Filling the gap between physical ionosphere models and scintillation models in equatorial region

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ABSTRACT

It is usually assumed that the scintillations observed on signals propagating through the ionosphere are linked to the occurrence of bubbles inside the medium. This paper focus on this issue. A theoretical approach has been developed based on the GISM scintillation model [Béniguel, 2011] coupled to an ionosphere medium bubble generator developed by [Yokoyama, 2014, 2015]. The calculation of scintillations for links crossing this medium has been performed. Concurrently to this theoretical approach, a data analysis has been performed using the West African MONITOR - SAGAIE network and database. A bubbles detector software has been developed and correlations between the bubbles occurrence and a simultaneous increase of the scintillation indices have been analysed.

1. INTRODUCTION

The signal fluctuations, referred to as scintillations, are created by random fluctuations of the medium's refractive index, which are caused by inhomogeneities inside the ionosphere. These inhomogeneities are substructures of bubbles, which may reach dimensions of several hundreds of kilometers as can be seen from radar observations. These bubbles present a patchy structure. They appear after sunset, when the sun ionization drops to zero. Instability processes develop inside these bubbles with creation of turbulences inside the medium. As a result, depletions of electron density appear. In the L band and for the distances usually considered for the satellite navigation systems, the diffracting pattern of inhomogeneities in the range of 1 km size is inside the first Fresnel zone and contributes to scintillation.

The modeling of the wave propagation through the ionosphere is usually done solving the parabolic equation which is an approximation of the most general Helmholtz wave equation considering a near axis propagation. This hypothesis is always verified for satellite to earth links. The models developed are for most of them, climatological models. They have been built using empirical laws to enter the geophysical parameters dependencies required in the corresponding algorithms. Such a model, named GISM [Béniguel, 2011] referenced at the ITU [Recommendation ITU-R P.531-11, 2012], briefly introduced in the next section, has been used for the work presented in this paper.

The modeling of the medium allowing reproducing the development of bubbles can been done concurrently using the continuity, momentum and energy equations for the different species in the medium, depending on the altitude. However, a full 3D resolution is a complicated task as many processes and terms in the equations shall be considered. It also requires significant IT resources as the space and time steps shall be small enough to allow the development of the inhomogeneities. The space step shall consequently be well below the outer scale of inhomogeneities. These different constraints can however be overcome if a 2D problem is considered. Such an attempt has been done by [Yokoyama, 2014, 2015, 2016] in a vertical plane and [Béniguel, 1996] in a horizontal plane at a given altitude.

A combined approach to reproduce the scintillation due to turbulences on an earth satellite link is presented in this paper. The solution is a 2D solution. Medium realisations in a vertical plane produced by the Yokoyama model have been used. The scintillation effects on signals after their propagation through the medium are evaluated using the GISM model.

An analysis of the scintillation due to the ionosphere bubbles has been done concurrently using the measurements data recorded in the frame of the MONITOR – SAGAIE network. The SAGAIE network (Stations ASECNA GNSS pour l'Analyse de l'Ionosphère Equatoriale) [Secrétan et al., 2016] is a network of scintillation receivers deployed in the West African equatorial sector to study the ionosphere. The deployment started in 2015. MONITOR (MONitoring of Ionosphere by innovative Techniques coordinated Observations and Ressources) [Béniguel et al., 2015] is a project conducted by the European Space Agency's GNSS Evolutions Programme with a similar objective. The two networks have been merged in 2016 sharing in particular a common data base of measurements data. In the frame of a CNES activity, Thales has developed a bubbles detector, detailed at section 4 of this paper. One analysis has been conducted on a whole year of recorded data to detect the occurrence of bubbles and record concurrently the values of the scintillation indices. The results obtained are presented at section 4.

2. MEDIUM DEFINITION

The effect of turbulences on the propagation of radio waves in the ionosphere can be evaluated solving the parabolic equation. The most convenient resolution technique consists in implementing a Multiple Phase Screen (MPS) technique. For this purpose, the medium is divided into layers in planes perpendicular to the Line Of Sight (LOS), each one of them acting as a phase screen. The extent of a layer in the transverse plane shall be much larger than the outer scale of the turbulences. The calculation can be done in a 2D reference system. The misalignment of the LOS with the terrestrial magnetic field is taken into account including an additional geometrical factor.

