Modeling and Simulation of GNSS with NS2

Tiziano Inzerilli[1], Daniele Lo Forti[2] , Vincenzo Suraci[3]
University of Rome La Sapienza, D.I.S
inzerilli@dis.uniroma1.it, danyloforti@tiscali.it, vincenzo.suraci@dis.uniroma1.it

***Abstract*—Deployment of GNSS systems has paved the way to the provision of location-based and navigation services with growing accuracy and reliability. The introduction of the Galileo system besides the GPS and GLONASS will constitute a major technological advance of strategical importance for Europe in particular. In such context instruments for investigation in the field of GNSS are perceived as particular important for the research community. In this work we present simulations of GNSS system based on NS2, a well known simulator in the field of telecommunication and network technology. Namely, we have implemented a model for calculation of positioning exploiting the existing NS2 satellite network models. We added the delay model of the ionosphere and the troposphere, the ionosphere and troposphere delay correction model and navigation algorithm. Performance of those models have been compared with those of a well-know reference simulator, i.e. STK. This comparison shows that NS2 models allows to better model location errors due to diurnal TEC variations.**

***Index Terms*— GNSS, NS2, Galileo, GPS, STK**

I. Introduction

THE huge spreading of wireless communications, especially in conjunction with wide band access, is leading to the deployment of numerous applications. A lot of them are location-based applications. Location information, obtained for example through a wireless phone network, represents useful information that can be exploited to provide added-value innovative services. In order to access these services the user has to get his location from positioning system, either terrestrial or satellite. A positioning system in a mobile device often requires that this includes an ad-hoc receiver which could acquire navigation signals and elaborate them to find its position in addition to usual facilities for connection to the network.

GPS is a satellite-based positioning system deployed and operated by the U.S. Department of Defense. It is based on a constellation of 24 space vehicles orbiting around the earth, constituting the Space Segment, and a set of monitoring stations, ground antennas and an operational control center that compose the Control Segment. A user equipped with a GPS receiver can easily compute his position by making measurements on the signals received by each satellite in line of sight. This measurements are then taken as inputs by the navigation algorithm which computes the position with a horizontal accuracy of 100 meters for civilian purpose. With augmentation services as EGNOS or WAAS or with the new Galileo system, that is to be launched, it can reach greater accuracy levels as about 10 meters or less. The low precision for a civil GPS user is also due to the Selective Availability (SA) operated by the system, that is an intentional degradation of the signal to reduce accuracy for unauthorized users.

An instrument for investigating which models either the Navigation System, GPS or the new born Galileo, and the network which provides all required information is needed for simulation of positioning scenarios. For this purpose it is useful to have a network simulator with a models for satellite simulations and with the navigation algorithm implemented.

It is also important to have a simple model of the positioning system with results that cannot be far from other positioning oriented simulators. Also, a simple simulator well known by the scientific community is advisable so that investigations can be largely reused and validated.

In this work we illustrate GNSS models obtained through NS2 simulator. We present some simulation results and compare them with those obtained with another well-know simulator, specific for satellite simulations, STK.

We begin by first describing the major causes of errors in the estimate of position in a GNSS (Global Navigation Satellite System).

II. Main positioning aspects

To compute his position does a GNSS user have to measure the path delay of the signal from each satellite. This measurement is affected by some errors such as the lack of synchronization between the user quartz clock and the satellite more precise atomic clock (user clock bias), the atmospheric delay, the satellites clock bias, the ephemeris error, the multipath, and the receiver noise. These causes affects reception of signals in various fashions. In this paper we are considering only the delay errors and not the other ones as attenuation, depolarization, etc.

As far as such delay is concerned we can compute a pseudorange parameter multiplying the measured signal propagation delay by the speed of light:

$$\rho = \left(t_{Au} - t_{Ts}\right) \cdot c \qquad (1)$$

where t_{Ts} and t_{Au} are respectively the transmission time of the satellite and the arrival time of the receiver and c is the speed of light. The pseudorange ρ is affected by all the above-mentioned errors, except the receiver clock bias which is compensated for by the navigation algorithm. So the most important aspect for a GNSS user is the errors correction that is applied to estimate the real range by subtracting the error components from ρ.

We will briefly examine the various causes of errors which affect the final calculation of a position and consider the most important ones.

When a wave crosses the atmosphere because of its non constant refractive index, its path curves. So the range measured from the user location does not correspond to a straight path but to a curved one. The position error which is introduced by neglecting path curvature largely varies from some meters to about 50 meters during normal conditions.

