ATMOSPHERIC WATER VAPOR ESTIMATE THROUGH MW ATTENUATION MEASUREMENTS ON LEO-LEO SATELLITE CONFIGURATION

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Abstract – In this work, we propose the utilization of a satellite system, composed by a couple of LEO (Low Earth Orbit) satellites operating in the 18-22 GHz range (close to the 22.235 GHz absorption line of water vapor), 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 show that IWV can be estimated starting from measurements of received spectral power.

I. INTRODUCTION

Monitoring of atmospheric water vapor is critically important in many scientific fields such as meteorology and climatology. In particular, a continuous-time estimate of the water vapor content is hard to achieve since its concentration can considerably vary both in time and with altitude. Water vapor is present in the troposphere up to 20 km altitude above the sea level and it is one of the main responsible of the spectral attenuation of radio-frequency signals crossing the atmosphere.

In this paper we report the main results obtained through an analysis study about the utilization of an active satellite system composed by two satellites on LEO orbit operating in the 18-22 GHz frequency range, in order to estimate the integral water vapor content (IWV) along the propagation path between the two satellites. By means of spectral sensitivity measurements, dependent on received spectral power measurements, we propose a method to estimate the IWV.

A radiosonde data set was used to simulate the receiver output in different atmospheric conditions; the measurement site is located close to Bologna (WMO Code: 16144), Italy. The receiver output has been simulated considering the MPM atmospheric model (Millimeter-wave Propagation Model) proposed by Liebe [1].

The simulated sensitivity data were exploited to estimate the correlation between the receiver output at 18, 19 and 20 GHz and the IWV.

II. SPECTRAL FUNCTIONS

Referring to Fig.1 and denoting with P_{tx} the transmitted spectral power, the spectral power P_{rx} received by the satellite is given by:

$$P_{rx}(f) = P_{tx}(f)\,\alpha(f)\,e^{-\tau(f)} \qquad \text{[W]} \quad (1)$$

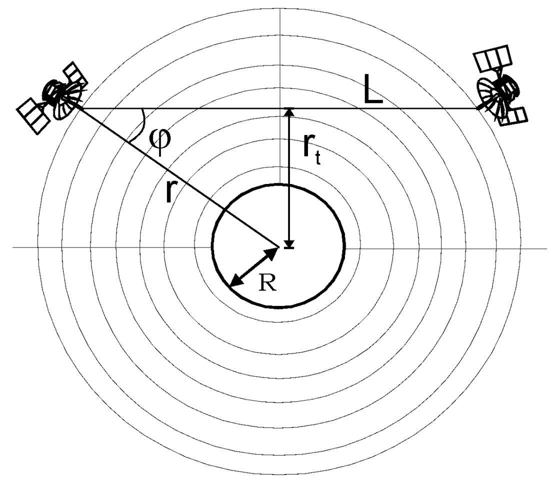

Fig.1 - Sketch of the LEO-LEO satellite link.

where $\tau(f)$ is the one-way optical depth, related to the atmospheric attenuation along the propagation path L while $\alpha(f)$ accounts for all the other attenuation contributions.

Defining the spectral attenuation $A(f)$ as the ratio between the transmitted and the received spectral power, and the sensitivity function $S(f)$ as the normalized first derivative of $A(f)$, we have:

$$A(f) = \frac{P_{tx}(f)}{P_{rx}(f)} \qquad (2)$$

$$S(f) = \frac{P_{rx}(f)}{P_{tx}(f)} \frac{d}{df}\left[\frac{P_{tx}(f)}{P_{rx}(f)}\right] \qquad \text{[s]} \quad (3)$$

In dry air conditions, $\tau(f)$ accounts for the main atmospheric absorption contributions (H_2O and O_2 in particular) along the propagation path.

