The DLR Project GalileoNAV: An Overview

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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 first 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 an 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 modeling 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 as well of high-performance as of 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 utilization of communication signals in an integrated NAVCOM 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 Figure 1. All the measurement results are stored to 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. The performance of the measurement system is as good that the atomic clocks can be measured in their full performance. 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.

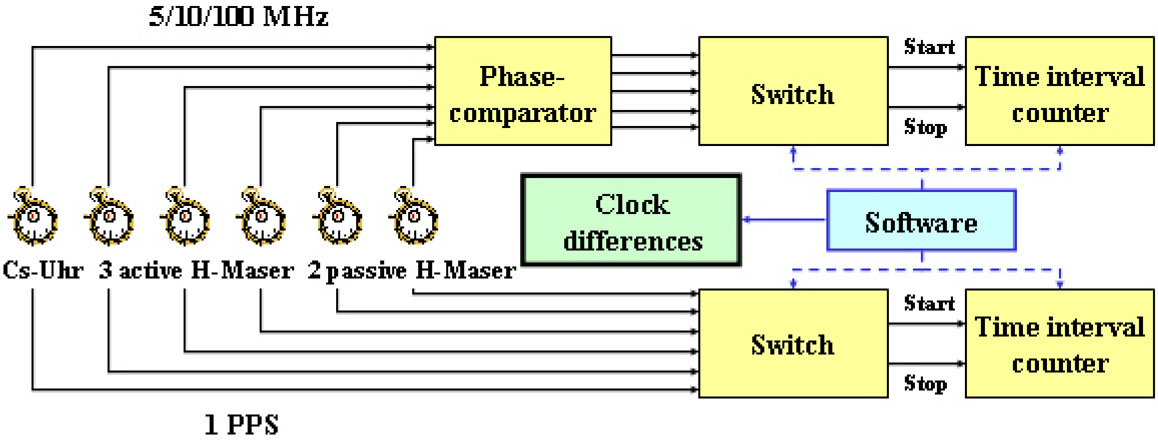

Figure 1: Scheme of clock comparison

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. The signal of the master clock is synchronized to a high stable VCXO using a PLL. Additionally the phase of the slave clock signal is shifted to the phase of the VCXO. 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.

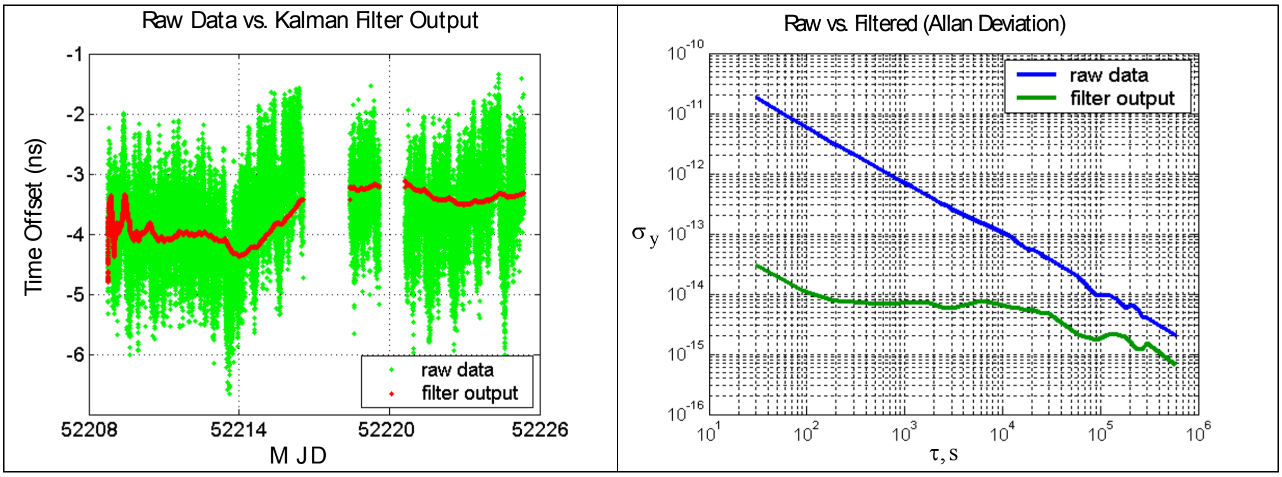

Figure 2: Time transfer software output before and after Kalman smoother

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 modeling 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 work package is focused on the modification and extension of the existing simulation tool NAVSIM [4] based on requirements of external founded projects, the development of detection and mitigation techniques for user terminals and local components to suppress the influence of ionospheric and tropospheric propagation errors, and finally to the development of verification methods and algorithms for the Galileo/GNSS performance monitoring and their implementation in the experimental verification system.

