Modular end-to-end software simulator for navigation systems

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1 Introduction

In the last few years the need for simulation for navigation systems has greatly increased. The problem of simulating navigation systems is on the one hand the handling of the large physical transmission bandwidth which causes a very high sampling frequency and computational complexity and on the other side the (comparatively) slowly changing scenario (ionospheric or tropospheric influences, satellite tracks, user movements, clock drifts, and others). This conflict of time-scales would normally result in an extensive simulation effort which is not acceptable since it would lead to excessively long simulation times. In this paper we will present a multi-layer approach which ensures the detailed description of the physical layer on the one hand and still handles simulations over long periods of time.

In the first step we create a simulation system for the physical layer. In the paper we sometimes refer to this as the lower layer. This system performs the detailed simulation of signal aspects including all aspects of digital signal processing, such as receiver noise, multipath effects, DLL and PLL Loop filters (Bandwidth, Filter Type, Detectors), spreading codes (C/A, PN, Gold), pulse shaping (Rectangular, Raised cosine, Root Raised cosine etc.), chip rate, transmission bandwidth, and other hardware and signal processing aspects in the transmitter and receiver path. The modeling of the physical aspects is undertaken by simulating 30 second long signal-sections for a reasonable number of carrier to noise ratios C/No and for the occurring multi-path channels. Due to the highly detailed simulation at sampling frequencies of 100 MHz and more, and the high computational complexity of interpolation and correlation, each of these simulations take about one day on a high performance workstation. The result of the simulation is a recording of the tracking error of the receiver loops, from which the variance, mean, and spectrum of the loop errors for each C/No-channel-combination are extracted. In a second step a model of the physical signal processing for the system layer is generated based on these statistical parameters and on the noise free dynamic behaviour (tracking error) of DLL and PLL.

In a third step the slowly changing system aspects are modelled: Satellite tracks, user movements, atmospheric distortions (ionosphere, troposphere, channel selection), antenna effects, system and satellite time behaviour and importantly the solution of the navigation equation. This (upper) layer is on the one hand used to estimate the states of GNSS signals described by CNR, ranges, phases and corresponding rates and to derive representative samples for the detailed simulation. On the other hand in this layer the corresponding delay measurements are composed (adding technical and natural/physical components) and used for positioning. This can be done for a specified number of dynamic or static users inside a defined region using one or several satellite systems. In this (upper) layer we are also able to test new algorithms such as navigation equation solvers, ionospheric estimation algorithms, intelligent directive antennas, clock models etc.

Since we use a flexible software and block based design we can quickly adapt to changes of the system during the definition phase of GNSS2. The assessment of an overall system constellation can then be done by measuring the accuracy, the availability and even the reliability. By splitting the overall simulation task into these two layers and by employing the concept of error signal modelling, we are able to successfully tackle the problem of different simulation time-scales.

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The paper is organized as follows: we begin by presenting the architecture of the simulation system and its separation into the upper Application Simulation Level (ASL) and the lower Signal Simulation Level (SSL). This is followed by (preliminary) simulation results and sample plots of interesting physical system quantities for a specific date and location in Europe. The paper summarizes the main results of our work in a brief conclusion.

2 Architecture of the Simulation System

2.1 Functional Diagram

The **NAVSIM** software simulation system consists of two levels: the signal simulation level (SSL) and the application simulation level (ASL). Both levels (Fig. 1) are necessary to determine the positioning performance of a global navigation satellite system (GNSS) under consideration of nearly realistic conditions.

