THE DLR PROJECT GALILEONAV: OVERVIEW AND STATUS

U. Grunert, A. Dreher , E. Engler, A. Hornbostel, A. Konovaltsev, D. Klähn,
A. Lehner , A. Moudrak, T. Noack, A. Schroth, S. Schlueter, A. Steingaß
German Aerospace Centre (DLR)
Institute of Communications and Navigation
P.O. Box 1116
82230 Wessling-Oberpfaffenhofen

1. ABSTRACT

In 2001 the DLR Institute of Communications and Navigation started an internal project called "GalileoNAV", which supports early work for the utilization, application and verification of Galileo. The project will last until 2006 and, therefore, is closely connected with the time schedule of the Galileo development and in-orbit-validation phases. The project consists of the following five main work packages:

- Clock synchronization and time distribution,
- Verification methods and algorithms,
- Experimental verification systems,
- Models and transmission methods,
- Terminal development.

This paper provides an overview about the structure and the main goals of the project and presents results which have been obtained.

2. INTRODUCTION

In parallel to the begin of the Galileo system design and development phase the DLR Institute of Communications and Navigation started in August 2001 the internal project “GalileoNAV” for the utilization, application and verification of Galileo, which will last 5 years and should support work carried out in externally funded projects, e. g. by ESA or the EU. Goal of the project is to contribute actively to the development and verification of Galileo and to perform preliminary work for the development of end user terminals, applications of Galileo and its success at the user market.

Galileo will bring new opportunities to the continuously growing market of timing applications which would allow to cover rising user requirements to clock synchronization. These opportunities originate from higher accuracy of satellite observations, provision of multi-frequency services for civil users and service guaranties and will allow to increase accuracy and reliability of satellite time and frequency transfer. On the other hand, these opportunities form a challenge to develop adequate algorithms and procedures that will allow to bring the full power of Galileo to its users. These aspects are investigated in the work package “clock synchronization and time distribution”. It includes the realization and operation of a clock laboratory, as well as the theoretical and experimental investigation of new methods for time transfer and synchronization of satellite and ground clocks.

In competition with GPS, Galileo must deliver at least the same accuracy and availability as GPS. Additionally, it will offer commercial and public regulated services, which shall guarantee higher reliability and integrity. This integrity can only be provided with help of a sophisticated ground monitoring network. The verification of the signal quality as well by simulation as by experiments at an early stage of the development phase is therefore of essential concern for Galileo. Two main work packages of GalileoNAV are therefore dedicated to these tasks. In the work package “development of verification methods and algorithms” the Galileo performance and methods for verification of the expected performance are investigated by end-to-end simulation. These methods are then applied in the work package “experimental verification systems”, where a network of interconnected monitor stations including the infrastructure for data archiving and central data processing is created.

In the work package “models and transmission methods” the Galileo signal structures, receiver algorithms and transmission methods are evaluated by simulation and measurements with respect to accuracy, robustness against interferers, and bit error probability. Multipath propagation is still one of the dominant contributions to the error budget in navigation. Therefore, special emphasis is paid to multipath modelling and mitigation methods. In order to develop statistical multipath channel models for navigation a dedicated channel sounding campaign utilizing a zeppelin as an artificial satellite has been performed.

For the future usage of Galileo the development of high-performance and low-cost user terminals for different applications is of central concern. In particular the development of high-end receivers, which utilize an adaptive antenna array for improved signal reception is covered in the work package “terminal development”. Besides the antenna hardware development, this includes the vector channel simulation and development of adaptive algorithms for suppression of interference and multipath signals by digital beamforming and adaptive receiver algorithms. Finally, also the combination of satellite navigation with other sensors or signals, e. g Bluetooth, in an user terminal for improved navigation in environments with difficult conditions for the reception of satellite navigation signals is investigated.

3. CLOCK SYNCHRONIZATION AND TIME DISTRIBUTION

3.1. Timing laboratory

The timing laboratory consists of a clock room where all the atomic clocks are located and of a measurement laboratory where all the signal distribution and measurement devices are placed. Both rooms are air conditioned to avoid time delays due to temperature variations of the hardware. In the clock room there are several atomic clocks located: 3 active hydrogen masers (CH1-75, Kvarz), 2 passive hydrogen masers (CH1-76, Kvarz) and a high performance Cs clock (5071A, Agilent). All the 5, 10 or 100 MHz sine wave signals and the 1pps (pulse per second, TTL) signals delivered by the atomic clocks are connected via cables to the adjacent measurement laboratory. In the measurement laboratory the signals of the atomic clocks are distributed and measured against a defined reference clock. The measurements of the sine wave signals are done with the use of several phase comparators and the measurements of the 1pps signals are done with the use of an accurate time interval counter, see FIG. 1. All the measurement results are stored on a PC. The measurements are done successively, controlled by a switch, in such a way that every 100 seconds a time difference between the reference clock and each of the other available clocks are measured. This data can be used for failure analyses and for creating clock ensembles. Several GPS timing receivers are installed in the measurement laboratory collecting Common View data of several clocks for clock comparison experiments with other national and international timing laboratories.

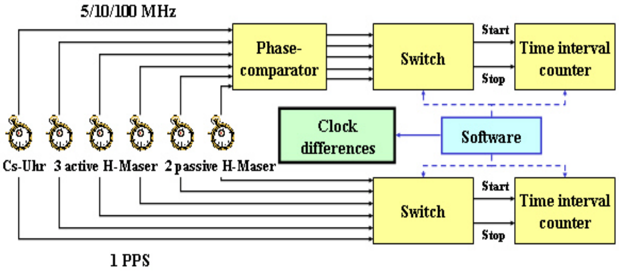

FIG. 1. Scheme of clock comparison

3.2. Phase-synchronous switching of satellite clocks

In satellite navigation systems like GPS, GLONASS or the future Galileo several redundant atomic clocks are mounted on each satellite. Only one clock is used at the same time. Sometimes it is necessary to switch between these satellite clocks. After a switch the new clock must be measured for a certain time before the clock and consequently the satellite can be used again. For GPS satellites for example this certain time is about 7 days. In order to shorten this certain time in GalileoNAV a phase synchronous switch between 10 MHz sine wave signals of two satellite clocks (master and slave) is developed. A high stable VCXO is synchronized via a FPGA to the signal of the master clock using a PLL. Additionally the phase difference between the slave clock and the VCXO signal is acquired with the FPGA. Then the signals of the master and slave clock can be switched without producing a phase jump at the output.

