Global Water Vapor Estimate In The Lowest Troposphere By Attenuation Measurements On LEO-LEO Satellites at 17.25 GHz

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Abstract – **In this work we present the simulation results concerning the possibility to estimate the tropospheric water vapor content along the propagation path between two satellites counter-rotating on two different LEO orbits. The estimation method is based on the measurement of a parameter referring to the differential spectral absorption at 17.25 GHz along the propagation link between the two satellites. The choice of that frequency allows to estimate the water vapor in the lowest troposphere, namely when the propagation path crosses the troposphere at tangent altitudes up to 6 km above the Earth's surface. Effects of different latitudes and atmospheric bending have been accounted for and are presented and discussed.**

Keywords-component; water vapor, microwave remote sensing, LEO satellite, troposphere.

I. INTRODUCTION

Monitoring atmospheric water vapor plays a fundamental role in meteorology and climatology. International Space Agencies (NASA, ESA) have been analysing for years the possibility to employ satellite systems to measure the atmospheric water vapor at global scale and at a minimum cost, but its estimation with adequate resolution in space and time is not an easy task since its concentration may considerably vary both with time and altitude (see [1][2][3] and [4]). Water vapor is present in the troposphere up to about 20 km altitude above the sea level and it is the main responsible of spectral attenuation of the radio signals crossing the atmosphere in the K and K_a bands.

Recently (see [5][6] and [7]), we suggested that the DSA (Differential Spectral Absorption) method could be employed in the 17-25 GHz range on satellite systems, 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). In particular, we found that the IWV can be directly estimated in the lowest troposphere (up to 6 km altitude) using the DSA method at 17.25 GHz.

Here we show that the differential spectral power at 17.25 GHz is linearly correlated to the IWV along LEO-LEO propagation paths crossing the troposphere at tangent altitudes below 5 km, independently of variations of the atmospheric

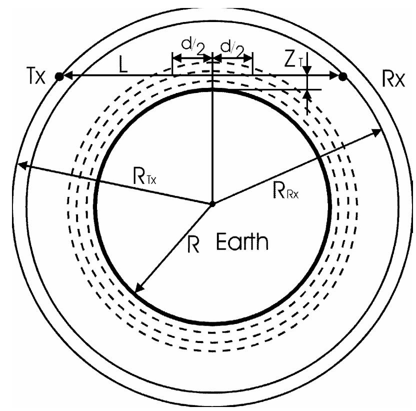

Fig. 1 - Geometry and parameters of a LEO-LEO link (with simplified rectilinear radiopropagation path).

conditions in a plausible range. Through an *ad-hoc* simulation software package developed for this study we computed the linear correlation coefficients between the differential spectral power at 17.25 GHz and the IWV for all tangent altitudes up to 6 km. Computations are based on a huge data set of radiosonde data and on a microwave atmospheric propagation model. The radiosonde data set allows to consider all the plausible atmospheric conditions separately in terms of latitude and temporal reference (hour/day/season). In other words, the correlation coefficients computed account for both latitude and time variations in the linear relationship between the differential spectral power at 17.25 GHz and the IWV.

II. THE DSA METHOD

The DSA (Differential Spectral Attenuation) method is based on the measurement of the sensitivity function *S(f)* defined as:

$$S(f)=\frac{1}{A(f)}\frac{d}{df}\left[A(f)\right] \qquad (1)$$

where *A(f)* is the power attenuation at the frequency *f* during the propagation in the atmosphere between the two LEO

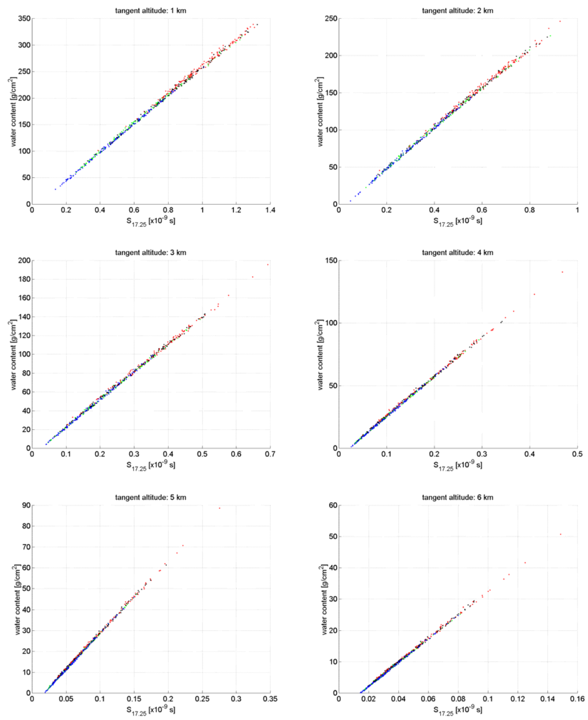

Fig. 2 – Reference *Iwv* , $S_{17.25}$ data for the reference radiosonde data set 1 to 6 km step 1 km (top left to bottom right). In abscissa S17.25 in ns, in ordinate the Iwv in g cm-2.

