NDSA Measurements For Water Vapor Estimate In The Lowest Troposphere By LEO-LEO Satellites: Performance Analysis In Counter-Rotating Configuration In The 17-21 GHz Range

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***Abstract*— A differential measurement concept for retrieving the total content of water vapor (IWV, Integrated Water Vapor) along the propagation path between two Low Earth Orbiting (LEO) satellites was proposed by the authors some year ago. The concept is based on the simultaneous measurement of the total attenuation at two relatively close frequencies in the K, Ku bands, and on the estimate of the NDSA (Normalized Differential Spectral Absorption) parameter that is highly correlated to the IWV content along the LEO-LEO link in the low troposphere. The measurement approach has the potential to minimize the effects of spectrally 'flat' and spectrally correlated phenomena (atmospheric scintillation among these) with respect to that of IWV. In this paper we report the results of a self-made software simulator used for estimating the measurement performance of the NDSA at 17 19 and 21 GHZ during a LEO-LEO set event. Impairments as thermal noise at the receiver, atmospheric scintillation, multipath and defocusing have been accounted for together with plausible LEO-LEO link power budget.**

Keywords: Satellites, atmospheric measurements, remote sensing, water vapor

I. INTRODUCTION

Recently, we proposed the utilization of NDSA (Normalized Differential Spectral Absorption) measurements based on the communication between two LEO (Low Earth Orbiting) satellites, to estimate the total content of water vapor (IWV, Integrated Water Vapor) along the propagation path between the two satellites (one of them carrying a transmitter, the other a receiver) [1]. In particular, we found that IWV can be directly estimated in the lowest troposphere (up to 12 km altitude) by converting the NDSA measurements in IWV through linear and/or quadratic relationships in the 17-21 GHz frequency range [2].

Through a microwave propagation model we found that, for each tangent altitude of the propagation path between 0 and 12 km, an optimum frequency exists that minimizes the error made when converting NDSA measurement into IWV through linear and/or quadratic relationship. In this view, it was important to estimate the uncertainty on the NDSA measurements to assess the association tangent altitude-frequency also in realistic measurement conditions. The NDSA measurements can be performed both in a counter rotating and in a co-rotating satellite configuration, but the propagation scenario is completely different. While in the co-rotating configuration the two satellites are always in sight and the propagation path is continuously immersed in the troposphere around a fixed tangent altitude, in the counter-rotating configuration the two satellites are in sight only during the set and rise events and consequently the propagation link submerges and emerges from the troposphere for limited time intervals. The worst case for the NDSA measurements is the counter-rotating one, where the tangent altitude varies quickly and the measurement time is limited.

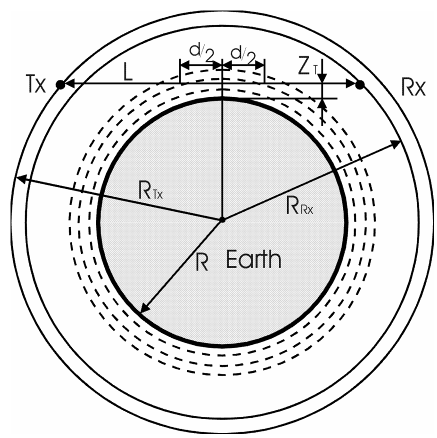

Figure 1. Geometry of a LEO-LEO link (with simplified rectilinear radiopropagation path).

We simulated a counter-rotating configuration with two satellites orbiting at different. We computed the uncertainty of the NDSA measurements at 17, 19 and 21 GHz. Such results are based on a self-made software that simulates the received power during the set event between the two LEO satellites. Through a Montecarlo approach we obtained estimates of the uncertainty on NDSA measurements considering standard atmospheric models and assuming the spherical symmetry for the atmospheric structure.

II. NDSA RATIONALE

Let's suppose that two tones with frequencies f_- and f_+ are transmitted. The NDSA measurement (referred to f_0 - see below) can be estimated by $\hat{S}(f_o)$ [2]:

$$\hat{S}(f_o) = \frac{P_{rx_-} - P_{rx_+}}{2\Delta f \; P_{rx_+}} \quad (1)$$

where P_{rx-} and P_{rx+} are the received powers at frequency $f_+=f_o+\Delta f$ and $f_-=f_o-\Delta f$ after propagation between the two Tx Rx LEO satellites along the link located at Z_T tangent altitude (see Fig.1) .