3.3. Algorithms for time transfer

The development of time transfer algorithms and procedures in the frame of the GalileoNAV project focuses on the following problems: investigation of advanced data processing techniques and development of time transfer software.

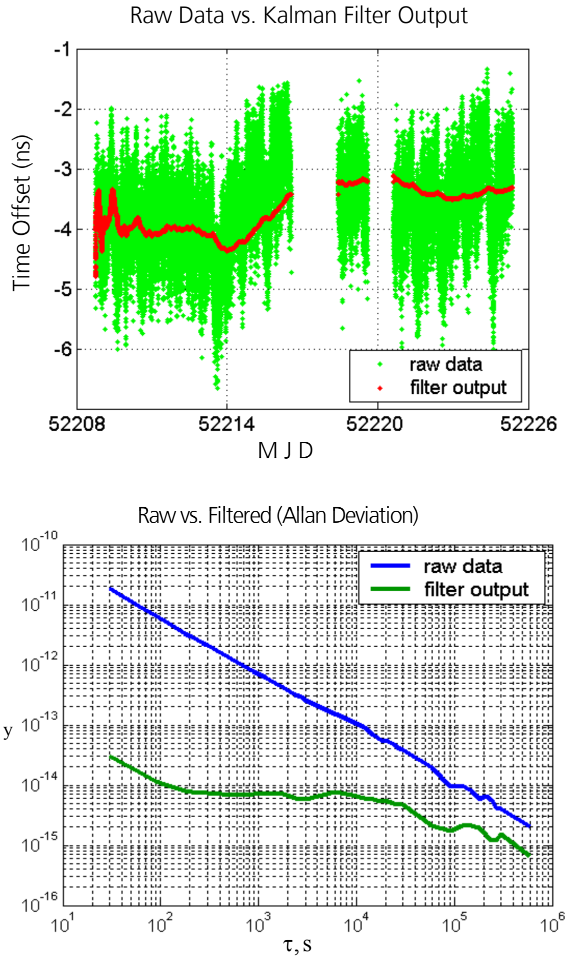

FIG. 2. Time transfer software output before and after Kalman smoother

Smart filtering like Wiener and numerous modifications of Kalman filtering is a promising tool for precise time and frequency transfer. The increase of accuracy could be reached here without additional investments into hardware but just by smart data processing. However, precise modelling of clocks and statistical characteristics of satellite observations required to obtain precise and reliable results still represent a serious problem. After early experiments with restitution of GPS-time with the help of a modified Kalman filter [1], present studies are focused on the process models required for Kalman filtering and statistical analysis of satellite observations to improve the performance of the least mean-squares [2] and the

Kalman filter. The analysis employs both real GPS observations and simulations made with DLR's GNSS simulator NAVSIM [4]. Additional fields of research are the investigation of global Galileo time transfer performance and optimization of time transfer procedures considering Galileo characteristics.

Earlier, the pre-processing of satellite observations for the purposes of time transfer was undertaken by the firmware of time receivers used in time laboratories. Recent experiments of BIPM for time transfer with the new generation of time receivers (Ashtech Z12T) - which have more channels than conventional receivers and possess advanced functionality, but do not have a dedicated time transfer firmware – revealed the need for a new satellite time transfer software capable of processing raw GPS/GLONASS (in future Galileo) observations. The time transfer software being developed in the frame of GalileoNAV [3] is able to compute frequency/time offsets between clocks of two remote stations from GPS pseudorange observations in RINEX format, which is de facto the international standard for the exchange of GPS observation data. Presently, the experimental software version is able to implement both broadcast and precise (as computed by IGS) GPS ephemeris. The ionosphere correction can be computed from broadcast GPS ionosphere model, IGS ionosphere maps or from dual frequency measurements. Two different troposphere models are implemented. The output data can be produced either in CGGTTS format (1 data point for 16 minutes) or in internal DLR format (same rate as raw observations). The modular architecture of the software allows an easy extension of its capabilities. Further work will concentrate on the elimination of anomalous noise for low elevation satellites and on the implementation of carrier phase smoothing of pseudorange observations.

To enable experiments with real GPS data and establish a link to external clocks, an Ahstech Z12T receiver was installed additionally to the other receivers in the timing laboratory and a measurement storage system was implemented.

4. VERIFICATION METHODS AND ALGORITHMS

The topics of the work package are the development of verification methods and navigation algorithms needed for the experimental Galileo/GNSS performance monitoring, for the detection and mitigation of propagation errors in user terminals and for the derivation and provision of augmentations in the frame of application specific local elements. A further task contains the modification and extension of the existing simulation tool NAVSIM based on requirements of external founded projects and on the engineering progress of Galileo.

4.1. Extension of NAVSIM end-to-end simulator

The GNSS SW simulation tool NAVSIM has been developed in a national founded project from 1997 up to 2001. The potential of the basic tool [4] is the simulation of GNSS down links in a specified spatial and temporal scenario considering all significant effects during signal transmission, propagation and reception. Following projects like the ESA project RailSIM (Tuning of train localisation algorithm) [5] and the national founded project GATE (development and establishment of a "Galileo Receiver Test & Support Facility") [6] created additional simulation requirements, which has been fulfilled by modifications and extensions of the basic simulation tool.