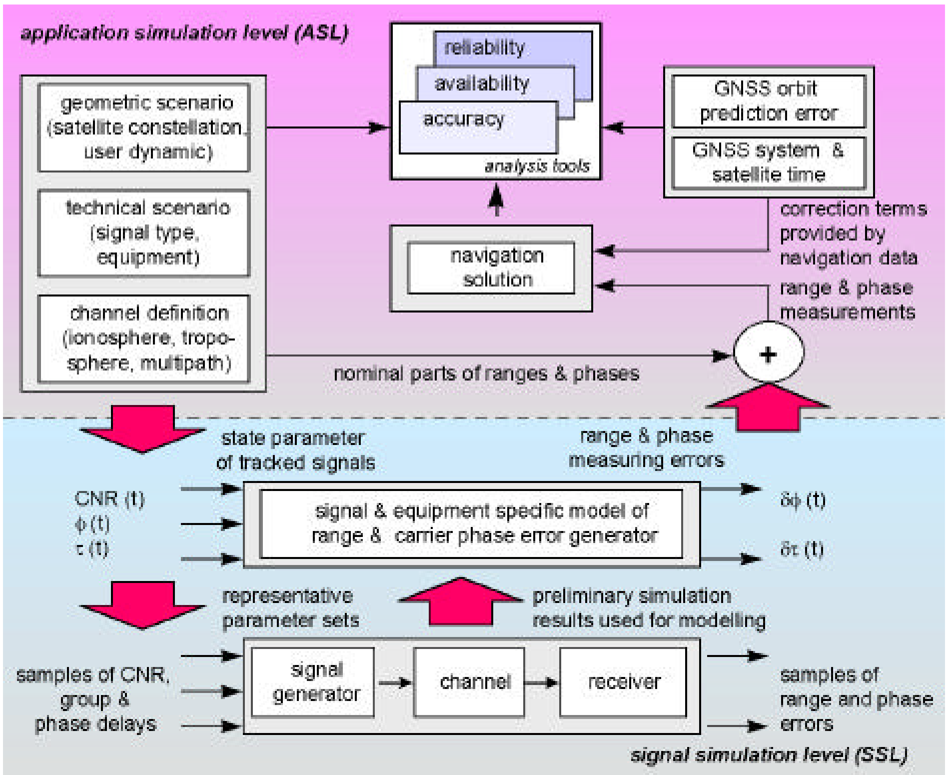

Fig 1 Functional diagram of the GNSS end-to-end software simulation system

The application simulation level is on the one hand responsible for the specification of the global simulation parameter like start and end point of simulation, considered region and sampling frequencies. On the other hand the simulation system composition of the end-to-end or the partial simulation is realised and comprises the selection of optional modules and the definition of the operation mode for possible simulation tasks. Based on these defined global parameters the next steps are the initialisation of each selected module and if used of the simulation subsystem SSL. At the end of simulation system setup the geometric scenario (satellite constellation, user dynamics), the considered components (e.g. type and models for signal generation, propagation channel, receiver hard- and firmware) and the aimed results (e.g. signal states, navigation solution) are defined.

During the simulation run the application simulation level generates the signal states at the receiver input (CNR, range and phase delays) and the nominal parts of range and phase measurements. The signal states are used by the SSL to derive at each time stamp the corresponding measuring errors for the range and phase measurements. Because the calculation of range and phase errors of a specified system equipment is very intensive regarding computer time and memory, an error generator model is therefore used during the run of the end-to-end simulation. This model is derived from preliminary simulation runs of SSL using several sample sets of relevant signal states (including worst case example). The measuring errors delivered by SSL are added to the nominal parts of range and phase (ASL). The so composed range and phase observations of the tracked satellites are the data base, which is used for positioning. In addition, the system and satellite time behaviour and the orbit prediction error are generated by the ASL. They are used as error correction terms for the navigation solution. By comparison of the calculated and the specified position of one or several users the accuracy, the availability and the reliability of positioning can be assessed. Both simulation levels are constructed modularly. Therefore, it is possible for further applications to substitute single modules by improved realisations or to compose extended simulation systems.

2.2 Application Simulation Level (ASL)

Inside the application simulation level the composition of the simulation system is carried out, which means the operation mode, the use of optional modules and the definition of universally valid parameter will be specified. Four basic types of operation mode are supported:

1. statistical analysis of signal states inside a spatial and temporal window
2. composition of GNSS observations (ranges & phases) and corresponding estimation of the accuracy and availability of positioning
3. extended composition of GNSS observations (range & phases) including the error generator model of the SSL and corresponding estimation of the accuracy and availability of positioning
4. estimation of GNSS reliability by evaluation of several simulation runs with different spatial and temporal windows for typical static and dynamic applications

After specification of the universally valid parameter the initialisation of each selected module follows. The selection of models and the specification of necessary parameters is realised per module by one or more dialog windows (Fig. 2).