4.1 Extension of NAVSIM end-to-end simulator

In the frame of the ESA project RailSIM the need occurs, to tune the train localization algorithm “SATURN” [5] of the enterprise Socratec GmbH (Regensburg) respectively the “Safety-of-Life” Service of Galileo under consideration of the availability of single, dual and triple carrier frequencies, and of the corresponding ranging behavior of the proposed signal types. Therefore the basic NAVSIM tool has been modified on the one hand to operate with real train trajectories describing the train movement. On the other hand it was necessary to develop and to implement a fast error generator module modeling the signal specific impact of multipath.

Based on previous simulations including the NAVSIM signal simulation layer the range and phase errors are analyzed to create signal and environment specific Look-Up tables, where the amount of the multipath error is specified in dependence on the CNR. During a simulation using this error generator, the multipath delays and the noise behavior are generated corresponding to the momentary CNR of each tracked satellite, which is directly a result of the spatial and temporal transmission behavior (Figure 3).

Furthermore several receiver clock models have been integrated to analyze their impact on the positioning performance.

Another requirement from the national founded project GATE (development and establishment of a “Galileo Receiver Test & Support Facility”) [6] was the validation of the test bed area considering Galileo and pseudolites. Therefore the NAVSIM tool has been extended respectively pseudolites (static/dynamic; with/without power control).

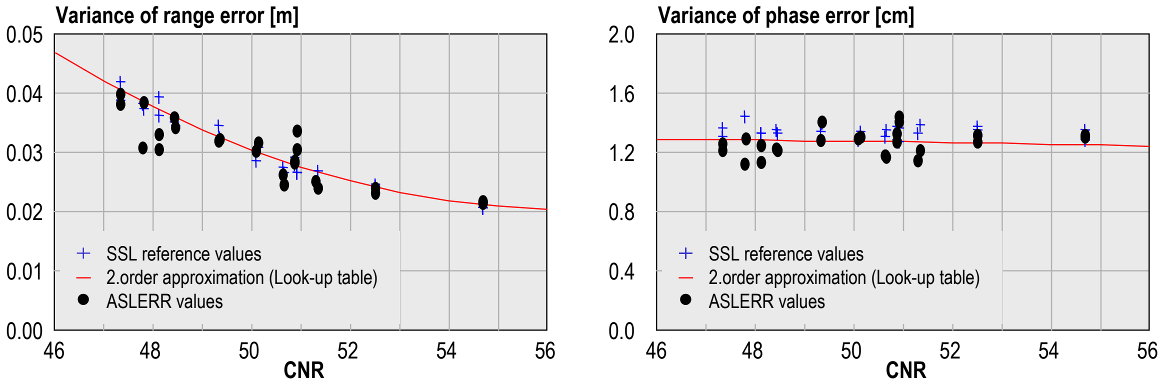

Figure 3: Comparison of error variances delivered by the NAVSIM signal simulation layer(SSL) and the fast "Error Generator" module (ASLERR).

4.2 Atmospheric modeling and measurements

4.2.1 Ionosphere

Running ionospheric activities are momentary focused on the real time detection of scintillations and their advanced modeling. Therefore DLR operates an experimental receiver in Tromsoe, which has the capability to record high-rate GPS raw data. These data will be used to study on the one hand the occurrence and the amount of this effect on the GNSS/Galileo performance (GSTB V1 Test Case "Atmospheric Performance Assessment Facility" [7]). In a second step their analysis shall result in advanced forecasting techniques for DLR projects in the frame of "Space weather".

4.2.2 Troposphere

Tropospheric activities are focused on comparison of standard correction models, which are implemented in GNSS-receivers, with more sophisticated methods, in particular ray-tracing through the atmosphere. In the past, for this ray-tracing standard atmospheres have been used [8]. Now real atmospheric vertical profiles from radiosonde soundings are under implementation. While in general the statistical mean error of standard correction models is known in their long-term behavior, these comparisons concentrate on local events with extreme weather conditions, like rapid changes or extreme values of temperature, pressure and water vapor.
Within the frame of the NAVSIM-extensions (see 4.1) the tropospheric reference module, based on ray tracing and further sub-modules for rain and clouds, has been adapted to include pseudolites geometries. Additionally, a sub-module for tropospheric scintillations has been developed and integrated.