Now NAVSIM has the capability to consider pseudolites as an additional source of navigation signals with the options of their static and dynamic positioning, with or without power control. Respectively for the user segment the opportunity is now given to simulate trajectories describing the real movement of users (e.g. train) and to consider the influence of clock type specific receiver clock error behaviour.

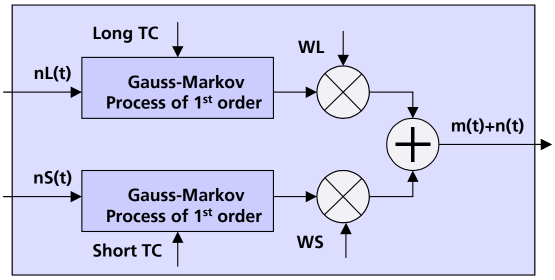

FIG. 3. Error generator model

To achieve an efficient tuning of train localisation algorithms under consideration of the Galileo "Safety-of-Life" service, the development of a fast error generator, modelling the signal specific impact of multipath and noise, was necessary. Based on previous simulations including the NAVSIM signal simulation layer the range and phase errors have been analysed to create signal and environment specific Look-Up tables, where the amount of the multipath and noise error is specified in dependence on the carrier to noise ratio (CNR). During a simulation using this error generator (see FIG. 3), the multipath delays and the noise behaviour are generated corresponding to the momentary CNR of each tracked satellite, which is directly a result of the spatial and temporal transmission behaviour.

A further ongoing work is the implementation of the BOC signals into the signal simulation layer corresponding to the engineering progress of Galileo.

4.2. Algorithms and processors to assess GNSS signals

The experimental assessment of GNSS/Galileo and the development of local elements in order to increase the navigation accuracy and integrity require the provision of corresponding specific algorithms and processors operating in real time.

A representative example is the developed amplitude processor, which has the capability to monitor the signal strength of the tracked GNSS signals and to detect anomalies respectively of the received signal power and their temporal variances. More details with respect to the amplitude characteristics and the developed algorithms are given in [8].

FIG. 4 shows the collected data and gathered results of the GPS satellite 11 tracked in Tromsoe at the 31st Oct. 2003. It can be seen, that the momentary deviation of the

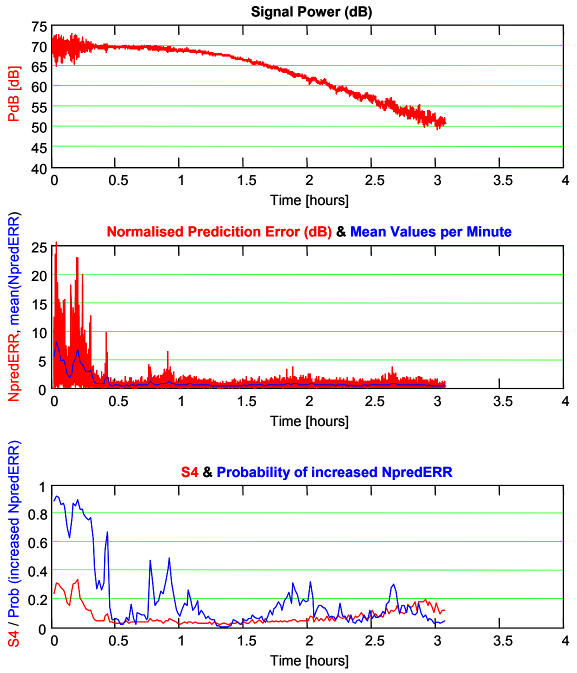

FIG. 4. Measured signal power, estimated power variance and corresponding 1 min mean values, S4 index (1 min) and probability of increased variances per 1 min segment

signal power (NpredERR) and the given probability of increased variances (Prob) are more sensitive to signal power variations in comparison to the S4 [9] index commonly used for ionospheric investigations.

The provided performance parameters by the amplitude processor can be used on the one hand to detect time spans with increased amplitude variances (see FIG. 5) and to investigate the causes around temporal tracking losses.

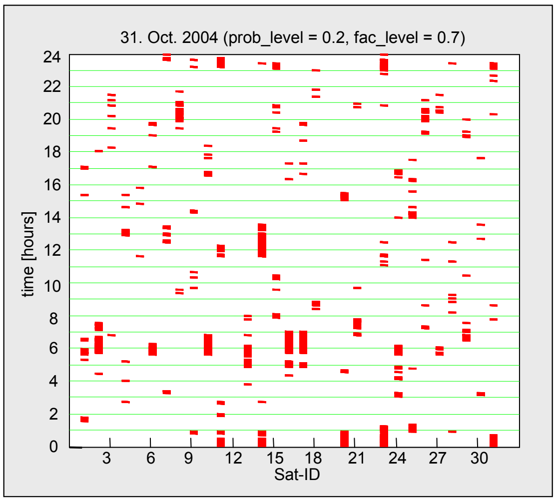

FIG. 5. Periods with increased signal power variances of tracked GPS satellites in Tromsoe at the 31st Oct. 2003

On the other hand they create the data base for the daily performance analysis of the GNSS signal strength behaviour. Similar developments are running in the work package, respectively the code and carrier phase behaviour.

4.3. Atmospheric modelling and measurements

4.3.1. Ionosphere

One of the DLR activities in the field of satellite navigation is the investigation of ionospheric effects on signal propagation. Within this domain ionospheric models play an important role for the investigation [9] as well as for the correction of ionosphere induced navigation errors.

A common ionosphere model application is the correction of GPS single frequency positioning by the use of the so called Klobuchar model, whose model coefficients are part of the broadcasted GPS navigation message. The evaluation of such types of correction models based on globally GPS/IGS-derived ionospheric observations has been one of the DLR activities within the GSTB V1. As an example, one of the results of these activities is given in FIG. 6. It shows (for every day in the year 2000) the 95% probability to obtain ionospheric residual errors below a certain value within the satellite receiver range measurements after applying the Klobuchar or NeQuick [11] correction model. The results are expressed in range delays for GPS L1 frequency. As a reference for the geomagnetic conditions the daily Ap indices [9] are included in the figure.