The ephemeris error is another important cause of error. and it corresponds to the not correct location of satellites which is transmitted in the navigation signal from space vehicles. It is due to the orbits perturbations by the gravitational field of the Earth, the Moon attraction, and other factors. The GNSS Space Segment regularly broadcast correction parameters to the user. For a single frequency receiver the bias on the range which is measured is estimated as about 2.1 meters for predictions of up to 24 hours.

The clock bias for a space vehicle is the error in synchronization with the GNSS time and it is evaluated as about 2.0 meters on ranges measurement for a 12-hours update from the Space Segment.

Multipath also affects accuracy of positioning. It is caused by the reflected signals on objects around the receiver that mask the direct signal correlation peak. The effect is a maximum error bias of 15 meters in worst conditions, when large reflecting surfaces are near the receiver. In most cases it decrease to 1 m bias.

Finally, the receiver noise also affects position calculation. It is due to the hardware delay and the limited precision of the software on the user terminal and it is evaluated as about 0.5 meters bias.

As we have seen the most important factor is the atmospheric delay not only for its size but also for its large and slightly predictable variations. The path curvature is caused by the value of the refractive index n which differs from that of free space (n=1). To estimate delay we need a model of n and to do this we have to distinguish the ionospheric delay from the tropospheric delay.

A. Ionospheric Delay

The ionosphere is a weakly ionized plasma, or gas, layer which extends from 50 km to 1000 km above the earth surface. It takes this characteristic from the effects of the collision of the ultraviolet ionizing radiation, coming from the Sun, on the higher layer of the atmosphere. As a consequence, it is not always the same and its variations are subjected to Sun phases (spots, CME, etc…). An important factor to consider is the *total electron content* (TEC) which is a measure of the total amount of electrons along a particular line of sight. Units of TEC are 10^{16} electrons per square meter and TEC factor has a large slightly predictable variation. Appleton and Hartree derived an approximate expression of ionosphere refractive index n that is:

$$n = 1 - \frac{N_E \cdot e^2}{2 \cdot \varepsilon_0 \cdot m \cdot \omega^2} \tag{2}$$

where N_E is the ionization density (el/m^3), e is the electron charge, ε_0 is the permittivity of free space, and m is the electron mass. The delay, in meter units, can be calculated as:

$$\Delta s = \int (1-n)\, dl \tag{3}$$

So we can calculate the total ionospheric delay by:

$$\Delta s = \frac{40.3}{f^2} \int N_E \, dl \approx \frac{40.3}{f^2} VTEC \cdot F \tag{4}$$

where f is the signal frequency (Hz), $VTEC$ is the zenith TEC, and F is the obliquity factor which is approximated as:

$$F(\vartheta) = \left(1 - \left[\frac{\cos\vartheta}{1 + h / R_e}\right]^2\right)^{-\frac{1}{2}} \tag{5}$$

where θ is the elevation angle (rad), R_e is the Earth radius and h is the altitude that, for the ionosphere, is taken as a constant value of 400 km.

B. Tropospheric Delay

The troposphere extends from the earth surface to about 12-17 km and the Stratosphere from 17 km to about 60 km where the ionosphere starts. This two atmosphere layers consist of dry gases and water vapour. Water vapour generally exists only below altitudes of 12 km above sea level and its density varies widely with position and time so it is much more difficult to predict than the dry atmosphere, which, instead, extends to 43 km of altitude. The delay introduced by these layers is due to the larger refractive index n ($n > 1$) of atmosphere than that of free space ($n=1$). At the frequencies which are used for navigation purposes, the tropospheric refractive index is practically constant vs. frequency but it varies with the altitude. This variation causes signal path to have a slight curvature with respect to the geometric straight line path. The delay can be calculated approximately as:

$$\Delta s \approx \int_{geo} (n-1)\, ds = 10^{-6} \int_{geo} N \, ds \tag{6}$$

A simplified model for the excess delay is the Black and Eisner model that gives the following formula for the total tropospheric delay:

$$\Delta s = 10^{-6} \int_{h_0}^{h_d} \left[N_d(h) + N_w(h) \right] \cdot F(\vartheta) dh \qquad (7)$$

where *F(θ)* is the last seen obliquity factor. For the two terms $N_d(h)$ and $N_s(h)$ can be used the Hopfield Two-Quartic model that calculates them as the product of the refractivity on the earth surface and a term depending on the altitude:

$$N_d(h) = N_{d0} \left(1 - \frac{h}{h_d}\right)^4 \quad for \quad h \le h_d = 43\,km \qquad (8)$$

$$N_w(h) = N_{w0} \left(1 - \frac{h}{h_w}\right)^4 \quad for \quad h \le h_w = 12\,km \qquad (9)$$