The calculation alternates scattering and propagation calculations from one screen to the next one to obtain the transmitted field after propagation through the turbulent medium. The phase screens are defined by a stochastic process. Three parameters are involved to define them: the strength of the turbulence Cs, the average size of the inhomogeneities L_0 and the spectrum slope p which is shown to be linear in a log – log representation.

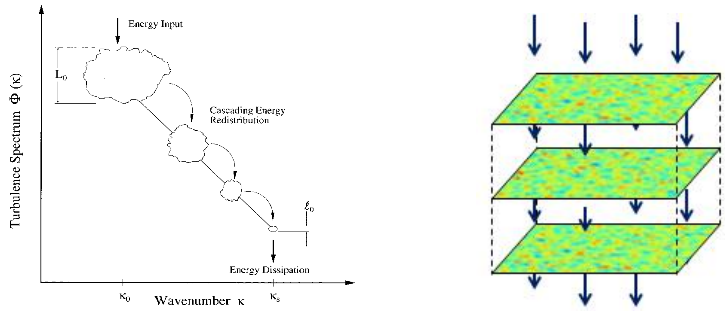

Figure 1: Wave propagation in the ionosphere. Left panel: the electron density inhomogeneities spectrum. Right panel: the phase screens attached to the sampling points along the line of sight.

The spectrum relationship is:

$$S_{\Delta N_e}(k) = C_s\,(k^2 + k_0^2)^{-p/2}$$

The knowledge of this spectrum allows performing the propagation calculation with the multiple phase screen technique. This has been implemented in the GISM model. It allows addressing the problem of scintillations in the equatorial regions. The model referenced in [Galiegue, 2015] addresses the polar region.

The major difficulty of such a modeling is the medium definition. A climatological model, such as GISM, uses empirical laws for the geophysical parameters to define the medium characteristics. These laws have been derived using databases built after processing the data recorded during measurement campaigns [Béniguel et al, 2017]. The empirical laws are probability laws for random processes and the propagation results are obtained accordingly, with a given probability.

An alternative to this approach is to reproduce the development of the ionosphere inhomogeneities by modeling. This means solving the continuity, momentum and energy equations for the different species at a given altitude, mainly O, O2 and N2. The Yokoyama model has been used for the work presented in this paper. One of its main advantages is the possibility to tune the inputs using a space weather model, the earth magnetic field model or any other empirical ionospheric (IRI, NeQuick). It also helps for a better understanding on the bubbles development which might be of interest for ionospheric turbulence forecasting. Figure 2 shows an example of results exhibiting the bubbles development with two different voxel space steps: 1km and 300m.

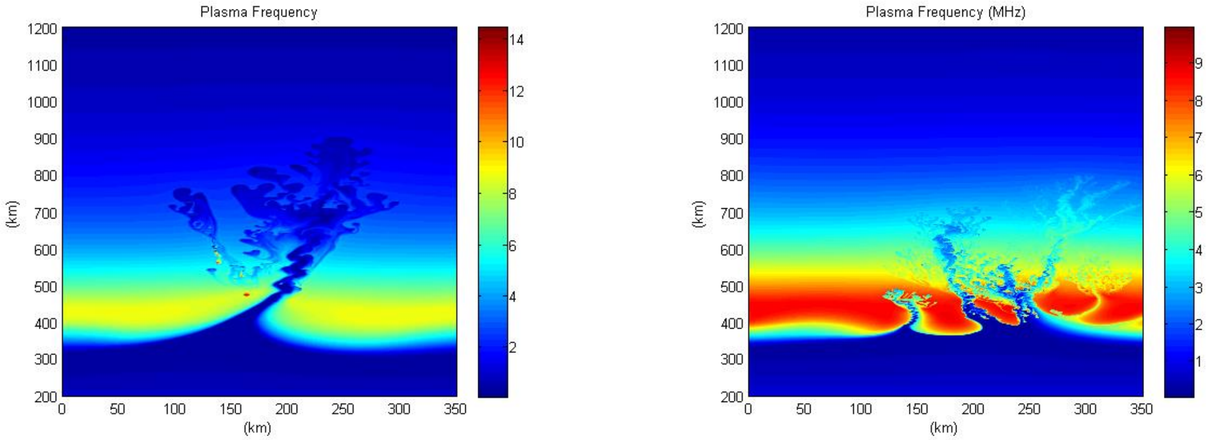

Figure 2: typical results for bubbles depending on the plasma frequency: left panel: space step 1km, right panel: space step 300m

