Normalized Differenzial Spectral Attenuation among Co-rotating LEO Satellites: Performance Analysis for Estimating the Tropospheric Water Vapor

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Abstract— NDSA (Normalized Differential Spectral Absorption) is as a differential attenuation measurement method for the estimation of the total content of water vapor (IWV, Integrated Water Vapor) along a tropospheric propagation path between two Low Earth Orbit (LEO) satellites. The NDSA has been deeply analyzed assuming two counter rotating satellites in Ku and K band for tangent altitudes up to 10 km. In this paper we present the main NDSA measurement characteristics of the CO-rotating configuration with one transmitting satellite and many receiving ones assuming the multi-band (K, Ku and M) approach on each radio link and plausible reference propagation conditions for tangent altitudes up to 15 km.

1. INTRODUCTION

The Normalized Differential Spectral Attenuation (NDSA) approach is based on the conversion of a spectral parameter called "Spectral Sensitivity" (SS) into the total content of water vapor along the propagation path between two LEO satellites. In [1] the potential of spectral sensitivity in providing direct estimates of Integrated Water Vapor (IWV) along LEO-LEO tropospheric propagation paths in the 15–25 GHz range is shown while in [2] the accuracy with which the spectral sensitivity parameter can be measured has been analyzed.

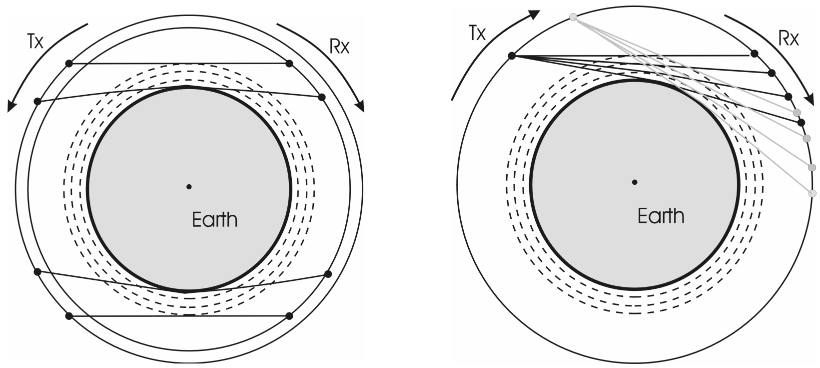
A basic result was that the spectral sensitivity measurement accuracy can be estimated through the theoretical approximation as long as the averaged Signal to Noise Ratio (SNR) keeps above 20 dB, while below such SNR level measurements become not reliable. Moreover, this holds as long as the integration time used for measurements keeps smaller than the decorrelation time of the scintillation phenomenon.

A complete simulation tool has been presented in [3] for the study of the NDSA measurement performance in counter rotating LEO-LEO configuration (see Figure 1(a)) at global scale for single and multiple global atmospheric profiles, assuming spherical symmetry for the atmospheric structure, realistic LEO satellites' orbit configuration, link budget, and disturbances sources. The main results of this performance analysis is that NDSA at 17.25 GHz can be measured in case of medium scintillation up to 6 km tangent altitude with NSED (the standard deviation of the absolute error) smaller than 50% and at 20.20 GHz can be estimated both in medium scintillation conditions between 3 and 7 km with NSED smaller than 20% and also in strong scintillation conditions with NSED smaller than 60%.

Some other studies about the NDSA in counter rotating LEO-LEO configuration in K/Ku bands have been completed under the independent ESA (European Space Agency) study called AlMetLEO [4] that provided a significant insight into the SS-IWV relationships up to 12 km altitude in the limb geometry based on an extended radiosonde data analysis, into the modelization of signal fluctuations due to tropospheric turbulence and into the SS accuracy achievable under given SNR and scintillation levels.

In [5] for the first time the use of M band for NDSA measurements, always in counter rotating LEO-LEO configuration, has been introduced. Specifically, 179 and 182 GHz have been proposed as good candidates for water vapor estimates at tangent altitudes higher than 11 km, since M band measurements are very robust to receiver noise and practically insensitive to scintillation effects.