5 Experimental Verification System

The Experimental Verification System (EVS) 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 EVS is to provide an opportunity for the development and verification of Galileo algorithms and hardware, including receiver technologies, at the most earliest by providing a monitoring network for currently operated GNSS, and additionally, by feeding near-reality synthetic Galileo signals (see section 4) into the EVS network. A rough scheme of the network is given in Figure 4.

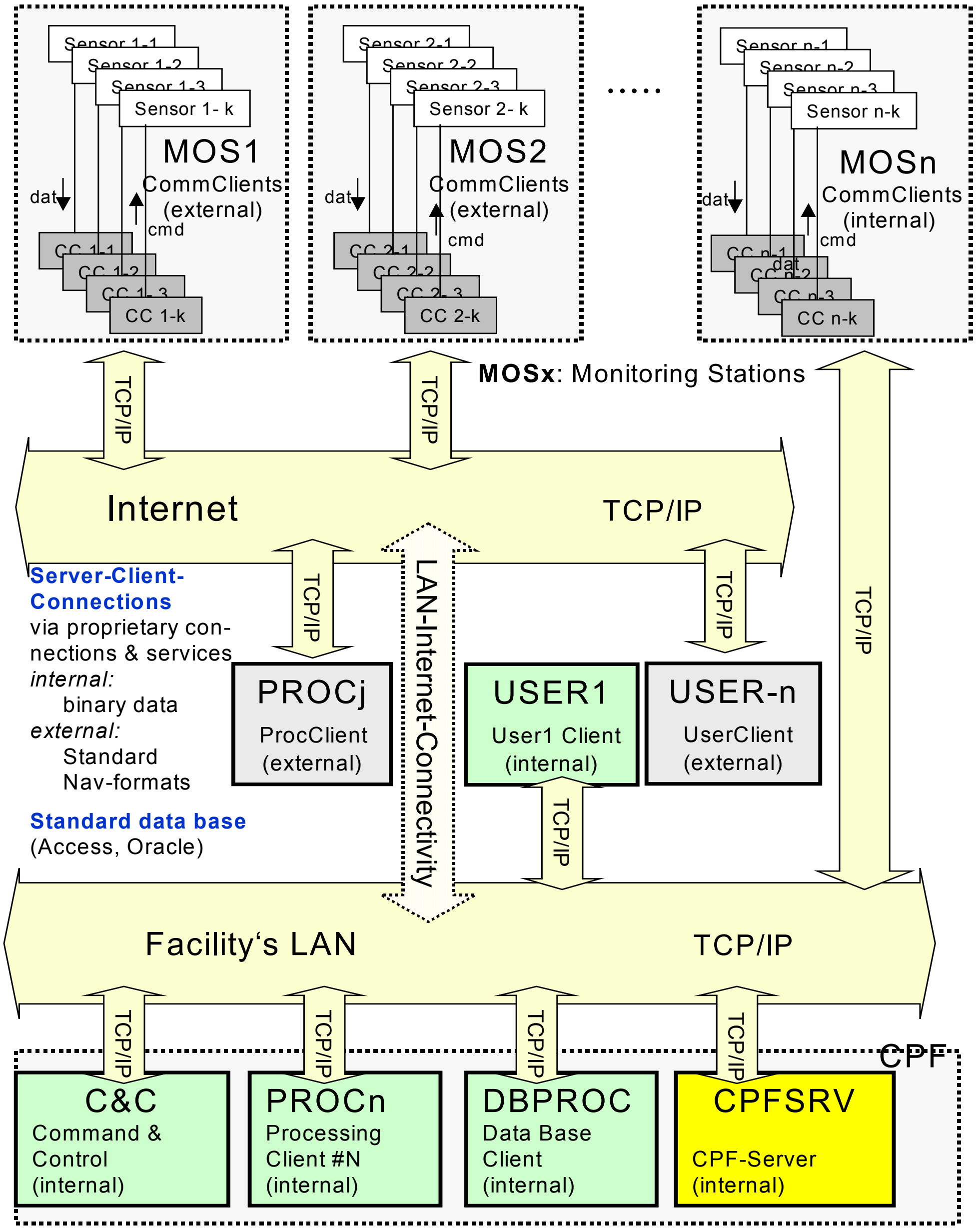

Figure 4: Structure and functionality of the GalileoNAV Experimental Verification Network

The EVS consist of the following components:

Monitoring Stations (MOS)

The monitoring stations of the EVS will be operated at specific European sites under remote control of the EVS Control Facility. All station can be equipped with various GNSS receivers and additional environmental sensors, e. g. meteorological sensors. In the first step of implementation, equipment for the reception of GPS, GLONASS, Loran-C, and EGNOS navigation signals, and meteorological sensor are foreseen at each station.

