Monostatic CW radar system for microwave attenuation measurements for atmospheric water vapor estimate

F. Cuccoli, L. Facheris
Tel: +390554796382 Fax: +39055488883 E-mail:*cuccoli@achille.det.unifi.it*
Dipartimento di Elettronica e Telecomunicazioni, Università di Firenze, Via di Santa Marta, 3 50139 Firenze - Italy

Abstract – In this paper we report the first simulation-based results concerning the potential of a CW radar system for differential attenuation measurements around 19 GHz. The objective is the estimate of the columnar water vapor from a LEO satellite or from airplanes carrying a nadir pointing radar system. Simulations are based on a microwave propagation model for atmosphere, radiosonde data, and ground backscattering cross section models. The correlation between the radar output and the columnar water vapor is shown.

I. INTRODUCTION

Recently, some feasibility studies [1] [2] pointed out the high correlation between the columnar content of atmospheric water vapor (IWV) and the normalized differential spectral attenuation function (from here on referred to as "sensitivity function") at 19 GHz. Such feasibility studies were made considering a bistatic measurement system based on a microwave transmitter on a geostationary satellite and a microwave receiver at ground. This measurement system was designed to obtain the estimate of the sensitivity function using amplitude-modulated signals. Such measurement system is thought to permit a continuous time monitoring of the IWV, but the spatial coverage depends both on the satellite position and on the number and the position of the receivers located at ground.

In order to have a IWV global monitoring system based on the exploitation of the sensitivity function, in this work we discuss the feasibility of such measurements by means of a FM-CW radar operating at 19 GHz and mounted on a flying carrier: airplane and LEO satellite. A differential approach is utilized for limiting Earth's reflectivity uncertainty.

The receiver output (the sensitivity function) has been simulated considering the microwave atmospheric propagation model by Liebe [3] and ground back-scattering cross section models. Simulation results are reported, together with some considerations about technical requirements, both for a spaceborne system mounted on a LEO satellite and for an airborne one.

A historical radiosonde data set was used to simulate the receiver output in different atmospheric conditions.

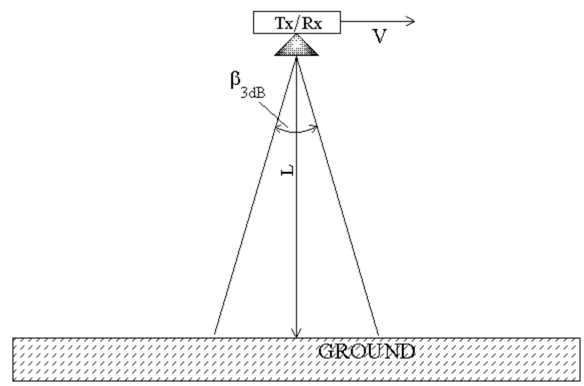

Fig.1 - Sketch of the nadir pointing radar system.

The computed sensitivity data were exploited to find out the correlation between the receiver output and the IWV.

II MEASUREMENT PARAMETERS

Referring to Fig 1, the spectral power P_{rx} received by the radar is given by:

$$P_{rx}(f) = \alpha(f) P_{tx}(f) \exp(-2\tau(f)) \tag{1}$$

where $\tau(f)$ is the one way optical depth, related to the atmospheric attenuation along the propagation path L, $P_{tx}(f)$ is the transmitted spectral power and $\alpha(f)$ accounts for all the other 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 ratio between the first derivative of $A(f)$ and $A(f)$ itself, from (1) we have:

$$A(f) = P_{tx}(f) / P_{rx}(f) \tag{2}$$

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

In dry air conditions, $\tau(f)$ accounts for the main atmospheric absorption contributions (water vapor, oxygen and nitrogen) along the propagation path.