While the counter-rotating configuration provides valid SS measurements data only during the relative set/rise occultation events the co-rotating one provide them in a time continuous manner. For this reason the authors decided to investigate the NDSA capabilities also in LEO-LEO co-rotating configuration (see Figure 1(b)).



(a) (b)

Figure 1: (a) Counter rotating and (b) co-rotating LEO-LEO configuration.

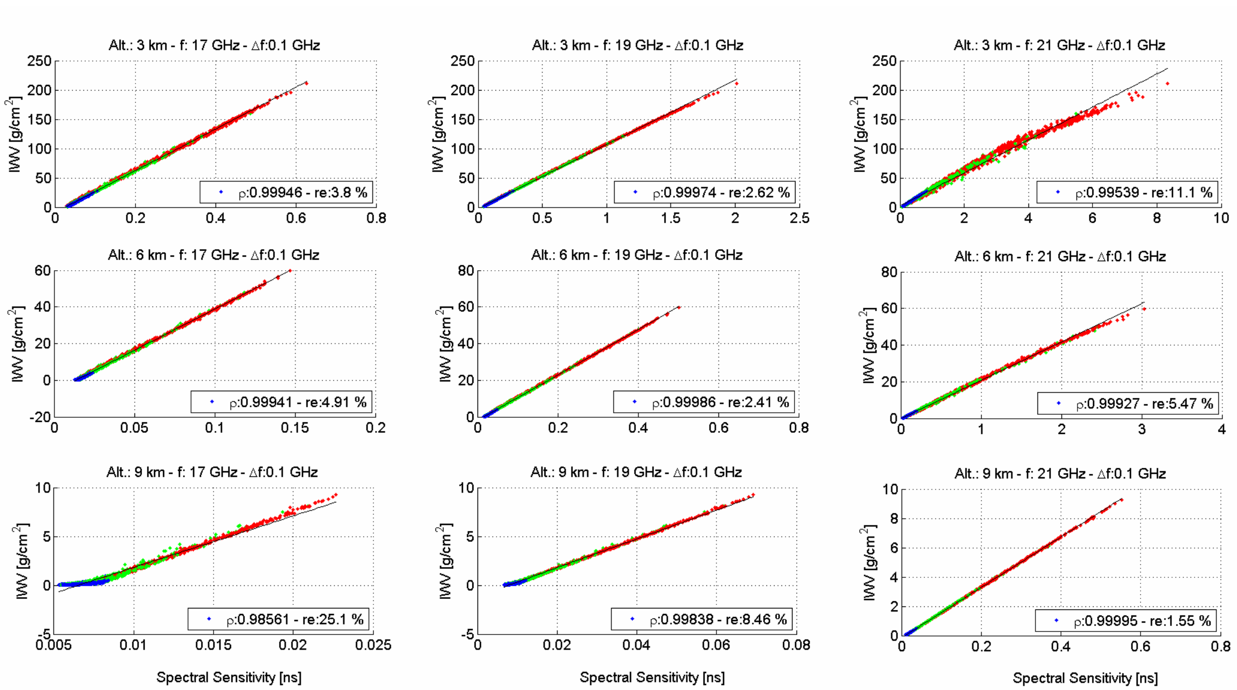


Figure 2: IWV at (top-down) 3, 6 and 9 km tangent altitude vs. SS at (left to right) 17, 19 and 21 GHz. For each plot the correlation coefficient ρ and the relative error re after a linear least squares fit are shown. Red, green and blue colors are related to the latitude range: red for [0°– 30°], green for [30°–60°] and blue for [60°–90°] both for the Northern and the Southern hemisphere.

In this paper we present the main NDSA measurement characteristics of the CO-rotating configuration (see Figure 1(b)) with one transmitting satellite and many receiving ones. We discuss the result of a performance analysis of the sensitivity measurements assuming the multi-band (K, Ku and M) approach on each radio link and plausible reference propagation conditions.