Both, GNSS and additional sensor data will be acquired by the Monitoring Station data processing, command&control computer and sent to the Control Facility through the EVS Network. On the other hand, all receivers and sensors can be configured remotely according to the needs of experimentations by the Control Facility.

EVS Network

The EVS Network provides the basis for the networked operation of the EVS by taking advantage of Internet TCP/IP connectivity. All data acquired in the Monitoring Stations will be transferred via the EVS Network to the Control Facility and Processing Facility. To provide the required security, all transfer, no matter if for data or commands, is based on proprietary secured protocols. Due to the usage of the Internet, the transmission capacity of a Monitoring Station is limited by the quality of the local Internet connectivity. To allow for the operation of high update rate receivers, the EVS is looking for monitoring sites, allowing for channel capacities of about 50-100 kByte/s.

Control Facility

The EVS Control Facility is aimed for the monitoring, command, and control of all components of the EVS. This includes the monitoring of the Monitoring Stations processing status, including the receivers and sensors, the state of the utilization of the resources of the EVS. The control facility also regulates the user access to the resources of the EVS, e. g. Monitoring Station data, data base, whether real-time or not, privilege for receiver and sensor configuration.

Processing Facility

The EVS Processing Facility is aimed for the implementation and operation of navigation data processors, that rely on the availability of EVS data received in real time or archived from several Monitoring Stations. Typically, this applies to performance verification processing, integrity processing, estimation of propagation errors, and geodetic network processing. Besides, the processor for the generation of synthetic Galileo data will be operated here. In consequence, the Processing Facility provides an opportunity for the development and verification of Galileo and combined GNSS algorithms to external users of the EVS.

EVS Data Base

All data as transmitted and processed in the EVS Network, can be passed to the Data Base of the EVN and can be used by the processors of the Processing Facility on request. Additionally, the data can be supplied under control of the Control Facility to authorized users via a WWW or ftp interface.

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.

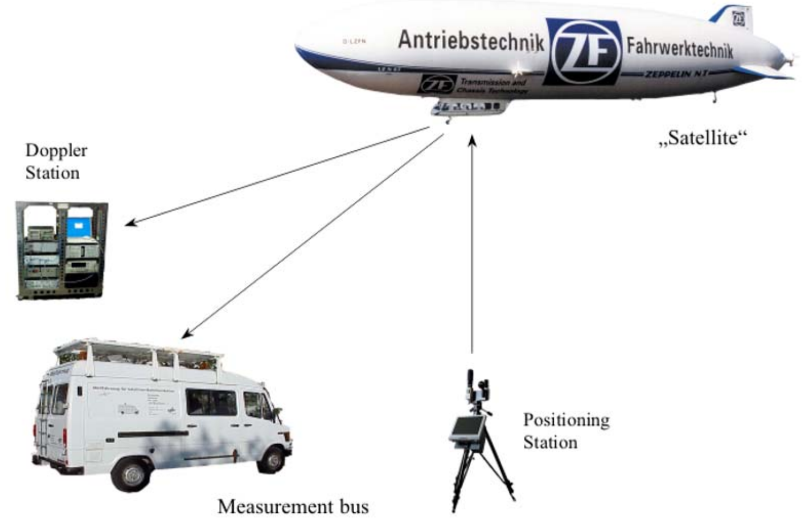

Figure 5: Measurement setup

For the accurate positioning of the airship we spotted the ship by a camera station on the ground, seated directly under the airship (see Figure 5). 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 a 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 this 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 [9] - [12].

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 Figure 6.

A future-directed technology for the realization of this kind of antenna is digital beamforming [13]. In contrast to conventional phased-array configurations that require complicated multibeam architectures, 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 transmitting and receiving modules. By their flat or also conformal design they can be integrated particularly well into the surface of vehicles or airplanes. More details are presented in another paper of this conference [14].