3. SCINTILLATION AT RECEIVER LEVEL: THEORETICAL APPROACH

The aim of this section is to reproduce the scintillation on signals after their propagation through the turbulent medium presented at the previous section. Figure 2 shows the development of the bubbles in a vertical plane with respect to the earth. This 2D medium has been used as an input to the wave propagation model.

In the calculation performed it has been assumed that the occurrence of scintillation is linked to the occurrence of bubbles. At each sampling point along the line of sight inside the bubbles region, a phase screen is attached. The inhomogeneities involved in the calculation are those developing in a plane transverse to the Line Of Sight (LOS). They are not estimated by the model. In the propagation calculation, the turbulence strength has been linked to the electron density value at the sampling point and typical values have been considered for the average inhomogeneities size L_0 and spectrum slope p. In the future, it might be of interest to estimate the sizes using again the continuity and momentum equations for an additional model in the transverse plane using the values obtained by the 2D model as a driver in this plane. Such an attempt has been initiated in the past [Béniguel, 1996], exhibiting the Rayleigh Taylor instability at a given altitude. This solution would be an intermediate between a 2D resolution and a full 3D solution which might be difficult to implement.

The calculation of the scintillation on a receiver located at ground level at the window center has been performed with the GISM model (distance = 180 km, altitude = 0). Figure 3 shows the variance of the electron density at the successive phase screens along the LOS for an elevation angle of 92° and a source point at an altitude of 1200 km. The variance decreases with the altitude as the electron density. There are 143 phase screens in that case corresponding to the number of sampling points inside the bubbles. The corresponding intensity and phase time series are shown on the right panel of the figure.

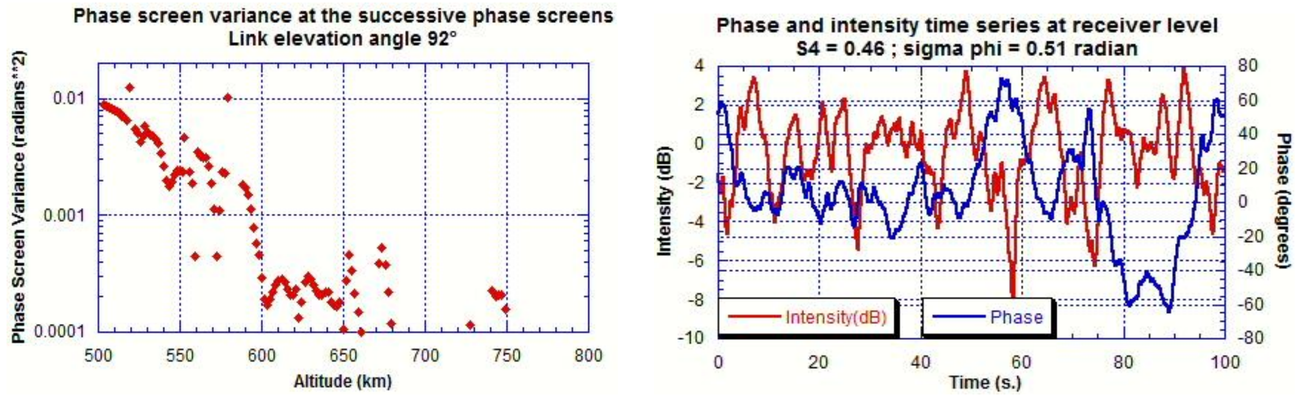

Figure 3 : Phase variance on the successive phase screens (left panel) and intensity and phase time series at the receiver location (right panel).