2. SENSITIVITY MEASUREMENTS VS INTEGRATED WATER VAPOR

In order to recall the main features of the SS-IWV relationships, Figure 1 shows the SS vs. the IWV for the 17, 19 and 21 GHz sensitivity channels at 3, 6 and 9 km tangent altitudes. The plots are computed basing on atmospheric vertical profiles at global scale related to the ECMWF (European Centre for Medium-Range Weather Forecasts) model for the 12:00 UTC on 15 October 2011 interpolated on a 5° latitude × 5° longitude grid. The SS are computed using the simulation tool developed in [3].

Notice that the highest correlations are: at 3 km for 17 GHz, at 6 km for 19 GHz and at 9 km for 21 GHz.

Table 1: Values of the link power budget parameters. f_0: sensitivity channel, $f_{1/2}$ frequency tones.

f_o [GHz]	f_1 [GHz]	f_2 [GHz]	Tx Power [dBW]	Tx & Rx Antenna Gain [dB]	Rx System noise temp. [dBK]
17.00	16.90	17.10	3.0	26.9	25.3
19.00	18.90	19.10	3.0	27.8	25.8
21.00	20.90	21.10	3.0	28.5	26.3
179.00	178.80	179.20	3.0	34.8	23.8
182.00	181.80	182.20	3.0	34.9	23.8

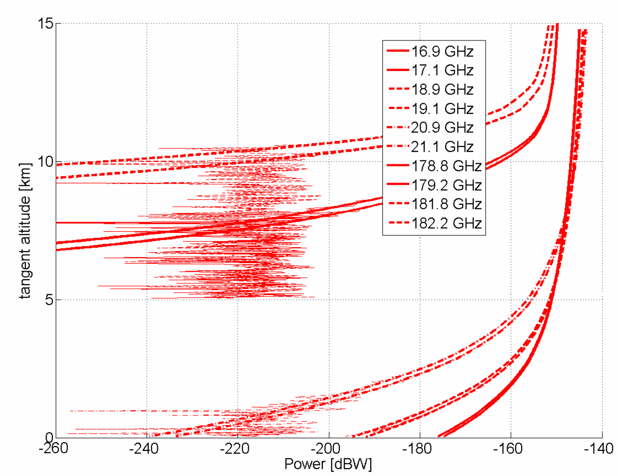


Figure 3: Received power vs. tangent altitude.

3. CO-ROTATING OBSERVATION GEOMETRY

Assuming an elliptical orbit with the semi-major axis of 6651 km, the spherical Earth with the radius of 6371 km, the eccentricity of 0.0005 and two satellites separated by an angle of 0.582398 rad (this case corresponds to the 0 km tangent altitude for circular orbit), the tangent altitude varies between 3 and 10 km and the LEO-LEO link length vary between 3777 and 3780 km corresponding, respectively, to 10 and 3 km tangent altitude. The revolution period for this kind of orbit is 5061 s that gives an average speed of about 8 km/s for the link projection point at ground. Assuming a sampling time of 1 s, the link altitude can be considered constant during the integration interval. Therefore, a sensitivity measurement each 8 km is provided and this is related to the constant tangent altitude, given by orbital position, within the 3–10 km range.

In order to sweep the troposphere between 3 and 15 km with the minimum number of two receiving satellites, the angularly separation must vary between 0.005232 and 0.005242 rad (that correspond to a distance of about 34 km). In this way, when the tangent altitude of the farther receiving satellite link is 3 km, the tangent altitude of the closer one is 8 km and when the tangent altitude of the farther receiving satellite link is 10 km the tangent altitude of the closer one is 15 km.

4. PERFORMANCE OF THE SENSITIVITY MEASUREMENT IN CO-ROT GEOMETRY

Using the theoretical analysis proposed in [2] it is possible to compute the Normalized Root Mean Square Error (NRMSE) of the spectral sensitivity as function of the SNR_m (the average SNR of the two tones received on the corresponding channels), the differential attenuation ΔA (between the two tones of each channel) and two other parameters for the scintillation impairment (i.e., ρ than accounts for the frequency tone correlation and σ_χ that accounts for the scintillation power).

