End to end simulation for Normalized Differential Spectral Attenuation (NDSA) measurements between two LEO satellites: performance analysis in the Ku/K bands.

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***Abstract* — The NDSA method is a novel differential measurement way for estimating the total content of water vapor (IWV, Integrated Water Vapor) along a tropospheric propagation path between two Low Earth Orbit (LEO) satellites. NDSA is based on the simultaneous measurement of the total attenuation at two relatively close frequencies in the Ku/K bands, and on the estimate of a "spectral sensitivity parameter" that can be directly converted into IWV. NDSA is potentially able to emphasize the water vapor contribution, to cancel out all spectrally flat unwanted contributions and to limit the impairments due to tropospheric scintillation. In this paper we focus on the measurement accuracy of the spectral sensitivity parameter. Specifically, we examine such accuracy at three different frequencies and for two models of atmospheric structure.**

Keywords- water vapor, LEO satellite, tropospheric scintillation, attenuation at microwaves

I. INTRODUCTION

The troposphere contains almost the totality of the atmospheric water vapor. Therefore, remote sensing of tropospheric water vapor is of extreme value for both meteorological and climatological applications. Recently, we introduced the concept and the underlying motivations of NDSA (Normalized Differential Spectral Absorption) measurements for tropospheric water vapor sounding utilizing a couple of LEO satellites, one carrying a transmitter, the other a receiver [1]. As explained in [1], to which the reader is referred for details, the NDSA method is based on the conversion of a spectral parameter that we called "spectral sensitivity", measured in the Ku/K bands, into the total content of water vapor (hereafter IWV, Integrated Water Vapor) along the propagation path between the two LEO satellites. The NDSA method requires the simultaneous measurement of the total attenuation at two relatively close frequencies (f_o-$\Delta f/2$ and f_o+$\Delta f/2$), symmetrically placed around an ideal reference frequency f_o, and the estimate of the "spectral sensitivity" S, defined as:

$$S = \frac{P_2 - P_1}{\Delta f \; P_2} \tag{1}$$

where P_1 and P_2 are the received powers corresponding to two simultaneously transmitted tone signals $s_1(t)$ and $s_2(t)$ with frequencies f_1=f_o +$\Delta f/2$ and f_2=f_o-$\Delta f/2$, respectively.

The appeal of the NDSA method are its potential to cancel out undesired spectral attenuation contributions that are sufficiently flat over the NDSA measurement bandwidth [f_o-$\Delta f/2$ ÷ f_o+$\Delta f/2$] and its potential to limit signal impairments that are correlated in time over the same bandwidth, such as those due to tropospheric scintillation [2]. In [1], we showed that spectral sensitivity can be exploited to provide direct estimates of IWV along LEO-LEO tropospheric propagation paths in the 15-25 GHz interval. Such analysis was made accounting for the natural variations of the atmospheric conditions at a global scale, assuming ideal measurement conditions (no disturbance at the receiver nor propagation impairments). Simulation were based on a microwave propagation model and on radiosonde data, and they showed the potential of the NDSA approach to provide direct estimates of IWV along LEO-LEO satellites links in the troposphere in the 15-25 GHz frequency range, under different atmospheric conditions. NDSA can provide IWV estimates directly by means of power measurements, without requiring any external information (for instance, in GPS/MET or LEO-LEO radio occultation the retrieval of water vapor profiles requires at least adequate surface temperature and pressure information and the inversion of the hydrostatic and absorption equations). In particular, we found that 17, 19 and 21 GHz are the most appealing frequencies for relating S to the IWV in the low troposphere, since they guarantee a high correlation between the two parameters.

In this paper we analyze the accuracy of spectral sensitivity measurements at the three aforementioned frequencies and for two values of Δf (200 and 400 MHz) through an end-to-end simulation of the sequence of measurements made between two LEO satellites assuming a specific orbital geometry and accounting for both thermal noise at the receiver and tropospheric propagation impairments as scintillation effects. We assume two reference atmospheric models (mid latitude summer and winter) and a simplified atmospheric structure, a two parameters scintillation model, a two parameter defocusing function and additive white Gaussian noise at the receiver.

