CLOUD EFFECTS ON THE NDSA MEASUREMENTS FOR WATER VAPOR ESTIMATE IN THE LOWEST TROPOSPHERE BY LEO-LEO SATELLITES IN THE 10-30 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 17-21 GHz range, and on the estimate of the NDSA (Normalized Differential Spectral Absorption) parameter. Such parameter provides directly the IWV content along the LEO-LEO link in case of dry air atmospheric conditions (no liquid water along the propagation path). In this paper we analyze the effects of liquid and solid water on NDSA measurements and how such effects must be accounted for in converting NDSA measurements in IWV. We quantify the effects of liquid water on NDSA measurements in the 10-30 GHz range. We show how NDSA at 30 GHz can be used to check the presence of liquid water and how liquid water influence the conversion in IWV at 17, 19 and 21 GHz. Finally we discuss the possibility to use the NDSA at 30 GHz for estimating directly the liquid water content along the propagation path as well as we propose the conversion of NDSA to IWV in the 17-21 GHz range.**

Keywords-component: Satellites, atmospheric measurements, remote sensing, water vapor, liquid vapor, clouds

I. INTRODUCTION

Recently, we proposed the utilization of the NDSA (Normalized Differential Spectral Absorption) measurements on satellite system, composed by a couple of 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) converting the NDSA measurements in IWV through linear and/or quadratic relationships in the 17-21 GHz frequency range [2]. Feasibility study, as one presented at this conference by the same authors, have been already done for evaluating the performance of the NDSA measurements in realistic conditions of available power at the receiving satellite [2][5][6].

All these works were based on microwave propagation models in atmosphere that did not account for the presence of liquid and water along the propagation path. In this work we show how the liquid and solid water influence the NDSA measurements and how such effects must be accounted for in converting NDSA measurements in IWV. The objective of this work is to check whether the NDSA measurements for the direct estimation of the IWV can be still used in presence of liquid and solid water or not.

All the results presented in this work have been obtained by simulation software of atmospheric propagation. We used the whole MPM93 propagation model (wet and dry section) [3] to simulate the EM interactions between microwave radiation and atmospheric components.

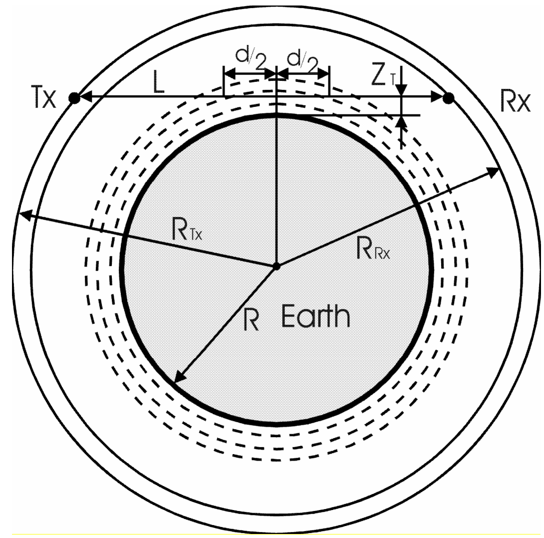

Figure 1. Geometry of a LEO-LEO link.

Many different cloud models (different for altitude position, thickness, width, concentration of liquid water and ice) have been accounted for in order to analyze the qualitatively and quantitatively effects on the NDSA measurements. This analysis allows to know how the presence of liquid and solid water modifies the NDSA measurements varying frequency and tangent altitude of the LEO-LEO propagation path.

II. DSA RATIONALE

Assuming the transmission of two sinusoidal CW signals with frequency f_- and f_+, the NDSA measurements at f_0 frequency can be estimated by $\hat{S}(f_o)$ [2]:

$$\hat{S}(f_o) = \frac{P_{rx\_} - P_{rx_+}}{2\Delta f\ P_{rx_+}} \tag{1}$$

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 in the *IWV* content along the propagation path by means of the following linear and quadratic relationships [2]:

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

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

where $I\hat{W}V$ is the estimate of *IWV*. The conversion errors at global level in the17-21 GHz in clear air conditions is reported in Table I for tangent altitudes below 12 km. Notice that for the lowest tangent altitudes the conversion errors are quite low using a quadratic relationship at 19 GHz.

TABLE I. CONVERSION ERROR BETWEEN NDSA AND IWV USING (2) AND (3) IN CLEAR AIR CONDITIONS. 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. LIQUID WATER CONTRIBUTION TO NDSA

The presence of liquid water along the LEO-LEO propagation path cannot be in general excluded at the lowest tangent altitudes, due the presence of clouds and/or rainfall. Since the spectral attenuation due to liquid water varies with frequency [3], clouds and rainfall have an impact on NDSA measurements, and it is therefore needed to understand to which extent they influence the NDSA-IWV relationships.