The surface refractivity N_{d0} and N_{s0} are calculated as:

$$N_{d0} = 77.624 \frac{P_0}{T_0} \qquad (10)$$

$$N_{d0} = 3.732 \cdot 10^5 \frac{P_{v0}}{T_0^{\ 2}} \qquad (11)$$

where T_0, P_0 and P_{v0} are respectively the temperature, the pressure (dry + wet) and the vapour pressure (wet) on the surface of the earth. The temperature is measured in °K and the pressure in mbar.

III. Satellite Simulators

In this section NS2 simulation models for GNSS are presented. To check the validity of the results obtained from NS2 simulator we chose as a reference the STK simulator, which is briefly introduced.

A. STK simulator

STK is an analysis software that supports planning, design, operation, and post-mission analysis for complex and integrated land, sea, air, and space scenarios. It has a satellite orbit module taking into account the perturbing factors and an atmosphere propagation module based on various models, the most frequently used for the earth is the Harris and Priester model. STK is also considered by the scientific community as a good reference to test other simulator software.

B. The Network Simulator 2

Network Simulator (NS) is an object oriented simulator developed by the Berkley University of California for general purpose network simulation. It is mainly use for TCP/IP architecture simulation. A great advantage of this simulator is that it is largely used within the research community of the Information and Telecommunication Technology (ICT).

It is written in C++ and uses an OTcl interpreter as a front-end. A Tcl script is used to create the scenarios and to run it through the simulator.

NS2 has a satellite extension that simulates satellites orbiting on circular orbits around the earth which is approximated with a geometric sphere. Satellites are connected to the earth terminals with one or more channel objects that take into account the delay due to the propagation from the transmitter to the receiver.

IV. GNSS Extension to NS2 Satellite Models

We extended available NS2 satellite models to obtain specific instrument for GNSS simulation. The release taken into account is the 2.27.

The major modifications include (i) estimate of propagation delay errors (ii) positioning based on triangularization of satellite signal propagation delay (iii) compensation for errors in the positioning calculation algorithm.

A. Estimate of propagation delay errors

NS2 does not implement a model of the propagation delay cause by the atmosphere crossing, which is particularly important for estimate of propagation delay in GNSS. As a consequence, two propagation delay models, neglecting the attenuations effects of atmosphere, are introduced in our models.

The first model is the ionosphere model and its delay depends on TEC as we have seen in section II. To model vertical TEC we used data in IONEX format obtained from the GIM site on the web [11]. These files, one for each day, contain values of TEC measured from a set of stations around the earth and taken with steps of 2 hours in time, 2.5 degrees in latitude and 5 degrees in longitude. The TEC values read from IONEX files are interpolated in time and space to obtain the value at the user position and time. The IONEX format and the interpolation methods are explained in [6]. The value obtained is then taken as the average value of a normal distributed variable with a standard deviation of 5% to take into account station measurement errors. Then the delay is calculated with the TEC value extracted from the distribution.

For the troposphere a model taken from [3] is adopted, which is based on a normal distribution of the delay and a division in four zones: the tropical, subtropical, temperate, and polar zone. Two tables give the parameters to calculate the average value and the standard deviation of delay for each zone.

B. Calculation of position

NS is a packet oriented simulator so the GNSS signal frames are modelled as a series of packets. To simulate a GPS or Galileo scenario a couple of agents are created. The first, the GNSS at agent, is put on each satellite and when started has to send each 6 s a time stamp packet filled with its position (ephemeris) and its time (GNSS Time). The second, the GNSS receiving agent, is put on the receiver and each time it receives a time stamp packet it memorizes it in a list adding the pseudorange computed from send time and arrival time, last one taken from its clock. The receiver is a single frequency receiver and its clock, quartz clock, is simulated as an object with a stability of 0.1 nanoseconds/second. During starting phase the receiver need to wait more than 6 s to receive ephemeris and correction data, exactly it waits 18 s for the first and 30 for the second. Each 6 s the agent on the receiver sends the time stamps list to the navigation algorithm which computes the solution. The solution is composed by position and time and it is called “state”. The navigation algorithm finds the navigation solution with a process of linearization that leads to the following linear system :

$$\Delta\boldsymbol{\rho} = \mathbf{G} \cdot \Delta\mathbf{x} \tag{12}$$

where:

$$\Delta\boldsymbol{\rho} = \begin{bmatrix} \Delta\rho_1 \\ \Delta\rho_2 \\ \vdots \\ \Delta\rho_N \end{bmatrix} \quad \mathbf{G} = \begin{bmatrix} -\hat{\mathbf{1}}_1^{\mathrm{T}} & 1 \\ -\hat{\mathbf{1}}_2^{\mathrm{T}} & 1 \\ \vdots & \vdots \\ -\hat{\mathbf{1}}_N^{\mathrm{T}} & 1 \end{bmatrix} \quad \Delta\mathbf{x} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ c \cdot \Delta b_u \end{bmatrix} \tag{13}$$

$\Delta\boldsymbol{\rho}$ is the vector of differences between the ranges measured and the ranges estimated and $\boldsymbol{G}$ is the cosine matrix. The ranges estimated are the sum of the geometrical range which is estimated and the atmospheric correction factors. Each time the navigation algorithm is run, it calculates the corrections to the actual estimate state to obtain the new, more precise state.

C. Compensation of propagation delay errors in position calculation

The atmosphere delay reflects itself with an error on the measured ranges, which are called pseudoranges for this reason. To improve precision do the ranges which are measured have to be corrected with an estimate of the atmospheric delay. This estimate is made with two models: a ionospheric correction model a tropospheric correction model.

As we already said, the ionospheric delay varies with TEC; it can be observed that its value changes so much during the day but has about a constant value during the night. Correcting the diurnal delay with a medium constant value can lead to a 50% reduction of the range error. A more complicated function is the “half cosine” that has a better fitting and leads to a residual of 10% error. It can be written as:

$$T_{iono} = F \cdot \left\{ DC + A\cos\left[2\pi(t-\phi)/P\right]\right\} \tag{14}$$

where DC is the offset term and is usually set to 5 ns, t is the local time, φ is the phase of the maximum with respect of the local noon and is taken as 14 h, A is the amplitude, and P is the period. This last two terms are calculated from user geomagnetic latitude and from eight coefficients which are broadcast from the satellites in the navigation signal. In NS we implemented this model to correct ionospheric delay. The coefficients needed are taken from daily data in RINEX format obtained from GIM site on the web.

The tropospheric model which is used to correct the delay is the Black and Eisner model, shown in section II. To calculate N_{d0} and N_{s0} values T_0, P_0 and P_{v0} of the zone are used. The first two quantities are responsible for the delay of dry air which is the major component but their values varies not so much and so it can be taken equal to their nominal values. The third parameter is responsible of the wet air delay but it has small values and so it is taken equal to its nominal value too.

V. Experimental Data

In order to assess performance of the NS2 models described in the previous section we performed parallel simulations with STK. Namely, we selected a scenario in which a fix user performs measurements of its location over an interval of time of 12 hours. The exact location of the user is known a priori, the calculated position using the GNSS signals is then compared with it using the two simulators. We have then examined performance of the two simulators in emulation of the calculated location by the GNSS.

The selected time interval was from the eight in the morning to the eight in the evening. The reason for choosing this period is that diurnal errors are bigger and with larger and less predictable variations than night errors due to the influence of TEC. So it could be a good choice to check the simulator validity in such interval. All simulations were made on the first of January 2004. Position was recalculated every of 6 s.

In the NS2 models, ephemeris and satellite clock error were taken as an average estimated value from [1]. Also TEC variations during the day were considered.

We inserted a Galileo constellation in the simulator to simulate position accuracy on two sites in Europe: the first was located in Rome (latitude 41, longitude 12) and the second in Paris (latitude 48, longitude 2). The measures we obtained were used to calculate the position of the user. We compared this with the user exact location and obtained estimates of global position error values (position + time).

As we can see from the graphs relative to both Rome and Paris, during early morning time the NS2 pattern (lower curve in both graphs) average value increases but STK one (upper curve in both graphs) oscillates around an average value. During afternoon time also NS2 pattern decreases and still the STK maintain a same average. This tendency in increasing and decreasing in statistics collected with NS2 models, which is not present in those obtained with STK, is due to the variation of the TEC value during the day time, modeled only in NS2. In the morning, TEC values typically increase to reach a maximum value around midday and during the afternoon tend to decrease to a minimum value which remains about unaltered during the night.