Another topic, also related to current DLR Galileo activities, is the investigation of phase and amplitude scintillations to small scale ionospheric irregularities. For such investigations DLR operates an experimental receiver in Tromsoe (Norway). The receiver has the capability to record high-rate GPS raw data. These data are used to study on the one hand the occurrence and the amount of scintillation effects based on developed and refined detection algorithms. On the other hand they are the necessary data base to clarify their impact on the GNSS/Galileo performance as exemplarily demonstrated in the previous section (e.g. GSTB V1 Stand Alone Test Case APAF, see also [7]) and to develop advanced forecasting techniques for projects in the frame of "Space Weather" dealing with the prediction and mitigation of propagation influences on satellite based navigation and communication systems.

4.3.2. Troposphere

Tropospheric activities are focused on the comparison of standard correction models, which are implemented in GNSS-receivers, with more sophisticated methods and high precision reference data. As one reference method ray-tracing by utilization of atmospheric vertical profiles for standard atmospheres and from radiosonde soundings has been implemented in NAVSIM. Alternatively, zenith delays which are derived by the IGS-network from post-processing of GPS measurements and are available by the IGS archive [12], are used. The statistical performance of correction models on a global scale as well

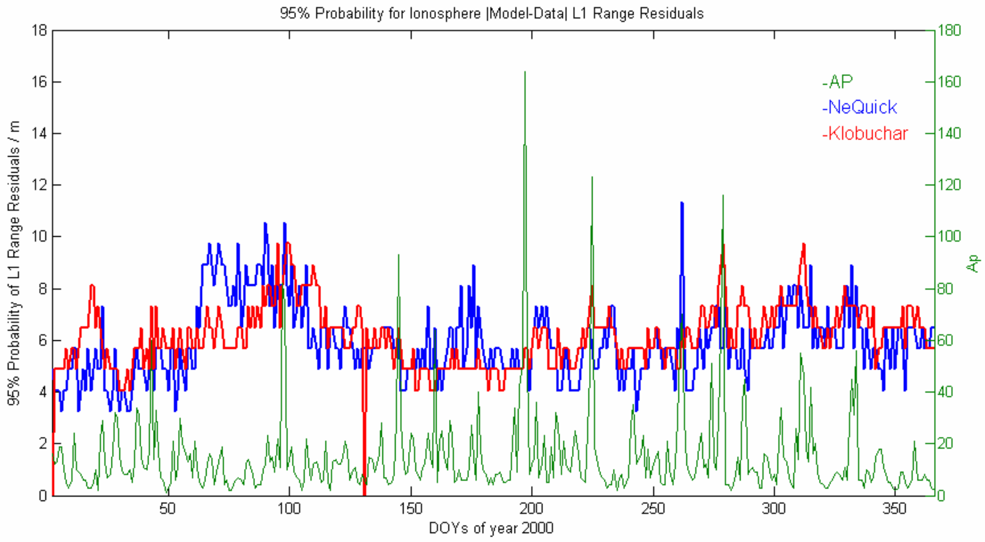

FIG. 6. Range residuals between measured and model data at L1 carrier.

as their behaviour in local events with extreme weather conditions like rapid changes or extreme values of temperature, pressure and water vapour have been analysed within GSTB V1 APAF [7]. The results are published in [13].

Within the frame of the NAVSIM-extensions (see 4.1) the tropospheric reference module described above and further sub-modules for rain and clouds have been adapted to include pseudolites geometries. Additionally, a sub-module for tropospheric scintillations has been developed and integrated.

5. EXPERIMENTAL VERIFICATION NETWORK

The Experimental Verification Network (EVN) aims on the design, implementation, and operation of an experimental facility to support the experimentation and verification tasks of various work packages of the GalileoNAV over-all project. The baseline of the EVN is to provide a network for the development and verification of Galileo algorithms and hardware, including receiver technologies, at the most earliest time by using different sensor stations of currently operated GNSS, and additionally, by feeding near-reality synthetic Galileo signals (see NAVSIM simulator in the section before) into the EVN network. One main feature of the EVN is the opportunity to operate as a near real-time network based on a flexible infrastructure consisting of modular hardware and software components. The network is foreseen to be operated for the reception and distribution of any kind of GNSS data to interested users over suitable communication links like e.g. the Internet. An illustration of the functionality of the EVN is given in FIG. 7.

5.1. Architecture

In principle, the EVN consists of five main elements

- Sensor Stations,
- Central Processing and Control Facility (CPCF),
- Database and Archive,
- Network,
- and Operating Software.

Sensor Stations

Intentionally, the sensor stations are located at various world-wide locations and operate under full remote control of the CPCF. Each sensor station is equipped with GNSS receivers and environmental sensors like meteorological sensors, for instance. Concerning the navigation components in the first step of implementation the reception of GPS, GLONASS, EGNOS, WAAS and Loran-C signals is supported. All sensors are connected to a Host-PC which runs, in connection to a Console Server, the EVN sensor station operating software to control the sensors and to acquire, pre-process, and send the measured and computed data through the EVN Network to the CPCF. Sensors can be connected via serial lines, USB, and/or Ethernet (TCP/IP).

Additional infrastructure hardware in the sensor stations allows for

- transparent access to the internet via LAN or ISDN/modem connection,
- firewall functionality,
- safe shutdown in case of power failures, and
- complete remote control (including remote power-on).

Central Processing and Control Facility (CPCF)

The CPCF acts as the heart of the EVN and is responsible for the monitoring, command, and control of all components of the EVN.