$S(f)$ can be measured in practice using the spectral incremental ratio. Denoting with $P_{rx+} = P_{rx}(f_+) = P_{rx}(f_0 + f_m)$, $P_{rx-} = P_{rx}(f_-) = P_{rx}(f_0 - f_m)$ and supposing $P_{tx+}=P_{tx-}$, an approximation of $S(f)$ is given by:

$$\hat{S}(f) = \frac{P_{rx-} - P_{rx+}}{2 f_m P_{rx+}} \qquad \text{[s]} \quad (4)$$

The objective of the receiver system is to measure both P_{rx+} and P_{rx-} in order to compute $\hat{S}(f)$ and to estimate the IWV through a linear relationship as [2]:

$$I\hat{W}V = m\hat{S} + q \qquad \text{[g/cm}^2\text{]} \quad (5)$$

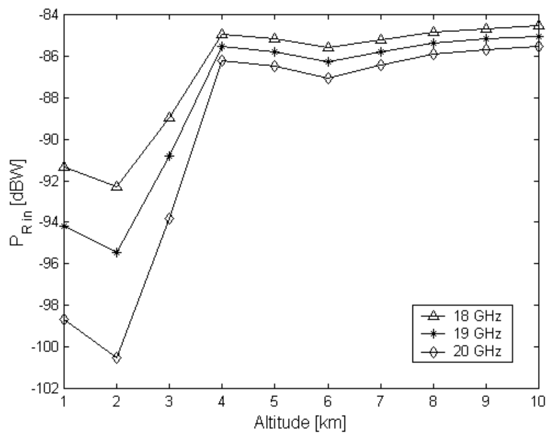

Fig.2 – Signal power at the receiver as function of altitude considering a rectilinear trajectory (data obtained considering the radio-sounding made on 2000, March 13 at 11 am).

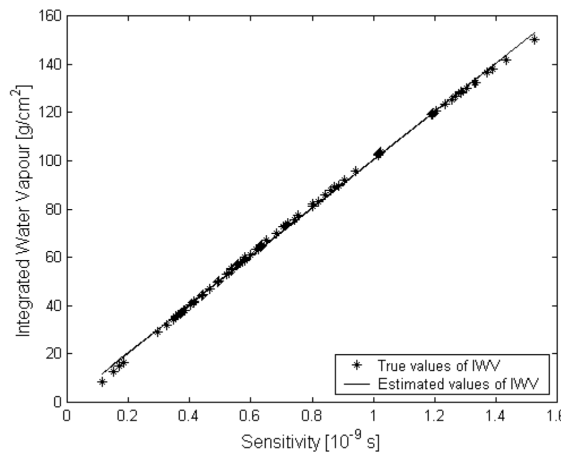

Fig.3 - Relationship between the sensitivity function at 19 GHz and the IWV (2 km altitude).

III. MPM MODEL

The atmospheric propagation characteristics are modeled by the Millimeter-wave Propagation Model in the [1, 1000] GHz frequency range and for atmospheric parameters up to 130 km altitude.

The main parameter computed by the MPM model is the complex refractivity N:

$$N = (N_0 + N') + j\,N'' \qquad (6)$$

where the real part N_o+N' determines the phase dispersion and the delay rate, while the imaginary part N'' accounts for the power attenuation.

The refractive index n is related to the complex refractivity by the relationship:

$$n = (\mathrm{Re}\{N\} \cdot 10^{-6}) + 1 \qquad (7)$$

Atmospheric parameters are the input variables to the MPM model: barometric pressure, temperature and relative humidity that is related to the volumetric density of water. In this work we used real parameters extracted from radiosonde data set gathered during the whole year 2000 and related to the measurement site cited in the introduction.

IV. LEO-LEO SATELLITE LINK

In the geometric optics approximation of the electromagnetic propagation, the ray path of an electromagnetic wave moving through a medium characterized by a varying refractive index is determined by Fermat's principle and Snell's law: the former describes globally the trajectory in terms of minimum length of the path between two points, the latter in terms of incidence angle between the gradient of the refractive index and the ray path ([3]).

Supposing that the local refractive index field is spherically symmetrical, the bending effect due to the variation of $n(r)$ with r is described in [4]. However, since in this work we used differential spectral attenuation measurements, the impact of bending on the correlation between the sensitivity measurements and the IWV can be assumed negligible.

Referring to Fig. 1, we define r as the distance of the satellite from the center of the Earth, r_t as the *tangent radius* (or asymptotic ray-miss distance), L as the geometric distance between the satellites and R as the equatorial Earth radius.

We considered the orbit of the LEO satellites at an altitude of 400 km; in this case, for r_t = 1 km L is about 800 km.

V. STATISTICAL ANALYSIS AND NUMERICAL RESULTS

In this section we describe the statistical analysis based on the radiosonde data set cited in section III.