satellites. The estimate of *S(f)* at a given frequency f_0 (referred to as carrier frequency in the following) can be made in practice by transmitting two signals with known powers P_{tx+} and P_{tx-} , spectrally separated (ideally two spectral lines) and centered at two frequencies $f_+=f_o+\Delta f$ and $f_-= f_o-\Delta f$ that are adequately close to f_0 , and measuring the power received in correspondence of each of the two frequencies. In this manner, the sensitivity as given in (1) can be expressed in terms of the received powers only:

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

Based on the results described in [1], we considered a linear relationship to relate *Iwv(z)* (the Iwv relative to the propagation path at a given tangent altitude *z*) to $S_{17.25}(z)$ (the spectral sensitivity at f_0=17.25 GHz and Δf=0.05 GHz):

$$\hat{Iwv}(z)=a_1(z)\cdot S_{17.25}(z)+a_0(z) \tag{3}$$

III. THE REFERENCE CASE

Using a reference radiosonde dataset (the whole year 2000 of radiosonde profiles gathered at the radiosounding site in S. Piero Capofiume, Bologna, Italy, lat=44.65 N, lon=11.62 E, WMO code: 16144) we computed the reference conversion coefficients $a_0(z)$ and $a_1(z)$ through linear regression applied to simulated data of *Iwv*(*z*) and $S_{17.25}(z)$ for tangent altitudes from 1 to 6 km step 1 km. The hypotheses under which such reference coefficients were simulated and computed are summarized below:

1. rectilinear propagation between the two LEO satellites;
2. spherical symmetry for the atmospheric structure;
3. no other propagation effect considered;
4. propagation model used for computing the attenuation coefficient along the propagation path: the MPM93 (Millimeter Propagation Model [8]),
5. vertical resolution of the radiosonde profiles: at least 125 m.

The simulated Iwv and $S_{17.25}$ data of the reference radiosonde data set are reported in the 6 plots of Fig. 2 , one for each tangent altitude.

The reference coefficients $a_1(z)$ and $a_0(z)$, that allow to estimate Iwv through (3) were computed through linear fit applied to the plots Fig.2, thus providing reference coefficients at each of the 6 tangent altitudes from 1 to 6 km.

In order to evaluate the error made to estimate the Iwv through (3), the following error parameters were used:

$$\varepsilon(z)=\frac{\hat{Iwv}(z)-Iwv(z)}{Iwv(z)}\cdot 100 \tag{4}$$

$$rms(z)=\frac{std\left(\hat{Iwv}(z)-Iwv(z)\right)}{mean\left(Iwv(z)\right)}\cdot 100 \tag{5}$$

The results of the linear fit are summarized in Table I.

TABLE I – REFERENCE a_1 AND a_0 COEFFICIENTS (LINEAR FIT) APPLIED TO THE YEARLY DATA PLOTS OF FIG. 2 . *Mean* AND *std* ARE THE MEAN AND THE STANDARD DEVIATION OF ε WHILE *rms* IS THE ERROR PARAMETER DEFINED IN (4) AND (5).

Tangent altitude *z* [km]	a_1 [g cm^{-2} ns^{-1}]	a_0 [g cm^{-2}]	*mean*(ε) [%]	*std*(ε) [%]	*rms* [%]
1	266	-7.2	0.2	1.9	1.6
2	283	-7.6	0.3	2.9	1.8
3	302	-7.2	0.4	3.2	1.8
4	323	-6.5	0.8	4.8	2.0
5	351	-6.0	1.1	7.7	2.4
6	383	-5.4	1.1	6.8	2.6

IV. GEOGRAPHICAL EFFECTS

Geographical effects are meant here as those effects on the relationship between spectral sensitivity and *Iwv*, that are related to the latitude of the projection of the LEO-LEO propagation link over the Earth's surface. The study of such effects has been carried out considering radiosonde data coming from sites located at a number of different latitudes of the Northern Emisphere (see Fig.3).