As one essential part it receives all real-time data streams from the sensor stations and distributes them to internal and external clients (customers). The sensor stations can be operated completely via remote control from the CPCF. Thus, no operator personnel is required at the sensor stations for regular operation. Even in case of most problems, maintenance diagnostics and operations can be performed via remote access.

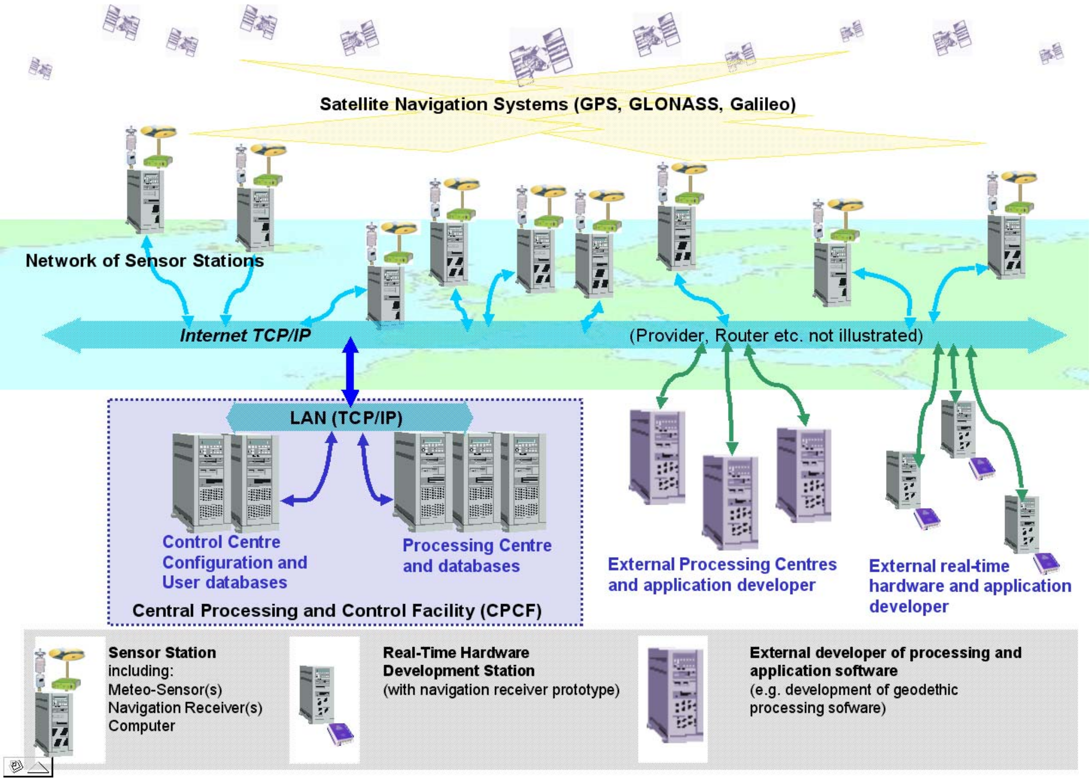

FIG. 7. Simplified scheme of the functionality of the EVN

In the processing centre, streams, received from the sensor stations, will be processed to higher level products which can also be disseminated to clients using the common distribution mechanism as mentioned for real-time data. In case of pre-processing special algorithms and methods for performance verification processing, integrity processing, the estimation of propagation errors, geodetic network processing etc. can be included. Also, the processor for the generation of synthetic Galileo data will be operated here. In consequence, the CPCF provides an opportunity for the development and verification of Galileo and combined GNSS algorithms to external users of the EVN.

Related to the steering aspects the CPCF monitors and controls the status of all involved components (Network, Sensor Stations, External Processing Centres) as well as the state of the utilization of the resources of the EVN.

FIG. 8 shows an overview of the CPCF GUI. The main components of this GUI are a browser (on the left), a logging window (at the bottom), and a working area. The browser shows all important components of the EVN and serves as the main source of control.

Database and Archive

The EVN contains a user database which is the central authority for any kind of access to all components. Access to real-time data streams can be controlled on a per-sensor level. An administrator can delegate control of certain sensor stations to other users allowing them to integrate functionality of the EVN in own experiments easily.

The CPCF keeps track of EVN configurations (operation modes of the various sensors) in a configuration database. This database allows to restore previous system configurations (for instance to repeat certain experiments).

To automatically store all real-time data streams and higher level products (or specific subsets), the CPCF possesses a data archive component. This archive comes with an API (application program interface) which provides read or write access to numerical processors according to the database specifications. Additionally, the data archive

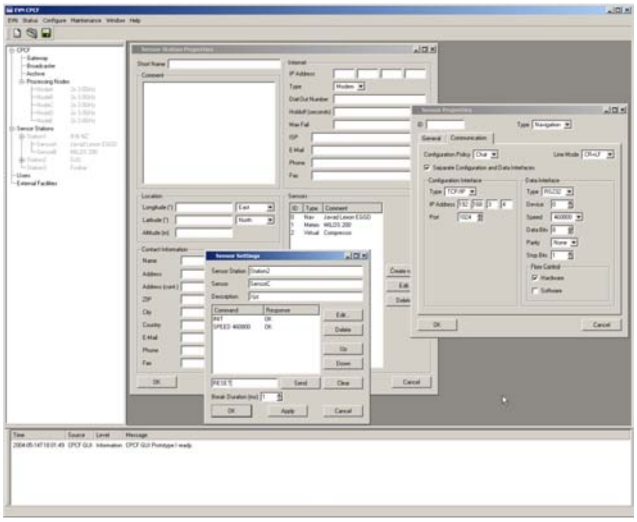

FIG. 8. CPCF Operating GUI

provides a WWW front-end which allows to download archived data via a usual web browser (e.g. Netscape or Internet Explorer) by browsing the archive contents on the basis of certain meta information associated with the actual data (for instance type of sensor and time of broadcast). The matching data is displayed on the web page and can then be downloaded selectively.