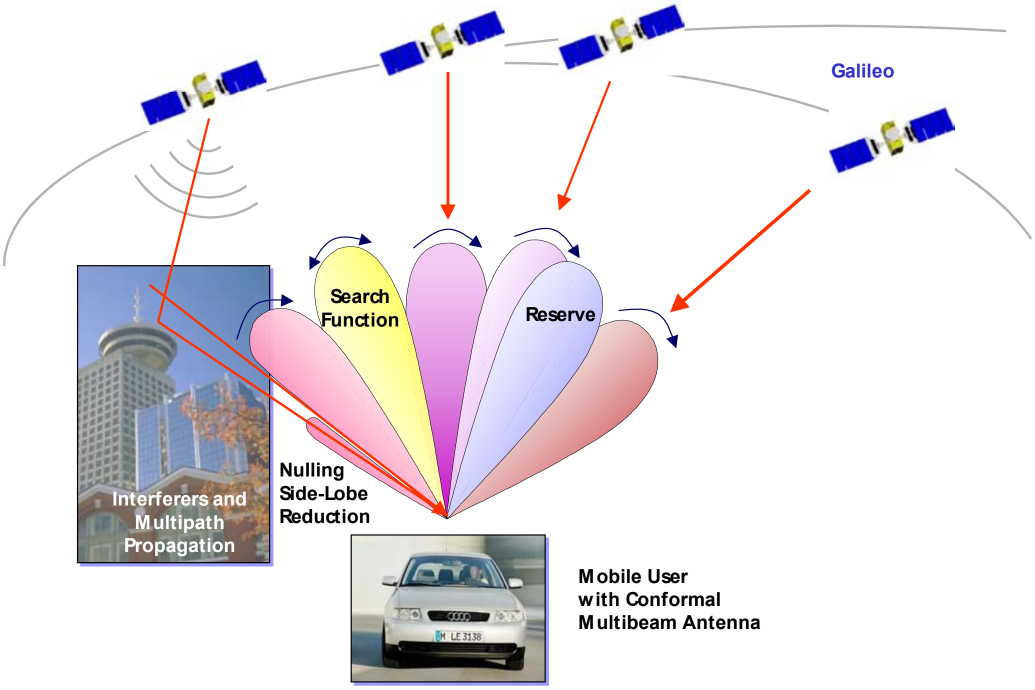

Figure 6: Scenario for the application of smart antennas

7.2 Multipath vector channel modeling and mitigation

In order to develop and test adaptive beamforming algorithms, which are able to track the satellite signals and can automatically detect and reduce or cancel unwanted signals like multipath signals and jammers, a special simulator for this purpose, presented in Figure 7, is developed.

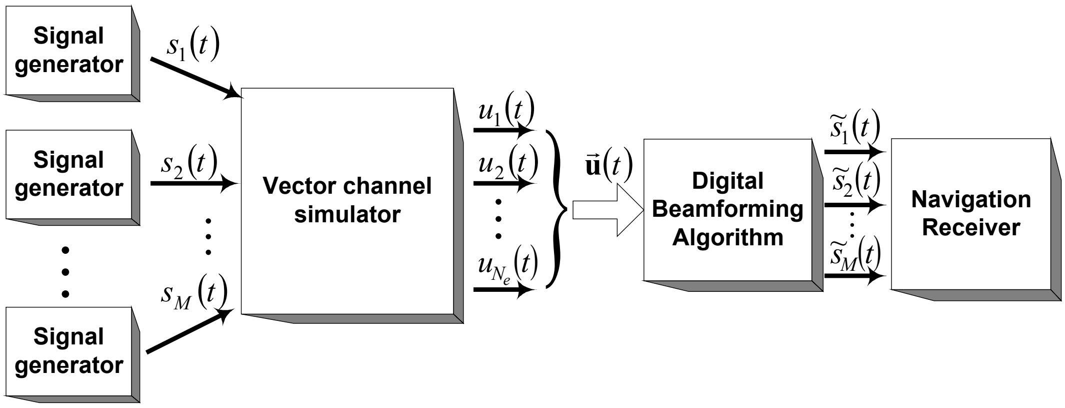

Figure 7 General structure of vector channel and beamforming simulation.

The signal generators correspond to M different navigation satellite signals. The vector (multi-input-multiple-output) channel simulator relates the satellite signals with the antenna array outputs $u_1, u_2, \ldots, u_{N_e}$ (N_e is the number of antenna elements). The digital beamforming block stands for beamforming algorithms under test and the navigation receiver block performs further processing of the M received navigation signals $\tilde{s}_1(t), \tilde{s}_2(t), \ldots, \tilde{s}_M(t)$ purified by beamforming and provides sufficient information to estimate the achieved performance improvement for the navigation user.

The vector channel simulator in the left hand part of Figure 7 provides information about both the spatial (antenna array geometry, correlations of signals among multiple antennas, direction-of-arrivals, angular spectrum) and temporal (multipath fading, Doppler shift, time-of-arrival) channel propagation factors. A first version of the vector channel simulator has already been implemented and is presented in more details in [15] and in another paper of this conference [16]. Suitable beamforming algorithms which now shall be tested by simulation are discussed in [17].

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, already 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 has been started. 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.

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