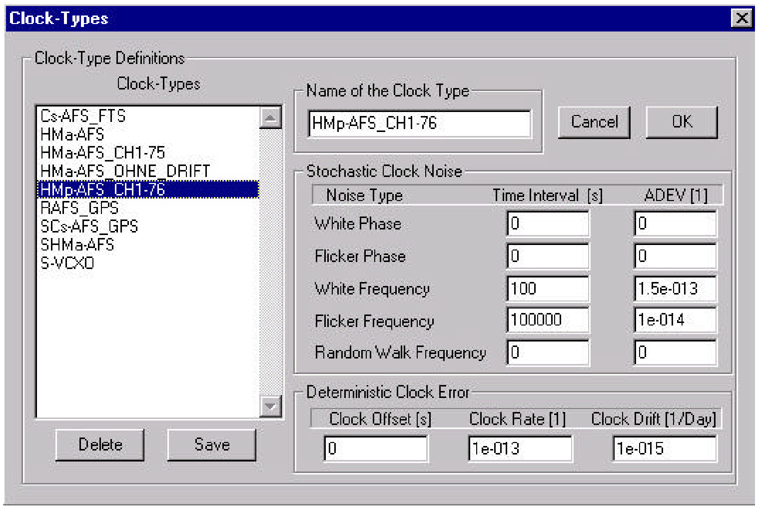

Fig 2 Initialisation of clocks for system and satellite time

Each initialisation step checks the value range, the parameter plausibility and the consistency before this initialisation step is accepted. A simulation run can only be started if all initialisation files are signed as accepted.

During the simulation run at each time step the geometric available satellite signals are determined. This is based on one or several satellite constellations described by a set of orbit parameters (almanacs or ephemerides) and on a user segment, where the position and motion of considered users is specified.

For these available links the most important effects which influence the ideal signal propagation from the satellite to the receiver are now calculated (satellite and receiver antenna effects, ionospheric and tropospheric propagation errors, multipath and shadowing).

To simulate the impact of regular and irregular ionospheric effects on radio propagation three models are implemented: IRI95 [BIL90] , BENT [LLE73] and GIM. Whereas IRI95 and BENT allow the reproduction of regular or mean ionospheric behaviour, GIM gives the basis for modelling amplitude fading and phase scintillation caused by small scale electron density irregularities in the ionosphere.

Included tropospheric propagation errors are delay, attenuation and thermal noise by the clear atmosphere and rain clouds. For the clear atmosphere vertical profiles of temperature, pressure and water vapour density for different regions and seasons are implemented. Additionally, rain effects can be included either for a preselected system availability utilising the ITU-R rain model [ITU94] or for a user defined rain rate applying a stratiform or cylindrical raincell model. For the computation of the specific delay due to rain the real part of the refraction index is calculated with the MPM89-model [LIE89].

Based on given radiation pattern of several satellite and receiver antennas its influence on signal strength and its capability to reduce multipath effects will be considered. Additionally, the variation of the antenna phase centre can be reproduced, which is essential to receive accuracy in the mm range by evaluating the carrier phase signal.

Another disturbing effect is known as signal multipath propagation and results from out the superposition of direct and indirect signal components, which comes from reflection in the near environment of the antenna. The multipath can be described alternatively by deterministic or statistical models. In ASL a deterministic model will be implemented, but is primary used to improve the statistical models used in SSL.