Network

All communication between distributed components of the EVN (that is: between sensor stations and the CPCF, and between the CPCF and external customers) is performed via the Internet. No dedicated communication lines are required.

Although the EVN is not intended to be a high-security network, reasonable measures are implemented to ensure integrity of the transmitted data as well as to reduce the risk of abuse. To achieve this, all Internet communication is encrypted and established only after successful authentication procedure using a public-key mechanism.

Due to the usage of the Internet, the transmission capacity of the Sensor Stations is limited by the quality of the local Internet connectivity. To allow for the operation of high update rate receivers, the EVN is looking for monitoring sites, allowing for channel capacities of up to 1 Mbps.

Operating Software

Currently, the EVN operating software is foreseen to run on Linux and Windows 2000, XP, and 2003 Server on x86-based machines. However, porting to other (POSIX) platforms is relatively easy as the platform specific code is restricted to a minimum and is encapsulated in libraries.

The EVN operating software has a modular structure. For instance, there are specific modules to

- upload real-time data streams from sensor stations or other facilities to the CPCF,
- download real-time data streams from the CPCF,
- download archived data,
- control the EVN (via a graphical user interface),
- manage the processing in the CPCF.

To attend the EVN, some of these modules are provided (in binary form) to the EVN customers. These modules have a C-language interface which allows for easy integration in user programs of various languages. For instance, the module to download real-time data streams will be for public use.

5.2. Application potential

According to our expertises and R&D activities in GNSS the main field of application is focussed on the provision of a suitable infrastructure component to support the development and operation of future satellite based navigation systems. However, as a consequence of its open architecture, the EVN can also be of interest for the large area of other applications dealing with provision and exchange of data via internet or other data transmission systems like ISDN, WLAN or satellite communications.

Examples for such fields of applications are:

- Weather observation ,
- Emission control (exhaust gas pollution, noise pollution),
- Acquisition of traffic information,
- Monitoring of the human environment,
- Exchange of information.

6. MODELS AND TRANSMISSION METHODS

To evaluate certain system parameters for the planned wideband services of Galileo using BOC signal structures, it became necessary to measure the wideband satellite navigation multipath channel.

The satellite was simulated by a Zeppelin operating at distances of up to 4000 meters from the receiver. It transmitted a special measurement signal with 10W EIRP and a bandwidth of 100 MHz, which had a rectangular shaped line spectrum consisting of several hundred single carriers. This guaranteed a time resolution of 10 ns for the channel impulse response. By applying an ESPRIT ("Estimation of Signal Parameters via Rotational Invariance Techniques") based super resolution algorithm, the time resolution for the final model will be increased to 1 ns.

For the accurate positioning of the airship we spotted the ship by a camera station on the ground, seated directly under the airship (see FIG. 9). The image of the camera was transmitted via a wireless radio link to a monitor in the airship for usage by the captain.

The heart of the measurement setup was a special measurement bus equipped with the channel sounder receiver, wheel sensors, laser gyros, video system, data recording and GPS sensors.

During the campaign 60 scenarios each lasting from 10 to 20 minutes were measured:

- Land mobile rural channels (freeway and country roads)
- Land mobile urban channels (large city – Munich including motorway)
- Land mobile suburban channels (small city – Fuerstenfeldbruck)
- Pedestrian urban channels (large city – Munich including a shopping street)
- Pedestrian suburban channels (small city – Fuerstenfeldbruck)

Apart from the measurement signal the Zeppelin transmitted an 18.8 GHz carrier for the pedestrian channel measurements. The carrier’s Doppler shift was logged on a ground station in order to measure the Zeppelin’s movement which is in the range of the movement of a pedestrian. This is necessary to calculate the Doppler spreads caused by the receiver and its environment only. For these measurements the bearer of the antenna walked on the pavement accompanied by the measurement bus.

The output of this measurement campaign will be a statistical elevation dependent wideband multipath channel model for the scenarios listed above. For more details and first results we refer to [14] - [17].