For the computation of SNR_m and ΔA we simulated the power at the receiver assuming the link power budget parameters listed in Table 1, the MLS Atmospheric model [1] and a spherical symmetry for the atmospheric structure. The propagation effects have been simulated using the core of the software tool developed in [3] that is based on the MPM93 propagation model [5]. Notice that the MLS model does not account for liquid and ice particles, therefore the simulated propagation scenario is related to a so called "dry atmosphere".

Figure 3 shows the received power for each tone and Figure 4 shows ΔA and SNR_m for each

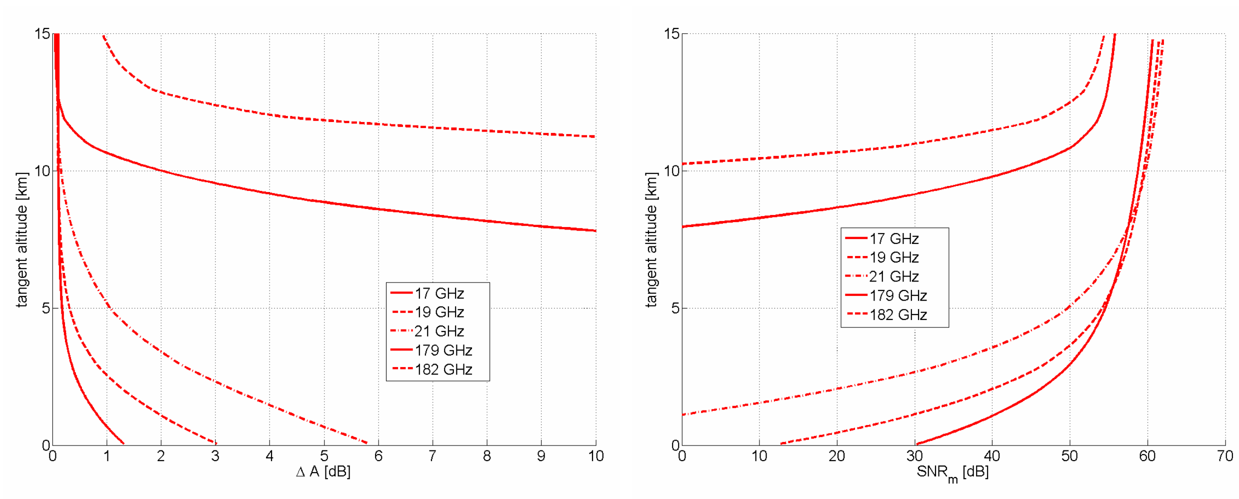


Figure 4: Differential attenuation and SNR_m vs. tangent altitude.

sensitivity channel. Notice that SNR_m is greater than 40 dB above 1 km at 17 GHz channel, above 2 km at 19 GHz, above 3 km at 21 GHz and above 10 km for the M band.

Considering ΔA greater than 1 dB and SNR_m greater than 40 dB (that are surely optimal conditions for converting the SS in IWV) the NRMSE of the spectral sensitivity computed using the theoretical analysis proposed in [2] is lower than 10% for medium scintillation cases ($\sigma_\chi = 0.3$ dB) and lower than 5% for low scintillation cases ($\sigma_\chi = 0.03$ dB).

5. CONCLUSIONS

The performance of the SS measurements in CO-RO has been evaluated in a reference atmospheric scenario. Assuming a plausible power link budget for a CO-RO orbital geometry covering the tangent altitudes between 0 and 15 km, the received power has been simulated for the frequency tones related to the 17, 19, 21, 179 and 182 GHz sensitivity channels. The *NRMSE* of SS has been computed for ΔA greater than 1 dB and SNR_m greater than 40 dB. In these conditions, the NRMSE is lower than 10% and 5% for hypothesis of medium and low scintillation effects, respectively. Even if the scintillation effects in CO-RO is still not fully developed it is envisaged that the CO-RO configuration should be characterized by low scintillation impairments. Further studies are in progress in order to develop a scintillation model for the CO-RO geometry following the same approach used in [3] for the COUNT-RO case.

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