The attenuation due to rainfall is very high in the bands of interest; it is expected that NDSA measurements are extremely degraded and not utilizable for the conversion to IWV when the propagation path intercepts rainfall cells. However, notice that rainfall is occasional and limited to the lowest tangent altitudes. Instead, the presence of clouds is not so occasional and liquid water inside clouds give rise to a lower contribution of attenuation than rainfall. The classification of clouds and their typical water content are reported in Tab. 2.

The first result we found is that NDSA measurement is directly affected by the quantity of liquid water along the propagation path (integrated liquid water - ILW), and not by type and shape of clouds, therefore the only parameter accounting for the effects of liquid water on NDSA is the ILW. Therefore, in order to maintain the spherical symmetry of the atmospheric structure, the cloud has been simulated as a spherical layers of 1 km thickness with uniform water density.

TABLE II. MAIN CLOUD TYPES [4].

Cloud Type	Base altitude [m]	Vertical extension [m]	Cloud composition	Water density [g·m^{-3}]	Ice density [g·m^{-3}]
Cirrus Cirrostratus	>6000	300	Ice	---	0.05
Cirrocmulus	>6000	300	Ice/water	0.05	0.05
Altostratus	2000÷6000	1200÷3000	Water	0.20	
Altocumulus	2000÷6000	300	Water	0.30	0.10
Stratocumulus	1500÷4000	150÷1000	Water	0.50	
Cumulonimbus	1000÷3000	3000÷12000	Water	2.50	0.20

Fig. 2 and Fig. 3 show the attenuation and the NDSA, respectively, in the 10-30 GHz range for a LEO-LEO link at 3 km tangent altitude assuming ILW=2.25 g·cm^{-2} along the propagation path. Such liquid content is like that of a cumulonimbus 10 km width with water density of 2.25 g·m^{-3} or an altostratus 100 km width with water density of 0.225 g·m^{-3}.

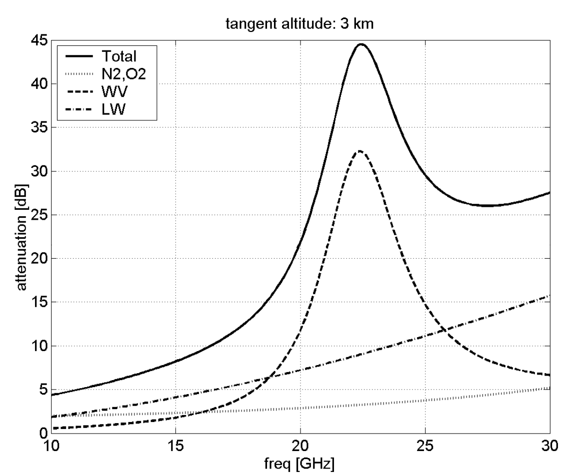

Figure 2. Total spectral attenuation in dB with separate contributions due to water vapor (WV), liquid water (LW) and N2/O2 computed at 3 km tangent altitide under the following hypotheses: constant (0.1 g·m^{-3}) liquid water

content from 3 to 4 km altitude, MLS atmospheric model profiles for clear air, rectilinear propagation path, spherical symmetry and MPM93 propagation model

Evidently, the contribution of liquid water to the total attenuation varies with frequency, though such variation is much less pronounced than that due to the presence of water vapor.

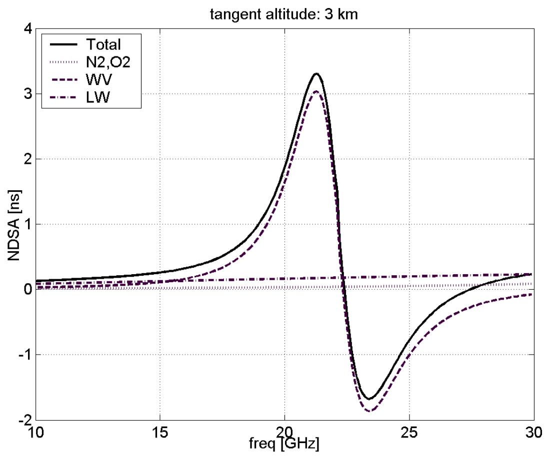

Figure 3. NDSA (2Δf=200 MHz) with separate contributions due to water vapor, liquid water and N2/O2 under the same assumptions of figure 2.

The effect of liquid water on the total spectral sensitivity is a positive bias, slightly varying with frequency. In particular, the ILW contribution dominates around 30 GHz: therefore, from a theoretical point of view, such carrier frequency could be exploited to detect the presence of liquid water along the radio path.