Figure 4 shows the values of the slant TEC and of the intensity and phase scintillation indices for a source point moving left to right at the top of the window, i.e. at an altitude equal to 1200 km, consequently well above the bubbles location. For this particular geometry, the elevation angle increases from 80° to 100°. The part of the link crossing the bubbles depends on this angle. As shown on the Figure, the propagation through the bubbles exhibits a decrease of the slant TEC and significant values of the scintillation indices.

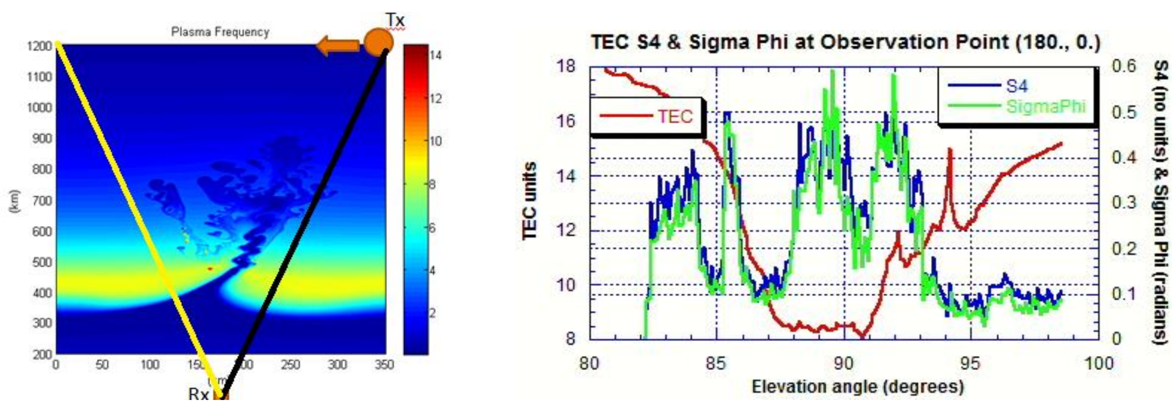

Figure 4: left panel Tx / Rx scenario, right panel: Slant TEC, S4 and $\boldsymbol{\sigma_\phi}$ scintillation indices

4. PROPAGATION THROUGH THE IONOSPHERE BUBBLES. MEASUREMENTS DATA ANALYSIS

An attempt to validate the results has been made using the experimental data recorded in Africa with the MONITOR - SAGAIE network. These networks were deployed to study the ionosphere variability at the equatorial region (both TEC and scintillations) and evaluate the constraints to be fulfilled for the operation of a mono frequency SBAS service in this region

In the frame of this project, a bubble seeker has been developed. Three conditions were considered to decide on a bubble occurrence:

- The slant TEC derivative (the slope) shall be greater than a given threshold,
- The TEC slope variance shall be greater than a given threshold,
- The TEC depth shall exceed a given value (15 TEC units).

The analysis has been performed in 2015 at 5 locations: Dakar, Lomé, Douala, N'Djamena and Ouagadougou. All these stations are close to the magnetic equator. The numbers of bubbles detected according to our criteria was 401 in total, i.e. 7 per month and per station on average. This is very low as compared to the number of scintillation events detected on the same period. As a comparison, the number of events detected in Dakar (S4 > 0.2) is rather significant (cf Figure 5).

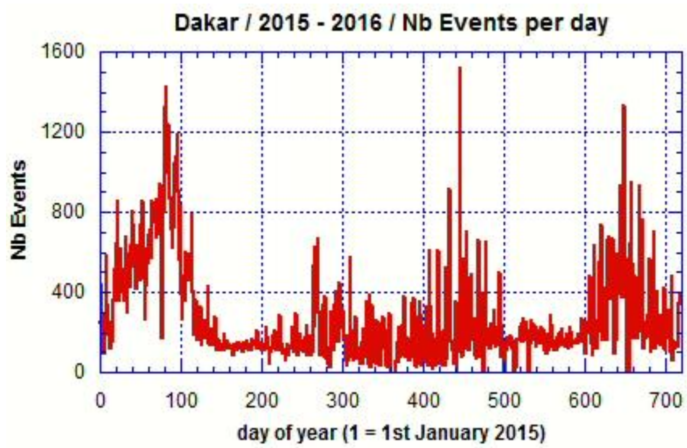

Figure 5: The number of scintillation events (S4 > 0.2) detected in Dakar depending on the day number.