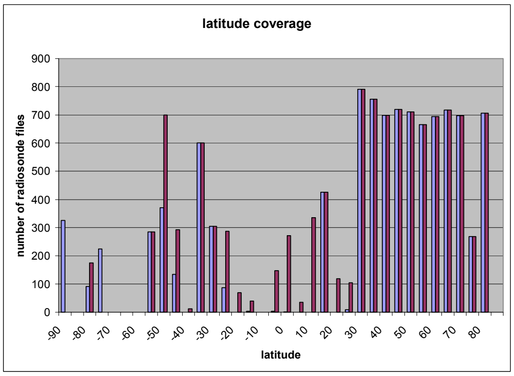

Fig. 3 – Number of radiosonde profiles versus latitude

For each radiosonde site with a maximum survey altitude of 15 km, we computed the $S_{17.25}(z)$ -$Iwv(z)$ pairs following the same procedure described for the reference case and the yearly linear fit coefficients $a_1(z)$ and $a_0(z)$ as described above.

In order to delineate the trend of the coefficients when varying latitude, after having computed the coefficients for each site, an adequate fitting was applied separately for each altitude: Fig. 4 shows the trend obtained for 1, 2 and 3 km tangent altitudes. It can be noticed that a_1 increases linearly with latitude for any given tangent altitude (this occurs also for the altitudes above 3 km not represented in the figure), while a_0 decreases with latitude, for any given tangent altitude. The

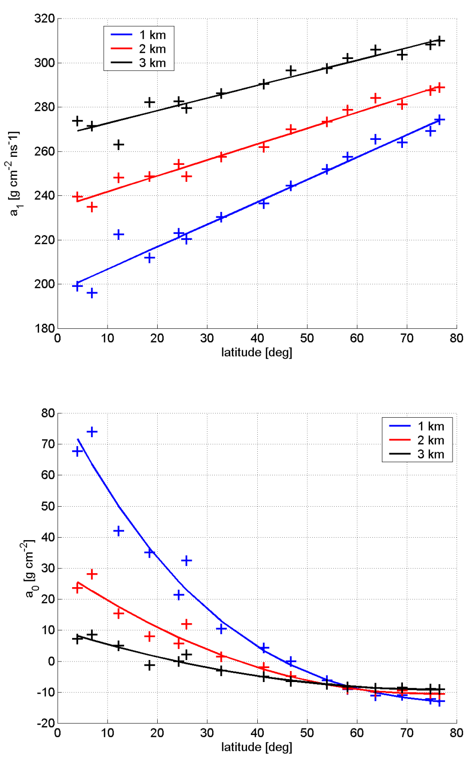

Fig. 4 – a_1 (left) and a_0 (right) coefficients at 1,2 and 3 km tangent altitude versus latitude for the linear $S_{17.25}$ - Iwv relationship. Cross marker: the coefficients corresponding to each radiosonde site considered; continuos curves: linear fit applied to the a_1 coefficients in the left plot (separately for each of the 3 altitudes considered), cubic (for 1 km altitude) and quadratic fit (for 2 and 3 km altitude) applied to a_0 in the right plot.

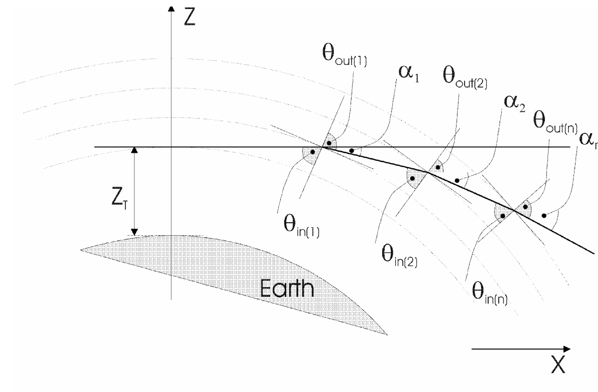

Fig. 5 – The 2D geometry assumed for the analysis of the bending effects. $2\alpha_n$ is the total bending angle considering n spherical shells with constant refraction index. $\theta_{in}(n)$ and $\theta_{out}(n)$ are the input and output angles at the n-th shell separating surface. θ_{out} is computed applying the Snell's law

relationship between $S_{17.25}(z)$ and $Iwv(z)$ keeps linear at every latitude, but evidently the coefficients $a_1(z)$ and $a_0(z)$ must also account for latitude.