The NDSA measurements can be directly converted into the *IWV* content along the propagation path by means of the following linear and quadratic relationships [2]:

$$I\hat{W}V = a_1\hat{S}(f_0) + a_0 \quad (2)$$

$$I\hat{W}V = b_2\left[\hat{S}(f_0)\right]^2 + b_1\hat{S}(f_0) + b_o \quad (3)$$

where $I\hat{W}V$ is the estimate of *IWV*. In [2] we computed the conversion errors between ideal values of NDSA and *IWV* for several tangent altitude-frequency combinations, assuming the MPM93 as microwave propagation model and a complete global radionsonde yearly dataset. We found that the 17-21 GHz range provides the lowest conversion errors (see Table I) for tangent altitudes below 12 km.

TABLE I. CONVERSION ERROR BETWEEN IDEAL NDSA AND IWV USING (2) AND (3). BOLD VALUES ARE THE LOWEST ERRORS FOR EACH TANGENT ALTITUDE [2].

	km	17 GHz		19 GHz		21 GHz	
		lin	quad	Lin	quad	lin	quad
Tangent altitude	**1**	5.7	2.4	10.4	**1.7**	25.4	10.1
	3	4.3	3.2	6.1	**1.2**	20.9	7.7
	5	4.1	3.5	4.0	**1.7**	15.2	4.7
	7	5.6	5.6	3.3	2.9	7.8	**2.5**
	9	23.1	18.7	9.8	9.6	2.9	**1.9**
	11	61.5	56.1	35.1	33.1	8.3	**8.3**

III. SIMULATION SCENARIO

The software we developed simulates the transmission, propagation and reception of two tones during the set event between two LEO-LEO satellites (Fig. 2). It accounts for link budget power, atmospheric propagation loss (absorption and defocusing), propagation disturbance (turbulence scintillation due to random variation of the refraction index), thermal noise at the receiver and ground multipath. The main output is the time sequence of the received powers P_{rx+} and P_{rx-} during the set event between two LEO-LEO satellites. Then the time sequence of the NDSA parameter *S(f₀)* is computed as in (1) after mobile window filtering on the P_{rx+} and P_{rx} time sequences.

The variability of the refraction index causes the bending of the propagation path. For our simulation purposes, such effect is of interest for two issues, i.e. the NDSA-Iwv relationships and the variability of the immersion rate during the LEO-LEO set event. As shown in [2] the NDSA-Iwv relationships are not modified by bending effect. Therefore, in order to limit the computational burden, we assumed a rectilinear propagation path immersing in the atmosphere with a variable immersion rate depending on the variability of the refraction index.

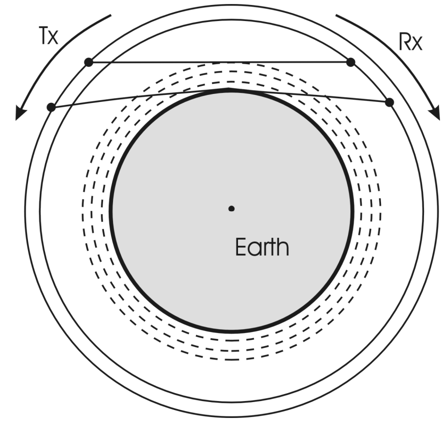

Figure 2. LEO-LEO set event simulated for evaluating the NDSA measurement performance.

A. *Basic assumption*

The software simulator we developed is based on the following main assumptions and characteristics:

- LEO orbits set at 650 and 850 km over the Earth' surface.
- Initial tangent altitude set at 12 km
- Decreasing immersion rate of the LEO-LEO propagation link.
- Spherical symmetry of the atmospheric structure with shell resolution better than 125 m
- Absence of liquid water along the propagation path (no rain and no clouds)
- Fixed defocusing profile [3]
- Unitary reflection by the Earth' surface for ground multipath computation.
- two parameters model for the scintillation impairment (assumed as multiplicative disturbance on the received signals) [3][4]: ρ (the $f_+ f_-$ channel correlation), and σ_χ (maximum scintillation power), set by the user.
- AWGN noise at the receiver
- Coherent reception
- Power link budget parameters as in Table II