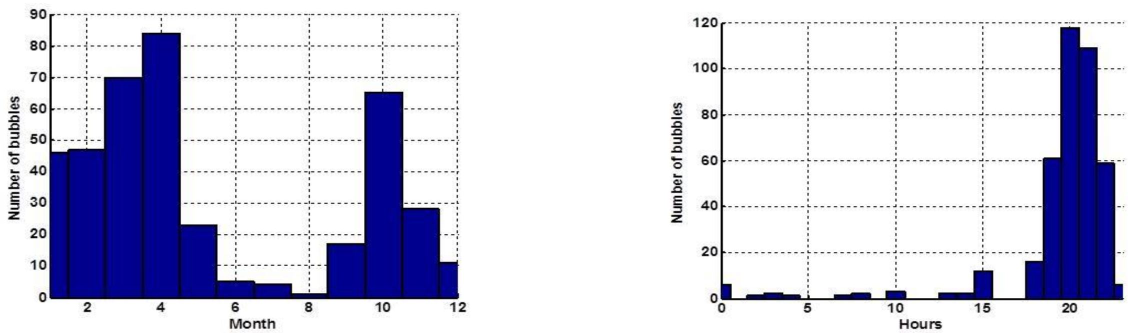

Figure 6: Occurrence of bubbles depending on the month and on the local time.

Figure 6 shows the bubbles occurrence dependencies. The behavior is similar to what is observed for scintillations with peak values around the equinoxes and after sunset. Figure 7 shows the distribution of the depth and duration.

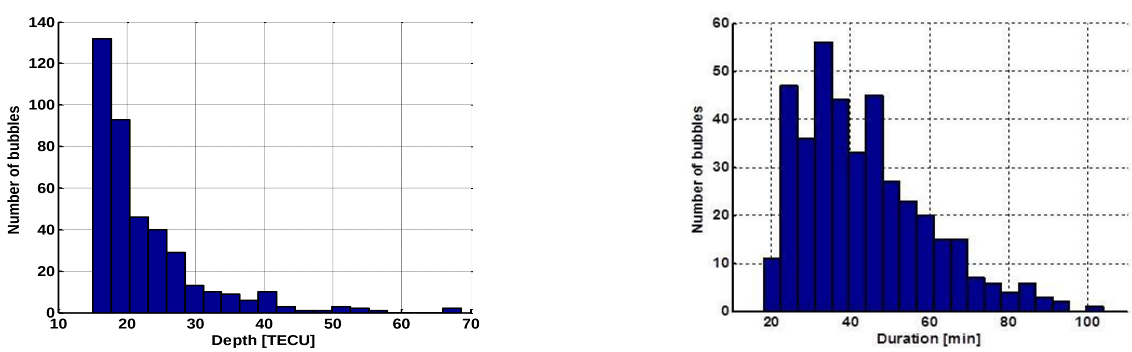

Figure 7: Bubbles depth and duration.

Figure 8 illustrates the correlation between the bubbles occurrence and a simultaneous increase of the intensity scintillation index. The left plots correspond to average values of scintillation. There is no correlation in the left top plot and they seem to be correlated in the bottom plot. The right top plot corresponds to a case of strong scintillation and there is no obvious correlation.

Finally the bottom right plot shows the correlation over the year 2015 between the bubbles and the maximum S4 value reached during the event. The correlation looks very poor.