The above mentioned modules and the additional free space propagation module are used to compose the signal states (CNR, group and phase delay) and the nominal parts of range and phase measurements, both determined under consideration of the specified technical link parameters like transmission power, polarisation and carrier frequencies.
The software also simulates the error effects caused by real physical clocks. For that the stochastic error of all used clocks are simulated by using a power-law model. Additionally the deterministic clock errors like clock offset, frequency rate and drift are modelled too. With the simulated physical times of all clocks, the software calculates with different algorithms the system time as well as the clock correction coefficients for each satellite. Additional a module is designated to reproduce the orbit prediction errors. Both modules are needed in combination with the composed range measurements to estimate the user positions by suitable navigation algorithm. For the simulation system two types of navigation solution are integrated for the time being. The first type of navigation algorithm is based on geometrical orientation of satellites and receiver [KLEU94]. The second type of navigation algorithm [BANC85] computes the receiver position as a solution of all satellites in view. Additional information like a preliminary receiver position are not necessary, but an iterative process has to be performed.
The on-line derived results (signal states or position accuracy) are directed to evaluation modules, where a region or time dependent analysis (e.g. mean values, RMS, distribution) can be realised and shown using various different graphic types like bar charts, plot charts, contour plots and histogram plots.

2.3 Signal Simulation Level (SSL)

Because the simulation system is primary designated to simulate GPS as well as the new Galileo system [EC99], the simulator is limited to a CDMA compatible signal structure.
While trying to simulate navigation systems one major problem occurs: There are extremely fast processes at chip level which are characterised by large bandwidths of about 20-40 MHz. On the other hand medium to extremely slow processes occur in the transmission scheme (e.g. troposphere, ionosphere, satellite movement ...). To obtain a meaningful result several cycles of the lowest process should be simulated which leads to a simulation duration longer than days in real time. If one would simulate the extremely fast processes on the chip level for that duration of real time the fastest computer would not be able to simulate the system.
To eliminate this problem a two stage process was selected (Fig. 3):

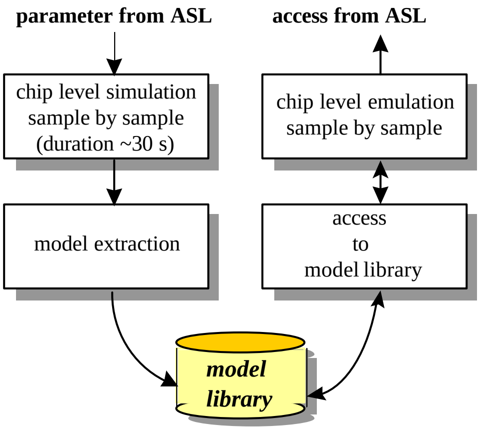

Fig 3 Model of the signal simulation level (SSL)

1. In the first step the application simulation level (ASL) generates a set of parameters and passes these to the signal simulation level. Within this level some highly detailed chip level simulations are simulated. A second instance extracts models from these simulations which are stored in a model library.
2. From the point of view of the slowest processes (ionosphere, troposphere, satellite movement) the physical synchronisation process does not change. Therefore the ASL can use the models from the Model Library to emulate the behaviour of a real simulation by using the stored models.

To model the physical behaviour the following terms are extracted:

- Variance of the synchronisation error
- Mean of the error
- Power spectra density of the error of a DLL and PLL.

The determination of the above mentioned terms is based on a specific composed model, where the

- Signal structure (chip rate, pulse shape, spreading code, carrier frequency...)
- Satellite equipment (High Power Amplifier, Output band pass filters ...)
- Channel conditions (Multipath)
- Desired Signal to noise level (SNR)
- Receiver layout usually a standard DLL & PLL as described in [GML93], [SDS98] and [PAR96]

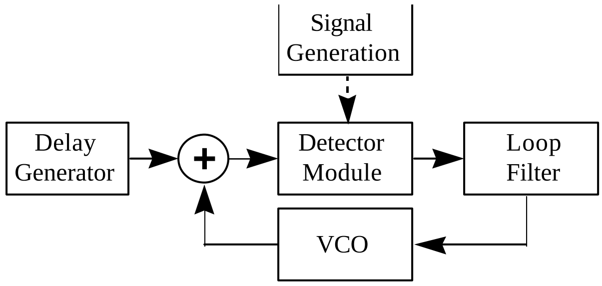

Fig 4 Layout used for chip level simulation

must be defined by many of parameters. On the chip level we use the simulation layout depicted in Fig. 4. First one frame (code word) of the transmitted navigation signal is generated. After having completed this, the delay generator generates 30 s of a signal whose values are proportional to the transmission-delay from the satellite to the receiver in the real world. The detector module calculates the output of the correlators of a standard DLL (see [PAR96]) and the actual deviation from the estimated pseudo range. This is filtered by a loop filter and forwarded to the voltage controlled oscillator. The result of that is the estimated pseudo range. This estimated pseudo range is substracted from the real range signal which closes the loop. Multipath errors are handled within the detector module by using a statistical model and cause both deviations in mean and in variance.