B. Transmitter and receiver

We assume the transmission of two tones at frequency f_+ and f_- with the same amplitude and the receiver is assumed to be coherent. Figure 3 shows a possible receiver scheme with its main functional blocks. Two branches are needed for separating the contribution of each of the two tones from the total received signal and for estimating the received powers P_{rx+} and P_{rx-}. However, the frequency of the received signals is not constant due to the relative motion of the satellites, therefore additional circuitry is required to recover frequency and phase of each of them, so that their amplitude can be estimated through mixing and integration, and consequently their powers P_{rx+} or P_{rx-}. In particular, the PLL (Phase Locked Loop, that starts tracking the signals before the link immerges in the atmosphere) provides a reference signal with perfect recovery of frequency and phase, including frequency deviation from the nominal value due to Doppler shifts and slow phase variations due to channel phase distortion.

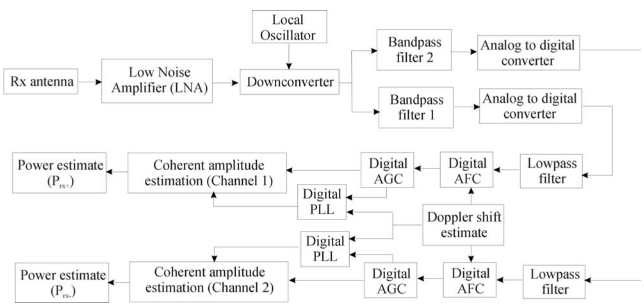

Figure 3. Main functional blocks composing the receiver

TABLE II. LINK BUDGET PARAMETERS [1]

Parameter	Value
Tx Power (on each channel f_+/f_-)	33 dBm
Tx Antenna Gain	28 dB
Rx Antenna Gain	28 dB
Implementation Margin	-1 dB
Noise Bandwidth	5 kHz
Noise Temp	398 K
C/N0 (without atmospheric absorption)	68 dBHz

IV. SIMULATION RESULTS

We defined a reference case study assuming the MLS (Mid Latitude Summer) atmospheric model for the vertical profiles of temperature, pressure and water vapor and the following parameter to be set by the user:

– frequency separation $2\Delta f$=0.2 GHz,

– scintillation parameters ρ=0.98 and σ_χ=1 dB

– time mobile window = 0.4 seconds.

– Frequencies: f_0=17, 19 and 21 GHz

The performance of the NDSA measurements are evaluated in terms of normalized standard deviation, σ_s/S_0, where S_0 is the ideal NDSA value without any disturbance and/or impairments and σ_s is the standard deviation estimated through the Montecarlo runs. The results of this reference case study are summarized in Fig. 4 and Fig. 5. The main outcome of Fig. 5 is that to each frequency corresponds an optimal tangent altitude interval:

- 4-10 km for NDSA measurements at 21 GHz, with errors lower than 10%
- 2-4 km for NDSA measurements at 19 GHz, with errors lower than 10%
- below 2 km NDSA measurements can be made at 17 GHz, with errors lower than 15%

Therefore, using the optimal frequency for each tangent altitude, the link budget of Table II allows NDSA measurements with relative errors generally lower than 15%.

Starting from the reference case, many simulations have been made varying the configuration parameters (noise level, scintillation power, correlation of the scintillation disturbances on the two receive channels, time window width) in order to assess the importance of each phenomenon on the NDSA measurements. The overall results obtained with these simulation trials can be summarized as follows:

– The optimal frequency-altitude relationship is independent of the disturbance power and signal to noise ratio at the receiver.

– Although the scintillation level is still hard to relate to the atmospheric characteristics in microwave LEO-LEO propagation applications, and the results of this work are based on simplified assumptions (two parameter models), NDSA measurements do not seem to undergo severe degradation due to scintillation impairments.

– Ground multipath does not influence the NDSA measurements above 2 km tangent altitude.

– Increasing the link budget power improves significantly the NDSA measurement performance: 10 dB of additional signal to noise ratio at the receiver reduce the relative errors of about 50% in any optimal frequency-altitude combination (see Fig 6 for the 17 GHz case).