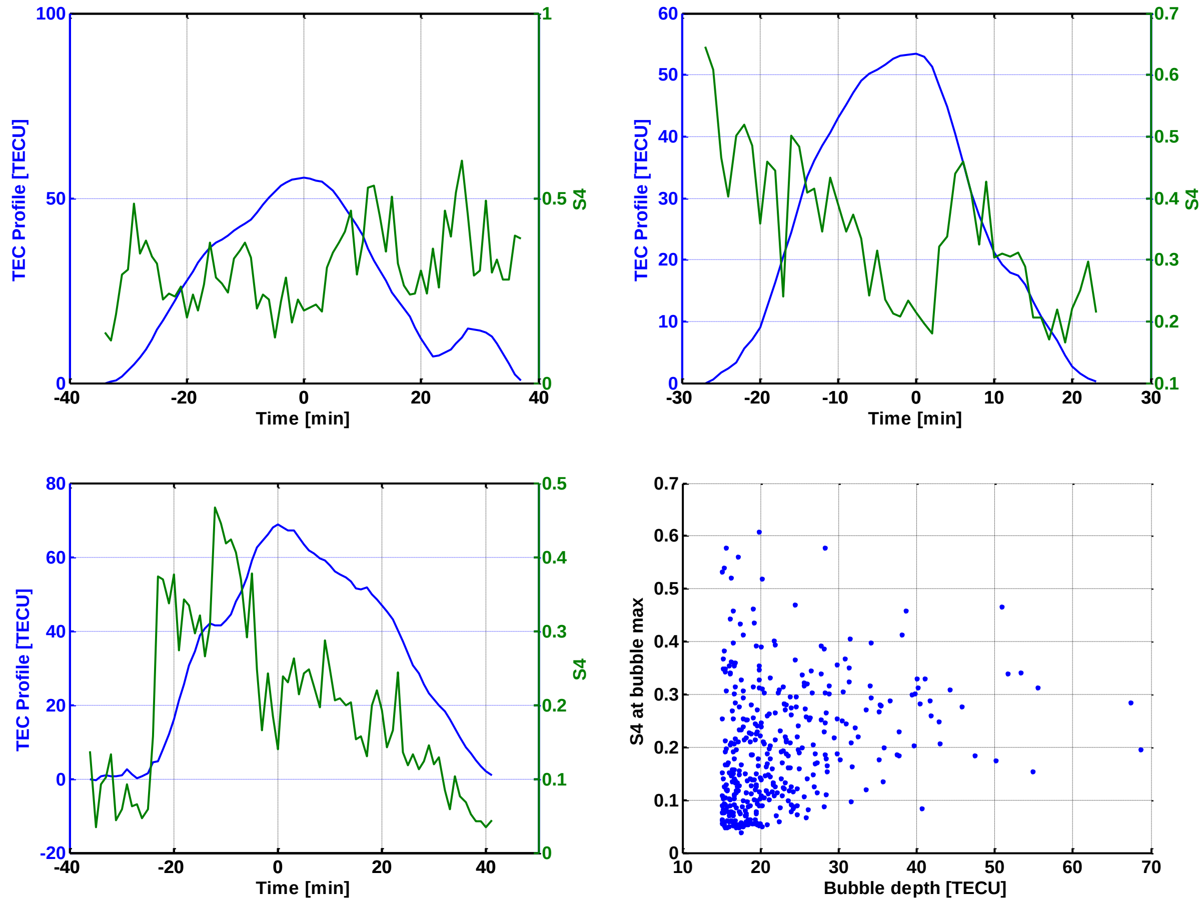

Figure 8: Three bubbles events showing the bubble depth (blue curves) and the S4 values recorded simultaneously (green curves) for two cases of medium scintillations (left plots) and one case of strong scintillation (top on the right). The right bottom plot shows the correlation between the TEC depth and the maximum S4 value during the corresponding event for the whole year 2015.

5. CONCLUSIONS

A preliminary analysis on the effects of electron density bubbles on the signals transmitted after propagation through these bubbles has been presented. The theoretical analysis and corresponding simulation gives values of the scintillation indices in the range of what is usually observed. The measurement data analysis was on the other side not so conclusive as the number of bubbles detected is quite low in comparison with the number of detected scintillation events. In addition the correlation between a bubble occurrence and a simultaneous increase of the scintillation indices is verified in a very small number of cases. This analysis will be refined in the future relaxing the criteria to decide on the occurrence of a bubble to check if the poor correlation between their appearance and the scintillation indices increase is verified.

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