In that pre-simulation the variance, mean and power spectra density of the synchronisation error is extracted and yields the models for the later simulation.

3 Preliminary Simulation Results

The project **NAVSIM** will be finished at the end of the year 2000. Therefore, at this moment in time only several examples of partial simulations can be given to show the capability of the future end-to-end software simulation system.

3.1 Receiving Conditions in Europe on January 1st, 2000

The composition of the signal states and the corresponding range and phase measurements is based on the calculation of the part of each technical component and natural impact. The tropospheric transmission behaviour results in signal disturbances described by attenuation and noise terms and by code and phase delays. All derived terms are a function of the regional weather conditions and their daily and seasonal variations. The ionospheric influence on signal transmission depends on the solar activity, which is correlated with the electron density inside the ionosphere and the appearance of irregular effects (e.g. scintillation). In the year 2000 the 22nd solar cycle will reach its maximum and in consequence the ionospheric influences will drastically increase. Corresponding signal disturbances are rapid changes of signal amplitudes, code and phase delays and result in information losses and reduced tracking capabilities.

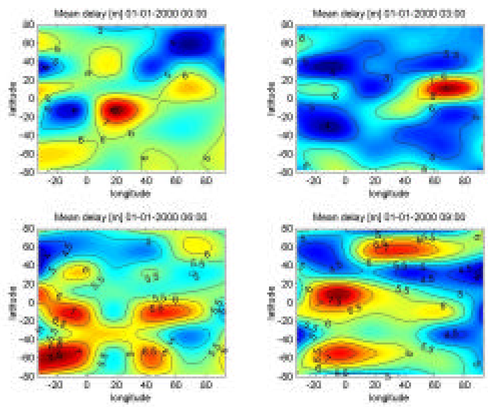

Fig 5 Mean atmospheric delay

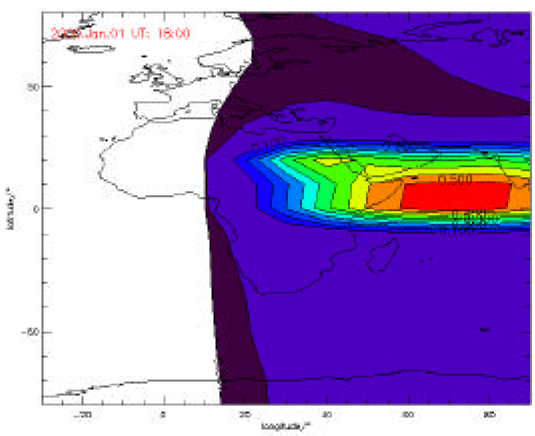

Fig 6 Scintillation strength S4 at 18 UT

Different models integrated in the simulation system give the capability to reproduce this receiving conditions in the neutral atmosphere and the ionosphere. For demonstration, January 1st in the year 2000 was chosen to compute the atmospheric scenario as it is been estimated by the simulator. The following figures show an excerpt of the parameter which influences the radio propagation. Fig. 5 is based on estimation of the refraction index in the troposphere and shows the mean delay of all L-band signals (GPS) received by virtual stations well-distributed in a region from –80° to 80° latitude and –30° to 80° longitude for a mask angle of 10° elevation. Similarly the ionospheric delay is determined using the IRI95 or the BENT model. The global scintillation strength distribution described by the S4 index is given by the GIM model (Fig. 6) and is the basis to derive the ionospheric influences.