– Increasing the time window filtering improves the performance of the NDSA measurements (doubling the window time, the relative error halves) but the vertical details of the NDSA vertical profile decreases.

V. CONCLUSIONS

The purpose of this paper was to provide the first overall performance evaluation about the direct conversion of NDSA measurements into IWV for LEO-LEO counter-rotating configuration. By comparing the estimated NDSA measurement performance with the conversion errors (see Table I) we can conclude that the main uncertainty in the IWV estimation directly by NDSA is due to the uncertainty on the NDSA measurements.

The proposed transmitter-receiver scheme and the results reported here indicate that NDSA measurements can be made with error lower than 10% assuming the link power budget of Table II. Three frequencies in the 17-21 GHz interval are sufficient for sounding all the tropospheric layers in absence of liquid water (rain and clouds). Further investigations are needed to better understand scintillation phenomena. Moreover, global simulations in all plausible atmospheric conditions should be made to assess whether the proposed NDSA measurements can be applied to any atmospheric condition and the influence of liquid water along the propagation path.

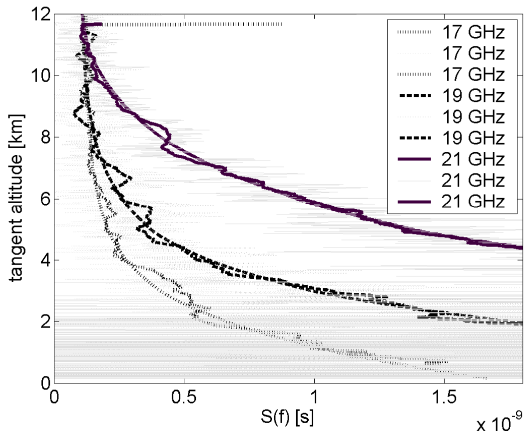

Figure 4. NDSA (abscissa) versus tangent altitudes (ordinate). Regular tick lines: ideal NDSA values; thick lines: mobile window filtering (0.4 seconds) of one Montecarlo run, thin gray lines: no filtering of one Montecarlo run

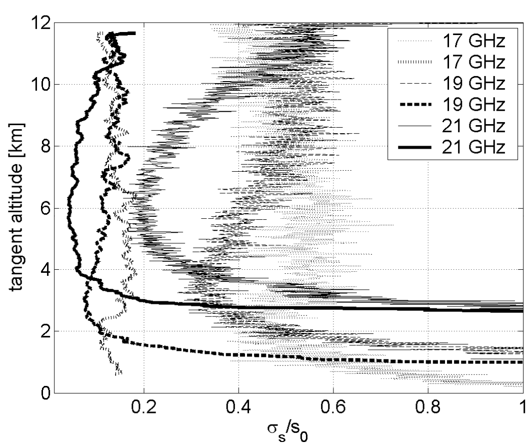

Figure 5. Normalized standard deviation (abscissa) versus tangent altitudes (ordinate) after 50 Montecarlo runs of NDSA measurements. Thick line: mobile window filtering (0.4 seconds); thin lines: no filtering.

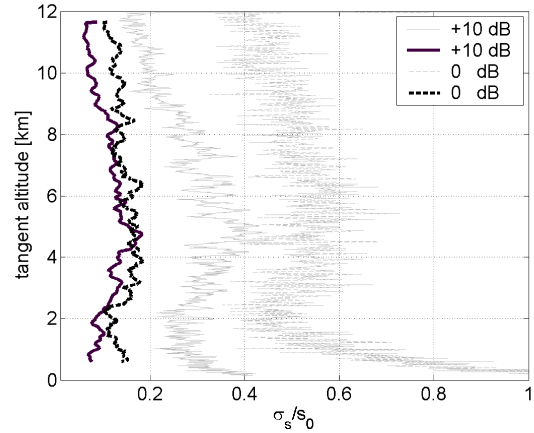

Figure 6. Normalized standard deviation (abscissa) versus tangent altitudes (ordinate) after 50 Montecarlo runs of NDSA measurements at 17 GHz. Reference link budget (0 dB curves) and +10 dB of signal to noise ratio at the receiver (+10 dB curves). Thick and thin lines: same meaning of fig 5

ACKNOWLEDGMENT *(HEADING 5)*

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