$S(f)$ can be estimated using the spectral incremental ratio instead of the first derivative: with $P_{rx+}= P_{rx}(f+f_m)$, $P_{rx-}=$

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$P_{rx}(f\text{-}f_m)$ and supposing $P_{tx+}=P_{tx-}$ an approximation for $S(f)$ is:

$$\hat{S}(f)=\frac{P_{rx-}-P_{rx+}}{2f_m P_{rx+}} \tag{4}$$

The objective of the radar system is to measure both P_{rx+} and P_{rx-} in order to compute $S(f)$ at 19 GHz and to estimate the IWV as [1]:

$$IWV=a+bS_{19} \tag{5}$$

III SURFACE RESPONSE

Considering the signal scattered from a surface, the spectral attenuation $\alpha(f)$ is given by [4]:

$$\alpha(f)=\iint_{Area}\sigma_0(\vartheta,\varphi,f)G^2(\theta,\varphi)\frac{\lambda^2}{(4\pi)^3R^4}ds \tag{6}$$

where σ_0 is the backscattering cross section per surface unit, G is the antenna gain, and *Area* is the surface illuminated by the transmitting antenna.

Assuming a parabolic nadir pointing antenna with a Gaussian radiation beam, and assuming that σ_0 is independent of both θ and φ, $\alpha(f)$ is given as:

$$\alpha(f)=\frac{\sigma_0(f)\left[G_0(f)\lambda\beta_{-3}(f)\right]^2}{32\ln(2)(4\pi L)^2} \tag{7}$$

where G_0 is the antenna gain and β_{-3} the 3dB beam angle.

In the above equations, only $\sigma_0(f)$ is not known *a priori* and it varies considerably according to the surface characteristic, but the frequency variations are such that $\sigma_0(f)\cong\sigma_0(f\pm f_m)$ for f=19 GHz and f_m <200 MHz. Under this assumption, $S(f)$ is not influenced by the backscattering cross section.

The power measurement at two closer frequencies ($f_+=f+f_m$, $f_-=f-f_m$) can be made transmitting and receiving two separate sinusoidal signals at such frequencies. However, the fading effect must be accounted for due to the motion of the radar beam with respect to ground. This causes a broadening in reception of the original transmitted spectrum, ideally composed by two spectral lines.

Small values of f_m in (4) give better estimate of $S(f)$, but the Doppler broadening limits the minimum value for f_m. If B_d is the spectrum width of a sinusoidal line due to Doppler broadening, and $f_m>B_d/2$, no overlapping between the two broadened lines occurs.

Also, B_d limits the minimum band of the receiving chain, thus influencing the signal to noise ratio requirements.

IV FM MODULATION FOR SPECTRAL SENSITIVITY ESTIMATES AND POWER MEASUREMENTS

In order to obtain a good estimate of the sinusoidal power measurement, a relatively long integration time is necessary. However, particularly in LEO satellite applications it would be desiderable to minimize such integration time to retrieve water vapor information with the maximum spatial detail. On the other hand, if one wants to estimate the sensitivity at a given frequency utilizing two spectral lines f_+ and f_-, the integration time is practically defined by the required uncertainty on the sensitivity estimate [1][2]. An idea to overcome this limitation is to utilize several close spectral lines to gather several corresponding attenuation estimates in a smaller integration time, to be then utilized together to provide a single average power estimate in correspondence of both center frequencies f_+ and f_-. The corresponding two "groups" of frequencies should be obviously spectrally disjoint.

Here we propose the simultaneous transmission of two FM-CW signals, spectrally centered on f_+ and f_- . The transmitted waveform is therefore:

$$V_{tx}(t)=V\left(\cos\left[2\pi f_-t+\theta(t)\right]+\cos\left[2\pi f_+t+\theta(t)\right]\right) \tag{8}$$

where $\theta(t)=2\pi k\int_0^t m(\tau)d\tau$ and

$$m(t)=\frac{2}{T}\sum_n(t-nT)rect\left(\frac{t-nT}{T}\right) \tag{9}$$

The power estimate at the two signal carriers f_+ and f_- can be made measuring separately the power of a number of lines of each FM-CW spectrum (using a pass band filter cascade).

Posing k=20·10^6 and T=5·10^{-6}, the transmitted spectrum is made up by two line spectra, with lines 200 kHz apart from each other. We chose f_-=18.9 and f_+=19.1 GHz. A cascade of 51 bandpass filters centered on each of the two carriers was assumed for each reception channel. Therefore the final power measurements is averaged over a bandwidth of 51*200 kHz ≅10 MHz.