3.2 Delay Error of a specific Signal Type

To model a certain satellite & signal constellation we observe the spectrum of the error signal as depicted in Fig. 7. Furthermore the power and mean of this error is estimated and modelled to emulate the measurement error for the ASL. Its distribution function is usually Gaussian.

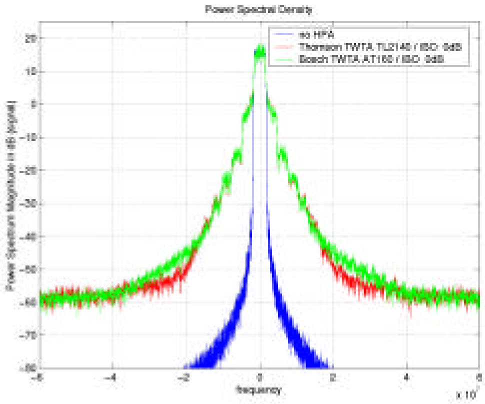

Fig 8 PSD of Galileo signals before and after HPA

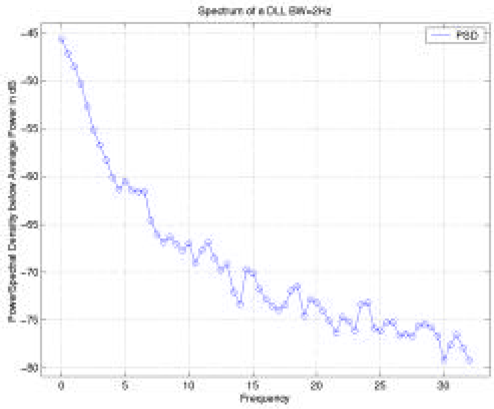

Fig 7 Error signal spectrum of a non-coherent DLL (Loop BW=2Hz) using SRC pulses

A "side product" of the simulation system is the capability to investigate the impact of real components e.g. high power amplifier on the signal spectrum (Fig. 8) and on the Loop-S curves of a DLL. On this foundation, recommendations for signal and component design can be derived.

3.3 Positioning Error

Depending on the composed simulation system, various influences on the positioning accuracy can be considered separately or in common. As an example the solution of the navigation algorithm is demonstrated for the 1st of January 2000 at the DLR location in Oberpfaffenhofen (N 48.08, E 11.28°, altitude 641.34 m) considering only the atmospheric influence under different conditions.

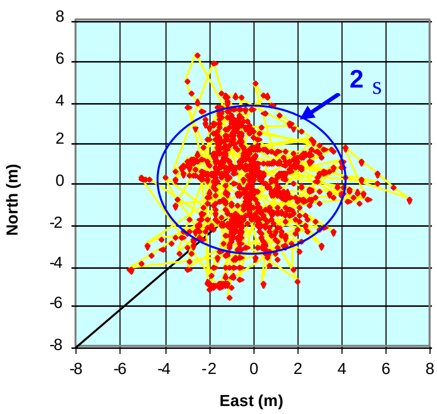

Fig 9 Tropospheric Position Error (no rain, 24 h) without corrections

Fig. 9 shows the position error of the location at DLR over 24 hours with the normal troposphere and no rain during the whole day. Similar plots can be generated if rain with different strength (10 mm/h, 100 mm/h) is implemented. The effect of rain is in the order of mm regarding to the L-band. Analysing the first simulations with the implementation of the navigation algorithms it can be seen that the results are within the theoretical values. The small differences between theory and simulation are only given by the numerical accuracy of the used computer.

4 Conclusions

The software simulation system developed in the project **NAVSIM** is considered as a suitable environment to develop and to evaluate models, algorithms and technical components in the navigation area under nearly realistic conditions. An example is the derived "signal and equipment specific model of range and phase errors" based on the gathered data by partial simulations in the SSL. For example, such models are important to lab-generate disturbed range and phase measurements in real time or to build up suitable signal simulators for receiver certification. To fulfil the requirements of an end-to-end simulation system the developed system consists of connected modules arranged in two simulation layers – the so-called signal simulation level (SSL) and the application simulation level (ASL). This is necessary to achieve an acceptable computational complexity and to be open for further developments inside the simulator and its application as a tool.

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