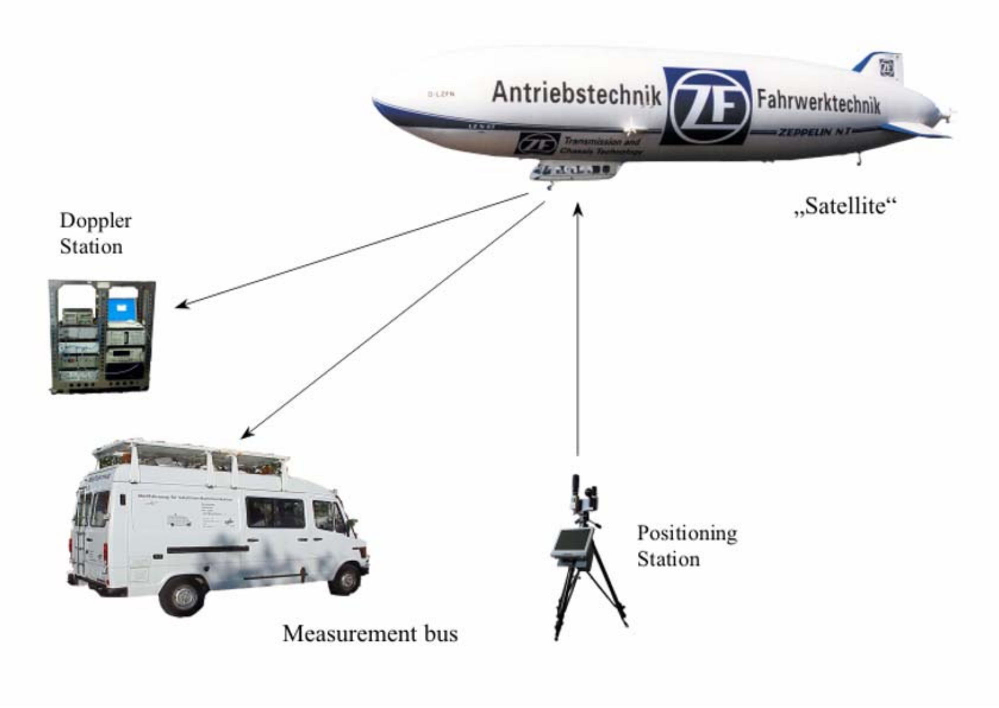

FIG. 9. Measurement setup

7. TERMINAL DEVELOPMENT

7.1. Antenna Development

For monitoring purposes and safety-of-life applications, the positioning accuracy of navigation systems can be improved significantly by using adaptive terminal antennas with intelligent beamforming and -steering. An additional gain provided by limited beam width improves the signal-to-noise ratio, while side-lobe reduction and generation of nulls decisively reduce interference caused by multipath propagation or jammers.

However, in case of non-geostationary satellites, the beam of the terminal antenna must follow the course of the satellite and also compensate any movements of a mobile terminal on the ground. For navigation purposes, a single steered beam is not sufficient. At least 4, better are up to 12 beams, must at the same time automatically track the satellites. Additional beams should implement a search function for the allocation of rising satellites and a replacement for faulty channels. Moreover, interferers must be detected and suppressed by suitable measures in the beamforming process. A typical scenario for the application of a smart multibeam antenna is shown in FIG. 10.

A future-directed technology for the realization of this kind of antenna is digital beamforming [18]. In contrast to conventional phased-array configurations, special multibeam architectures are not required, and the RF part is free of adjustable electronic components. The beamforming procedure is shifted into the digital data processing stage, which facilitates an enormous increase of flexibility. The accuracy can still be improved significantly by calibration and suitable error-correction algorithms, to keep the system independent of external physical influences to the largest possible extent.

In combination with planar patches, active elements can be integrated to build complete receiving modules. By their flat or also conformal design they can be integrated particularly well into the surface of vehicles or airplanes.

7.2. Multipath vector channel modelling

In order to develop and test adaptive beamforming algorithms, which are able to track the satellite signals and automatically detect and reduce/cancel unwanted signals like multipath and jammers, a special simulator for this purpose is developed (see FIG. 11).

The signal generators in FIG. 11 correspond to M different navigation satellite signals. The vector (multiple-input-multiple-output) channel simulator relates the satellite signals with the antenna array outputs (N_e is the number of antenna elements). The digital beamforming block stands for beamforming algorithms under test. The navigation receiver block performs further processing of the received navigation signals purified by the beamforming algorithms and provides sufficient information to estimate the achieved performance improvement for the navigation user.

The vector channel simulator has been realised as a Simulink®/Matlab® software. It accounts for both the spatial (antenna array geometry, correlations of signals among multiple antennas, direction-of-arrivals, angular spectrum) and temporal (multipath fading, Doppler shift,

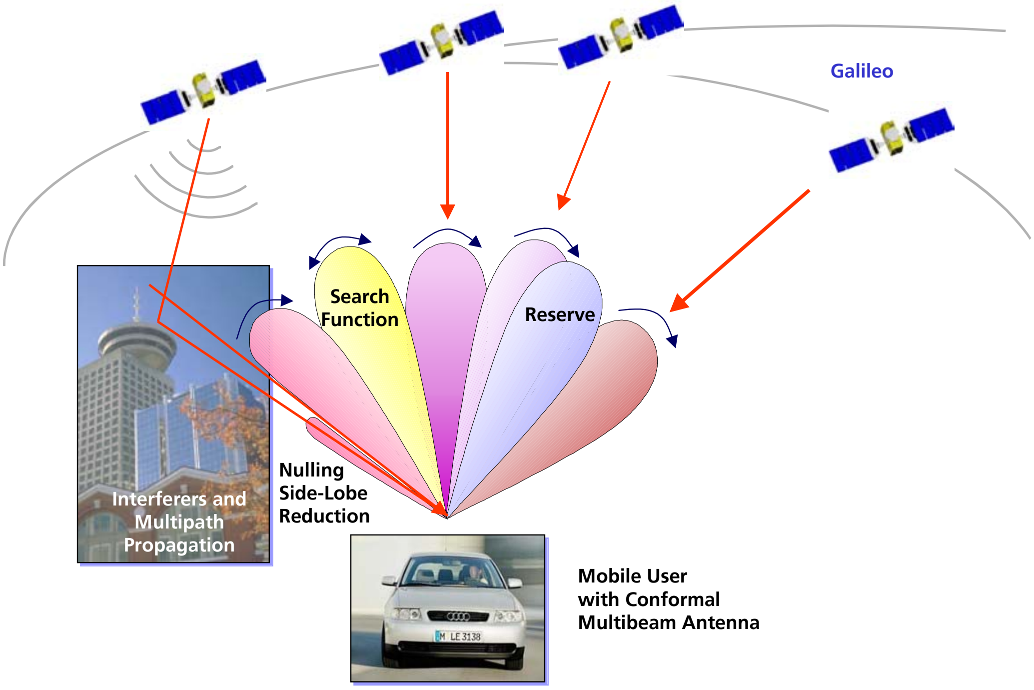

FIG. 10. Scenario for the application of smart antennas

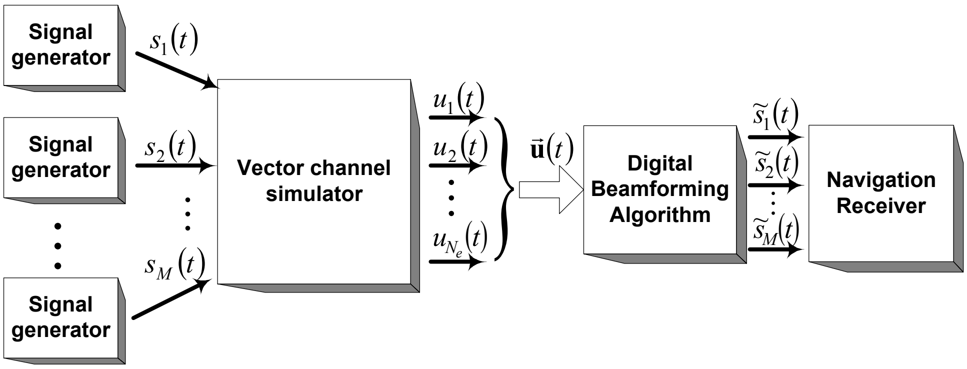

FIG. 11. General structure of vector channel and beamforming simulation.