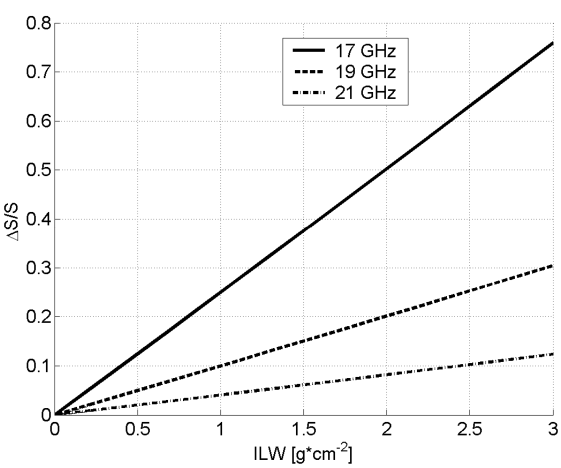

Figure 4. relative deviation of the NDSA versus the ILW on the propagation path at 3 km tangent altitude for 17, 19 and 21 GHz.

Fig. 4 shows how NDSA varies with the ILW for the three frequencies usable to convert NDSA directly in IWV. It is evident that ILW presence is not negligible on the NDSA measurements especially for the 17 GHz case. This means that the NDSA measurements must be cleaned by ILW contribution before converting them into IWV, otherwise its estimation by using (2) or (3) would prove overestimated.

The NDSA measurements around 30 GHz should allow to know whether liquid water is present or not. Negligible positive and negative NDSA values would indicate the absence of liquid water along the propagation path. In this case the estimation of IWV by using (2) and (3) in 17-21 GHz range, would be correct and not overestimated by NDSA contribution due to ILW

Fig 5 shows the NDSA at 30 GHz in absence of liquid water and with 2.5 and 5.0 $g \cdot cm^{-2}$ for tangent altitudes from 3 to 10 km. At any tangent altitude NDSA is almost completely due to ILW contribution. Moreover, notice that doubling the ILW content, NDSA doubles at each tangent altitude.

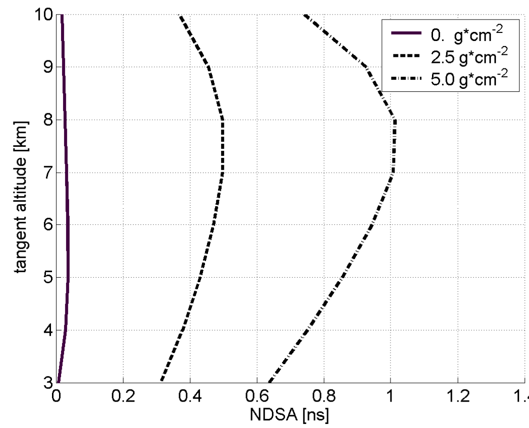

Figure 5. NDSA (2Δf=200 MHz) at 30 GHz for three different contents of ILW at 3-10 km tangent altitudes.

IV. SOLID WATER CONTRIBUTION TO NDSA

Also in the case of solid water, the NDSA measurement is directly affected by the total content of ice, IIW (Integrated Iced Water), and not by type and shape of ice clouds. An IIW of 4 $g \cdot cm^{-2}$ (i.e. an ice cloud 200 km width with uniform iced water density of 0.2 $g \cdot m^{-3}$) located at 1 km tangent altitude produces less than 0.15% of NDSA amplitude in the whole 15-30 GHz range. Since this IIW is definitely high we can assess that NDSA measurements are not influenced by iced water along the propagation path.

V. CONCLUSIONS

The presence of liquid water along the propagation path affects spectral sensitivity measurements since the spectral attenuation due to liquid water varies with frequency. The effect on the spectral sensitivity is a positive bias depending on the total liquid water content along the path. Therefore, single NDSA carrier measurements would bias the IWV estimate if a direct conversion is applied. However, it is envisaged that a multi-carrier NDSA approach could help to detect the presence of liquid water and/or mitigate its effects on the IWV estimates.

Even if this work is based on standard models of atmospheric composition and simplified hypothesis for the atmospheric structure, notice that the magnitude of the NDSA measurements at 30 GHz are smaller than that in the 17-21 GHz range, also for high presence of liquid water along the propagation path. A feasibility study accounting for realistic propagation conditions, as that in [5] and [6], should be done in order to find out the minimum measurable value of NDSA at 30 GHz in suitable signal to noise ratio. This minimum value will give the corresponding minimum value of estimable liquid water content.

ACKNOWLEDGMENT

The authors thank Mr. Luca Capannesi for his technical support.

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