The aim of this analysis is to highlight the relationship between the real IWV values computed starting from the radiosonde data, and the sensitivity function calculated for several frequencies and for several tangent radius r_t of the rectilinear trajectory between the satellites.

In order to estimate the received spectral power P_{rx+} and P_{rx-}, the transmission of a modulated carrier (AM [2] or FM [5]) by a sinusoidal signal at frequency f_m can be used. Both modulation systems allow the transmission of separate lines with a spectral distance dependent on the modulation frequency f_m. In this work we assume the AM solution considering carrier frequencies in the [18, 20] GHz range and f_m = 100 MHz. In this case we obtain two separated lines whose spectral distance is 200 MHz.

In order to account for the noise effect, we simulated such effect as an AWGN process in input at the receiver: the noise bandwidth was set at 100 kHz and the receiver equivalent temperature at 296 K.

The signal power at the receiver, without considering the noise contribution, is:

$$P_{R\,in} = EIRP - P_{FS} - A_{ATM} + G_R \qquad \text{[dBW]} \qquad (8)$$

where:

$EIRP$	is the equivalent isotropically radiated power (in dBW);
P_{FS}	is the propagation loss in free space (in dB);
A_{ATM}	is the atmospheric attenuation (in dB);
G_R	is the receiving antenna gain (in dB).

For a LEO-LEO configuration we assumed $EIRP$ = 48 dBW and G_R = 44 dB (see [6]). In Fig.2 we report the signal power at the receiver $P_{R\,in}$ as function of r_t and for f_0 = 18, 19 and 20 GHz, computed considering the radio-sounding made on 2000, March 13 at 11 am local time.

Fig.3 shows the relationship between the IWV and the sensitivity function at 19 GHz, calculated for r_t = 2 km; the strongly linear relationship allows to estimate the IWV quite accurately through (5), where $m = 99.84 \cdot 10^9$ g/s·cm^2 and q = 0.54 g/cm^2.

In Fig.4 we report the correlation coefficient between the sensitivity measurements and the IWV, calculated at 18, 19 and 20 GHz and for r_t up to 10 km; the plot shows that we can estimate the integrated water vapor content up to 7 km altitude by means of the received power measurements, with a correlation coefficient practically 100%. However, at 20 GHz and for altitudes higher than 7 km, we can estimate IWV with a correlation coefficient of 95%.

CONCLUSIONS

The scientific objective of this research was the investigation about the feasibility of atmospheric water vapor estimates by means of the received power measurements made in a LEO-LEO satellite link, operating close to the 22.235 GHz water vapor absorption line. In particular the results indicate that it seems feasible to estimate the integrated water vapor content, along the propagation path between the two LEO satellites with tangent radius up to 10 km altitude, with a correlation coefficient of 95%.

The sensitivity function measurement allows a direct estimate of the water vapor, with better performances for 20 GHz. Further investigation is needed to better understand the impact of the antenna defocusing effect and different values of signal-to-noise ratio on the accuracy of the sensitivity measurements. Moreover, in case of counter rotating satellites, the Doppler effect must be accounted for, since the relative motion between the satellites produces a frequency shift.

ACKNOWLEDGEMENTS

This work was supported by CNIT (Consorzio Nazionale Interuniversitario Telecomunicazioni). The authors wish to acknowledge the UKMO for the radiosonde data supply.

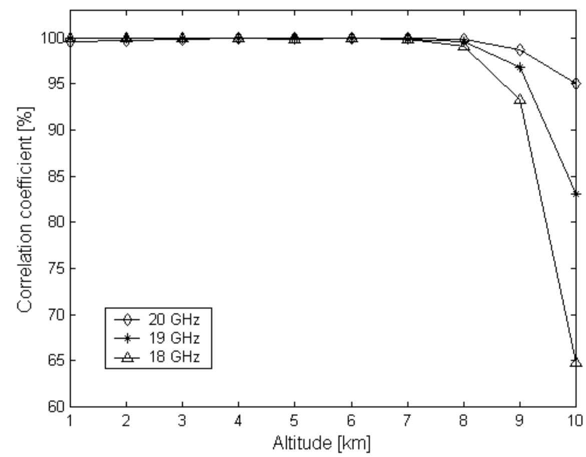

Fig.4 - Correlation coefficient between sensitivity and IWV as function of altitude.

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