time-of-arrival) channel propagation effects. The vector channel simulator has been presented in more details in [19] and [20]. Some results for beamforming algorithms performance obtained with the help of the channel simulator have been presented in [21].

8. CONCLUSIONS

The contents and time schedule of the DLR internal project GalileoNAV fits well to the actual tasks within the Galileo development and validation phase. Since it has started end of 2001, some valuable results have been obtained. In particular, a timing laboratory has been build up and brought to an operational phase for clock comparisons, time transfer experiments, and UTC-contribution. The end-to-end simulator NAVSIM has been extended to satisfy the requirements from national and international Galileo testbeds and other projects. A dedicated signal measurement campaign in urban, suburban and rural environments was performed, which delivered a large amount of new and useful data for the improvement of multipath models. Another measurement campaign has been started with respect to ionospheric scintillations. The architecture of an internal verification network was defined and its realization is in good progress. A vector channel simulator was developed, which supports the development of adaptive beamforming algorithms for improved signal reception with multibeam array antennas. All these results provide an excellent basis for the future work in the verification und application of Galileo as well in the ongoing GalileoNAV-project as in external projects together with national and international partners.

9. REFERENCES

[1] [Hahn, J., Kraemer, R., Schmidt, L.: “Results in GPS System Time Restitution with Kalman Filters”, Proceeding of Joint EFTF/IEEE FCS Meeting, 1999, pp. 255-258.

[2] Moudrak, A., Grunert, U.: “Frequency Comparison Experiments with Geodetic Receivers”, Proceeding of Deutscher Luft- und Raumfahrt Kongress 2002, Jahrbuch 2002, Band 3, pp. 2083-2086.

[3] Moudrak, A., Grunert, U.: ”Precise Clock Comparison with Geodetic GPS Receivers”, Proceedings of European Telemetry Conference 2002 ETC, Garmisch-Partenkirchen, 22nd-25th May 2002, pp. 331-342.

[4] Engler, E., A. Steingass and S. Schlüter: “End to End Simulator for the Evaluation of GALILEO”, Galileo’s World. Summer 2001.

[5] Fraile,.M.: "SATURN-An Innovative Concept for GNSS-based Localisation of Railway Vehicles", Proceedings of GNSS'2000, Edinburgh, United Kingdom. May 1-4, 2000.

[6] G. Hein, R. Wolf: “GATE - The German GALILEO Test Environment“, GNSS 2003, Graz, Austria, 22nd-25th April 2003.

[7] GSTB V1 Test Case Specification, GT-DS-DLR-STC No. 187 (12/2002).

[8] Engler, E.: GalileoNav - Technical Note AP 3140, „Validierung signalleistungsbezogene Rohdaten (Javad / Tromsoe) und Prozessorentwicklung“

[9] Hargreaves, J. K.: The solar-terrestrial environment: an introduction to geospace - the science of the terrestrial upper atmosphere, ionosphere and magnetosphere. Cambridge University Press, 1992.

[10] Jakowski, N., K. Hocke, S. Schlüter, S. Heise, Space Weather Effects detected by GPS based TEC Monitoring, Workshop on Space Weather, WPP-155, ESTEC, Noordwijk, 241-244, 1999

[11] Radicella, S. M., “Galileo Ionospheric Model for Single Frequency Receivers”, ESA doc, Ref.-Nr.: ESA-APPNG-SPEC/00344-BAR. 2002

[12] ftp://igs.ensg.ign.fr/pub/igs/tropo/

[13] Hornbostel, A., Hoque, M.: Tropospheric Correction Models for Local Events, ENC-GNSS2004, Rotterdam, 17th-19th May 2004.

[14] Steingass, A., Lehner, A.: "Measuring Galileo's Multipath Channel", GNSS 2003, Graz, Austria., 22nd-25th April 2003.

[15] Lehner, A. , Steingass, A.: “The Influence of Multipath on the Position Error”, GNSS 2003, Graz, Austria., 22nd-25th April 2003.

[16] Steingass, A., Lehner, A.: "Characteristics of the Land Mobile Navigation Channel for Car Applications", GNSS 2003, Graz, Austria., 22nd-25th April 2003.

[17] [Lehner, A. , Steingass, A.: “Characteristics of the Land Mobile Navigation Channel for Pedestrian Applications”, GNSS 2003, Graz, Austria., 22nd-25th April 2003.

[18] Litva, J., Lo, T. K.: Digital Beamforming in Wireless Communications, Artech House, Norwood, MA, 1996.

[19] Konovaltsev, A., Hornbostel, A., Fu, Z.: “Software Vector Channel Simulator for Satellite Signal Multipath Propagation”, DGLR-Jahrbuch 2002, pp. 1135-1140.

[20] Konovaltsev,A., Esbrí, O., Hornbostel, A.: “An Approach to Physical-statistical Modelling of the GNSS Vector Radio Channel“, GNSS 2003, Graz, Austria., 22nd-25th April 2003.

[21] Konovaltsev, A., Belabbas, B., Denks, H., Hornbostel, A.: “Adaptive Antenna against Multipath?”, GNSS 2004, Rotterdam, the Netherlands, 16th-19th Mai 2004.