V. SPACEBORNE CASE

We considered a LEO satellite case, orbiting at an altitude of 400 km with a speed of 7 km/s. The transmission/reception system is based on a parabolic antenna with diameter of 1 m, therefore with β_{-3} smaller than 1°. In this situation, the Doppler broadening of each spectral line is 14 kHz, which practically eliminates the problem of spectral overlapping in reception.

Simulations of the received signals were made considering $\sigma_0(f_-)=\sigma_0(f_+)$=-1 dB and P_{tx}=10 kW. An integration time of 10 seconds was used. Also, several radiosonde profiles were used as input to the MPM propagation model [3] in order to compute the optical depth in different meteorological conditions.

The standard deviation of the percentage error made on the sensitivity estimate (Eq. (4)) is about 15%, considering an ensemble of 60 radiosonda profiles. Fig. 2 shows the scatterplot between the retrieved Integrated Water Vapor

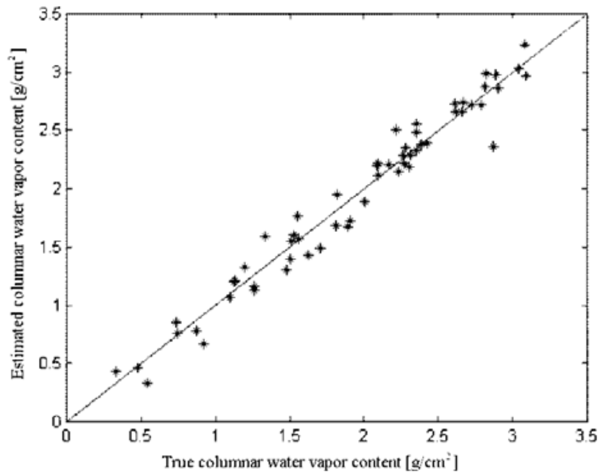

Fig. 2 - The columnar water vapor content estimated versus the 'true'one in the spaceborne case.

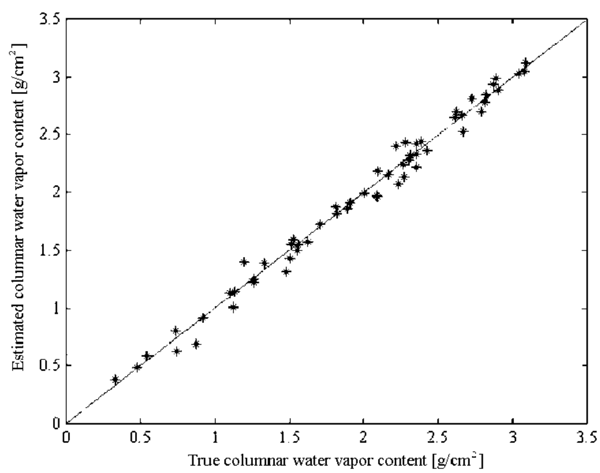

Fig. 3 - The columnar water vapor content estimated versus the 'true'one in the airborne case.

(IWV), computed through the linear relation of Eq. (3), and the "true" one, obtained considering the aforementioned vertical profiles.

VI. AIRBORNE CASE

For the airborne case, we considered an altitude of 10 km and a speed of 0.27 km/s. The same antenna parameters were considered as in the satellite case, therefore the Doppler broadening of each spectral line is 555 Hz. The transmitted power was set at 0.25 W and the integration time at 250 sec: this was done to allow the same specifications as in the spaceborne case, in particular in terms of noise power at the receiver and of spatial coverage along the flight direction.

The simulations were made considering the same 60 radiosonde profiles used in the spaceborne case: the standard deviation of the percentage error on the sensitivity estimate is about 9%. Fig. 3 shows the scatter plot between the retrieved IWV and the 'true' IWV (the latter obtained as in the spaceborne case).

CONCLUSIONS

This work contributes to assess the feasibility of atmospheric water vapor estimates by means of a wideband CW-FM radar system operating at 19 GHz. In particular, it comes out that it is possible to measure the sensitivity function at 19 GHz by both LEO satellite and airplane platforms. Such measurements allow a direct estimate of the columnar water vapor, certainly with better performances in the airborne case, as can be noticed by comparing Fig. 2 and Fig. 3. Further investigation is needed especially to characterize the backscattering cross section behavior to better understand its impact on the sensitivity measurements.

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