II. Simulation Scheme

The two transmitted signals can be expressed by:

$$s_i(t) = V_i \exp\left[j(2\pi f_i t + \varphi_i)\right] \quad i = 1,2 \tag{1}$$

The tones received on each channel and degraded by propagation effects can be modeled as:

$$r_i(t) = a_i(t) \cdot s_i(t) \cdot \exp\left[j\frac{2\pi}{\lambda_i} l(t)\right] + n_i(t) \qquad i = 1,2 \tag{2}$$

where $a_i(t)$ is an attenuation coefficient; $\exp(j2\pi l(t)/\lambda_i)$ is the Doppler effect due to the relative motion between the two satellites (λ_i being the wavelength of $s_i(t)$ and $l(t)$ the propagation path length); $n_i(t)$ *is* the additive thermal noise disturbance, assumed as zero-mean, white and Gaussian (AWGN). The noise terms affecting the two channels are assumed as independent with the same power spectral density $\sigma_n^2 = k_B T_{eq}$, where k_B is the Boltzmann's constant, and T_{eq} the equivalent noise temperature of the receiver. The equivalent noise bandwidth will be referred to as B_{eq} and depends on the cutoff frequency of the two lowpass filters (integrators) that are required in order to provide an estimate of the amplitude on each of the two receive channels (and consequently of P_1 and P_2). More specifically, $a_i(t)$ can be written as:

$$a_i(t) = \chi_i(t) L_{F,i}(t) L_{A,i}(t) L_{D,i}(t) \sqrt{G_{T,i} G_{R,i}} \ , \ i = 1,2 \tag{3}$$

where

- $G_{T,i}$ and $G_{R,i}$ are the transmit and receive antenna gains;

- $L_{F,i}(t)$ is the free space propagation loss;

- $L_{A,i}(t)$ is the loss due to absorption by water vapor, oxygen, nitrogen and clouds along the propagation path. It can be computed as the integral of the extinction coefficient along the propagation path (see [1]). In the frequency range considered here, the attenuation factor $L_{A,i}(t)$ significantly varies with frequency at any altitude. $L_{A,i}(t)$ is the only term of interest in (3), since it provides the attenuation information needed for spectral sensitivity measurements.

- $L_{D,,i}(t)$ is the defocusing loss, that is due to 'large scale' variations of the atmospheric index of refraction It can be modeled in general as a power loss depending on the tangent altitude $z(t)$ of the propagation path. The loss is maximum at the lowest altitudes and is assumed independent of frequency The expression we utilized is obtained experimentally as an average of different atmospheric conditions (z in km) [2]:

$$L_{D,1}(t) = L_{D,2}(t) = 10^{-\frac{1}{2}\exp(-0.089 z(t))} \tag{4}$$

$-\chi_i(t)$ is the tropospheric scintillation disturbance, generated by diffraction effects related to fluctuations of the refraction index [3]. Scintillation introduces random signal fluctuations that can be modeled as a multiplicative noise annoying each of the two tones. It is assumed that $\chi_1(t)$ and $\chi_2(t)$ are wide sense stationary processes with log-amplitude variance σ_χ^2, defined as:

$$\sigma_\chi^2 = Var\left[20 \cdot \log_{10}\left(\frac{\chi(t)}{mean(\chi(t))}\right)\right] \tag{5}$$

The scintillation coefficients χ_1 and χ_2 can be modeled as two correlated log-normal random variables, hence their joint pdf is [4]:

$$\begin{aligned} p_{\chi_1\chi_2}(X_1,X_2) &= \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}X_1X_2} \\ &\times \exp\left\{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{\log X_1-\mu_1}{\sigma_1}\right)^2 - 2\rho\frac{(\log X_1-\mu_1)(\log X_2-\mu_2)}{\sigma_1\sigma_2} + \left(\frac{\log X_2-\mu_2}{\sigma_2}\right)^2\right]\right\} \end{aligned} \tag{6}$$

where μ_1, μ_2 , σ_1 and σ_2 are the means and standard deviations of the underlying Gaussian variables, whereas ρ is their correlation coefficient. Under the hypothesis that the two channel frequencies are relatively close, it can be assumed that $\mu_1=\mu_2=\mu$, $\sigma_1=\sigma_2=\sigma$, so that the two marginals $p_{\chi_i}(X_i)$ i=1,2 are identical log-normal distributions. The power of χ_i is typically expressed in dB and is related to the variance of the underlying Gaussian as follows:

$$\sigma_{\chi_i}^2 = var\left[10 \cdot \log_{10}(\chi_i)^2\right] = (8.686)^2 \cdot \sigma^2 \tag{7}$$

whereas the average of the scintillation coefficients can be assumed as unitary, i.e. $E[\chi_i] = 1$ (it follows that μ must be chosen as $\mu=-\sigma^2/2$). Since turbulence increases with decreasing altitude, for the sake of simplicity we assumed that σ_χ (in dB) decreases with altitude as follows:

$$\sigma_\chi(z) = \sigma_{\chi 0} \cdot 10^{-0.1084 z} \tag{8}$$

where z is in km and $\sigma_{\chi 0}$ is the value of σ_χ at z=0. Spectral sensitivity measurements require the estimation of the powers P_1 and P_2 of the two tones $r_1(t)$ and $r_2(t)$ after having compensated the Doppler phase. As mentioned, the information of interest is contained in $L_{A,i}(t)$. The other terms in (3) either cancel out when the power ratio P_1/P_2 is taken, or must be considered as sources of error for the spectral sensitivity estimates.