V. Bending Effects

The spatial variation of the refraction index implies that the radio propagation is not rectilinear. Crossing the atmosphere,

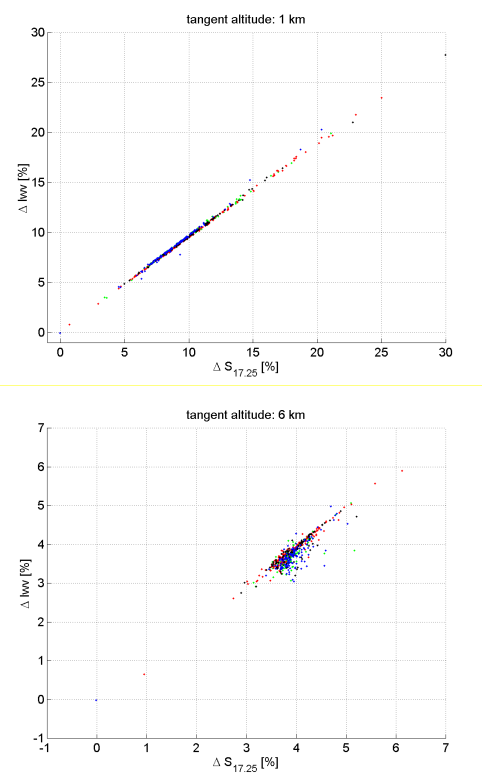

Fig. 6 – Percent variations at 1 and 6 km tangent altitude (with respect to the rectilinear propagation case) of $S_{17.25}$ versus those of Iwv accounting for bending effects. The percentage comparison is made with respect to the reference $S_{17.25}$ Iwv data of fig.2

the microwave radiation describes a curvilinear trajectory. With respect to the case of rectilinear propagation, bending has an impact on DSA measurements since it produces a different spectral sensitivity measurement and also a different water vapor content to which such measurement is related, and therefore in general it should be accounted for. Specifically, in this section are evaluated the effects that such bending has on the relationship between sensitivity and Iwv.

Such evaluation was made supposing that the atmosphere is made up by a finite number of spherical shells and that within each shell the refraction index is constant. Under this simplifying assumption, bending is due to the variation of the refraction index at two shells' separation surfaces. Assuming that these surfaces are locally plane, the trajectory variations can be computed through the Snell's law applied to each shell boundary (see Fig.5).

In simulations, first the propagation path is computed as a set of linear segments as shown in Fig. 5, then Iwv and the propagation parameters are computed for each segment and finally $S_{17.25}$ and the total Iwv are provided. In the following, the "S_{1725} - Iwv pair at altitude z" shall be meant as that related to the propagation path for which z is the minimum distance from ground. The results of the simulations using the reference radiosonde data set are reported in Fig. 6 in terms of the percentage difference for $S_{17.25}$ and Iwv with respect to the values of the reference case for tangent altitudes 1 and 6 km. Bending gives increased values of $S_{17.25}$ and Iwv at each tangent altitude (here only 1 and 6 km are shown), but the ratio between their percentage increments is close to one for all the radiosonde data. For this reason the relationship between $S_{17.25}$ and Iwv keeps linear also when accounting for the bending effects. Table II reports the values of $a_1(z)$ and $a_0(z)$ computed by linear fit on the $S_{17.25}$ - Iwv data accounting for bending effects: comparing them with those reported in Table II.

TABLE II – a_1 AND a_0 OBTAINED BY LINEAR FIT ON THE REFERENCE $S_{17.25}$ IWV DATA SET, ACCOUNTING FOR BENDING EFFECTS. MEAN, STD AND RMS HAVE THE SAME MEANING OF THOSE IN TABLE I.

Tangent altitude z [km]	a_1 [g cm^{-2} ns^{-1}]	a_0 [g cm^{-2}]	$mean(\varepsilon)$ [%]	$std(\varepsilon)$ [%]	rms [%]
1	264	-6.4	0.2	1.9	1.6
2	281	-7.7	0.3	2.3	1.8
3	301	-7.5	0.3	2.8	1.8
4	323	-6.8	0.5	3.5	2.0
5	351	-6.2	0.7	4.5	2.3
6	383	-5.6	0.8	5.1	2.6

It can be noticed that $a_1(z)$ remains unchanged to the 3rd significant digit, while $a_o(z)$ exhibits variations.

VI. CONCLUSION

The water vapor content along the propagation paths between two LEO satellites crossing the lowest troposphere can be directly estimated by measuring the spectral sensitivity function at 17.25 GHz. The effects of the geographical and seasonal variations of the atmospheric parameters have been accounted for. Such variations have a small impact in the linear relationship between Iwv and sensitivity at 17.25 GHz. The same results have been obtained accounting for bending effects due to the variations of the refractive index along the propagation path. Further studies should be done to analyze the communication link performance, in order to obtain a sufficient signal to noise ratio at the receiver for the measurement of the sensitivity parameter depending on the link power budget.

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