depending on the registration level of the user)
- Product provision (Download, E-mail, FTP, HTTP)
- Product (Routine, Alarm, Special)

The following basic products are to be provided for the time periods and areas respective the individual stations as selected by the user:

- Protection Levels for Stations as well as for selected Area (Simulation module)
- Real Protection Levels for individual Stations (presented in the time domain or by statistics)
- Ranging Errors for individual Stations
- Position Error of individual Stations
- Satellite Orbit and Clock Errors in different formats (over time and statistics, e.g. SISA, SISRA etc.)
- Precise Orbits (SP3) based on own calculations and (partly) own measurements
- Various supplementary data like
    - sorted Receiver Data in (Rx) Raw Data or RINEX format, Rx Computed Data, GNSS (Transmitted) Tx Data
    - Own Station Data
    - collection of NANU, Bulletins etc.

The compilation of the individual tables, plots and summaries will be developed in detail in the coming development phase and also its structuring and representation in the externally accessible representation. The reports will be provided to the user in several formats for different use cases e.g. for printing, presentation on screen or further evaluation by other tools.

One of the main challenges concerning the presentation of results via the Internet is to provide an intuitive, easy to understand and easy to use graphical user interface. This GalTeC interface shall enable the user to browse the huge amount of information in a structured and common way.

To achieve this objective, the design will be developed following approved and standardized methologies of current interface design for web applications.

The following screen shot should give a first impression how the GalTeC results will be presented.

The example gives an impression how the various reference data that are recorded by GalTeC on a daily basis can be retrieved be the user. The user can select the data types he wants to see or to download and he can select the time range. To do so he is supported by a calendar function.

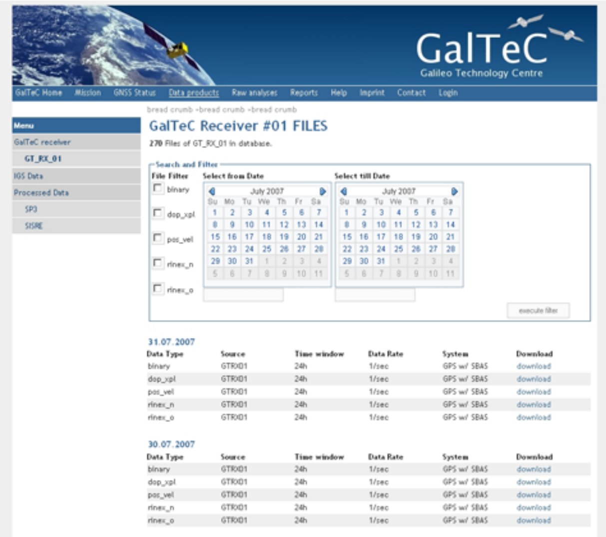

Figure 23: GalTeC Web Interface for archived reference data

CONCLUSIONS AND OUTLOOK

The project Galileo Technology Centre is well on its track and can in its Version 1 implementation already be used offline for basic analysis and regular GNSS data collection (e.g. in [2]). In Version 1 the analysis capability is focussed on GPS signals and EGNOS Augmented GPS. The implemented Simulation capabilities include powerful analysis capability for Galileo and Galileo Integrity concept as currently published.

The future development will concentrate on expansion of the analysis functionalities for multiple GNSS, Inclusion of receiver independent PVT and RAIM computation and Inclusion of Giove analysis capabilities.

Very important is the implementation of the Data Base together with the Services-via-Web. Some concepts have already been prototyped in a closed network environment which help to specify the design.

GalTeC Version 2 should be ready for Testing Q4/2008 and a short demonstration period is planned afterwards, where GalTeC will go online, for an open access trial.

ACKNOWLEDGMENTS

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