III. SIMULATION RESULTS

We estimated the accuracy of the spectral sensitivity measurements versus tangent altitude by means of Monte Carlo simulations (50 runs per case), assuming two reference atmospheric models. These are the Mid Latitude Summer (MLS) and Mid Latitude Winter (MLW). Two atmospheric structures were then generated, by spherical symmetry extension of such vertical profiles. A scintillation disturbance process with ρ=0.98, following the profile (8) with $\sigma_{\chi 0}$=1 dB was chosen. Since below 12 km tangent altitude the atmospheric attenuation due to water vapor significantly lowers the received power, our analysis starts at that altitude. The link budget and orbit parameters considered are shown in Table 1 (values were selected based on the ESA ACE+ study [5]. Atmospheric attenuation computations were based on the MPM 93 model [6]. Coherent reception was assumed.

TABLE I. LINK BUDGET AND ORBIT PARAMETERS

First LEO satellite orbit altitude	650 km
Second LEO satellite orbit altitude	850 km
Tx Power (on each channel)	33 dBm
Tx Antenna Gain	28 dB
Rx Antenna Gain	28 dB
Implementation Margin	-1 dB
Noise Temperature	398 K

The average signal-to-noise ratio at the receiver is $SNR_m=(SNR_1+SNR_2)/2$ where $SNR_i=A_i^2/\sigma_n^2$ is the signal-to-noise ratio over the i-th receive channel. Fig. 1 shows SNR_m versus tangent altitude for MLS and MLW, respectively, and for six couples of tones with frequencies separated by 200 and 400 MHz, assuming a reference B_{eq} of 50 Hz.

Fig. 2 shows the normalized root mean square error (NRMSE) versus tangent altitude for the three frequencies and the two values of Δf considered. Observe first of all that the frequency providing the best accuracy changes with altitude: at higher altitudes higher frequencies are preferable. Notice also that measuring S with Δf=400 MHz is always preferable, at all frequencies and altitudes considered. Fig. 3 shows the NRMSE with a SNR_m increased by 20 dB, for Δf=400 MHz.

IV. CONCLUSIONS

The expected NDSA performance evidently depends on the value of SNR_m. Neglecting the possibility to increase the power link budget above a certain level, fixed by technological limits, the only free parameter is B_{eq}, which implies an integration time of $\approx 2/B_{eq}$. Therefore, the rate at which S measurements are provided is a basic design parameter, that constrains the spatial resolution to the measurement accuracy.

If the two LEO satellites are counter-rotating, the radio link is immersing in the atmosphere or emerging from it (with a variable speed that depends on the orbits and on the bending of the e.m. propagation path), and therefore measurement rate is directly related to the vertical resolution. With the parameters in Table 1 the vertical velocity of the link varies in a range of about 1-3 km/s.

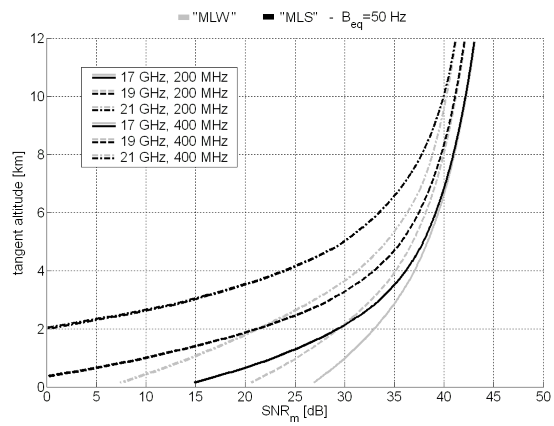

Fig. 1 - SNR_m versus tangent altitude for MLW and MLS at 17, 19 and 21 GHz and for Δf=200 and 400 MHz

With B_{eq}=50 Hz, for instance, we get a vertical resolution varying between 10 and 30 metres. Instead, in the case of two co-rotating satellites with the same orbit (assumed circular for simplicity), the propagation path keeps practically at a constant tangent altitude and moves tangent to an ideal circle in the atmosphere with the same angular velocity of the satellites. Considering one of the two orbital radii of Table 1, the path moves with respect to the Earth surface with a velocity of about 7 km/s. With B_{eq}=50 Hz, this implies a potential horizontal (with respect to the Earth surface) resolution of about 70 m.