NS2 takes into account this variation, whereas STK uses for the ionospheric delay computation a model from Harris and Priester. This is the main reason for that divergence of the results obtained with the two simulators. In fact the STK curve approaches the NS2 curve when multiplied by a scale factor that takes into account the diurnal variation of the TEC. During the midday there is not a complete match of the two curves due to the lack of modeling of the multipath error, the satellite clock and ephemeris (constant values) in NS2 models.

Both NS2 and STK curves show some oscillations in the estimation of the location errors. These are due to the modeling of location errors of the GNSS, which increase when handovers of satellite are performed by the GNSS system.

To sum up, both STK and NS2 models provides an estimation of location errors which is affected by the movement of satellite in the GNSS constellation. STK models are complete and incorporate several cause of errors including clock, ephemeris and multipath errors, while they do not consider and important cause of error which is variation of TEC over the day. From this point of view NS2 models seem more accurate.

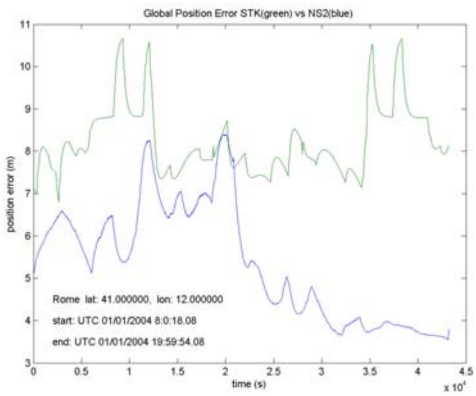

Fig.1 – Global position error: Rome 1/1/2004

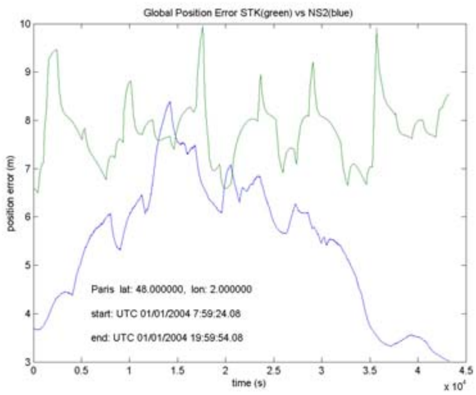

Fig.2 –Global position error: Paris 1/1/2004

VI. Conclusion

In this paper we have presented simulation of GNSS through the well-known network simulator NS2.

We began by discussing the main causes of errors in the estimate of positioning by a GNSS. We then described the simulation models that we obtained with NS. Namely, we extended the already available NS satellite network models by introducing a model for propagation delay in the atmosphere including ionospheric as well as tropospheric effects.

We compared simulation results obtained with such models with those obtained by STK, another well-know simulator.

We can conclude that, though the NS2 models do not incorporates some errors causes such as those due to multipath, ephemeris errors and clock errors, have better modeled errors due to variation of TEC during a diurnal interval of time.

References

[1] B.W. Parkinson, J.J. Spilker Jr., "Global Position System: Theory and Applications," American Institute of Areonautics and Astronautics, Inc., Washington

[2] Gain Architecture Team , "Baseline System Design Definition Document. Part. 2: Galileo Physical Architecture," Galileo Industries, 2002.

[3] A. Martellucci, "ESA-Document Galileo Reference Troposphere. Description of Models," ESA, Galileo Project Office, 2002

[4] A. Martellucci, "ESA Document. Galileo Reference Troposphere for mild conditions", ESA, Galileo Project Office, 2002

[5] A. Martellucci, "ESA Document. Galileo Reference Troposphere for worst conditions", ESA, Galileo Project Office, 2002

[6] S. Schaer, W. Gurtner, J. Feltens "IONEX: The IONosphere Map Exchange Format Version 1," Proceedings of the IGS AC Workshop, Darmstad, Germany, February 9-11, 1998

[7] Jorge Pita, "ESA Document. Galileo Reference Ionosphere for mild conditions", ESA, Galileo Project Office, 2002

[8] Jorge Pita, "ESA Document. Galileo Reference Ionosphere for worst case conditions", ESA, Galileo Project Office, 2002

[9] S. Radicella, R. Leitinger, "ESA Document. Galileo Ionospheric Model for Single Frequency Receivers", ESA, Galileo Project Office, 2003

[10] K. Fall, K. Varadhan, "ns Notes and Documentation," The VINT Project, UC Berkeley, LBL, USC/ISI, Xerox PARC, 2003

[11] CODE Analysis Centre of the IGS at AIUB, "Global Ionosphere Maps," Avaible: http://www.aiub.unibe.ch/ionosphere.html