A significant SNR_m increase (like that of 20 dB considered in Fig. 3) achieved only by reducing B_{eq} is certainly appealing for a co-rotating configuration: a degradation of the horizontal resolution of a factor 100 is perfectly adequate (an horizontal resolution of 7 km is more than compatible with horizontal water vapor dynamics). For a counter-rotating configuration, instead, such a degradation is not tolerable.

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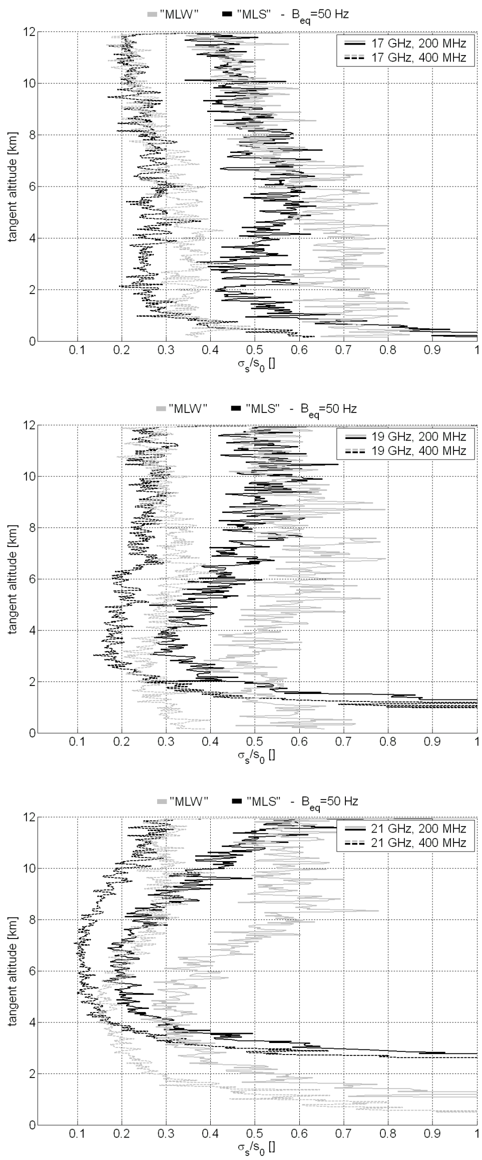

Fig. 2 - NRMSE at 17, 19 and 21 GHz in the MLW and MLS cases and for Δf=200 and 400 MHz .B_{eq}=50 Hz.

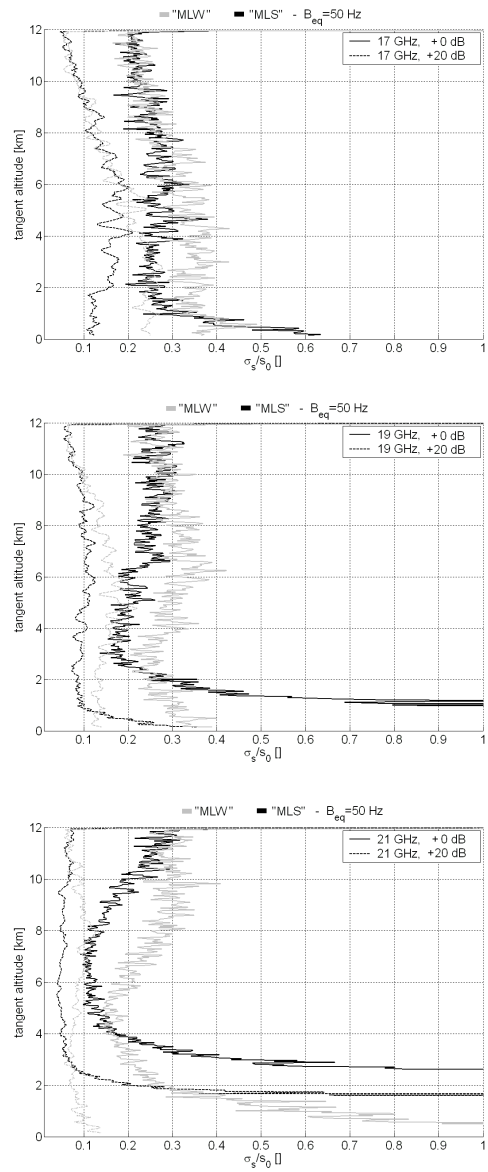

Fig. 3 - NRMSE obtained at 17,19 and 21GHz with a 20 dB SNR_m increase in the MLW and MLS cases, for Δf=400 Hz, and B_{eq}=50 Hz