Numerical Weather Prediction Models for the Estimate of Clear-Sky Attenuation Level in Alphasat Beacon Measurement

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***Abstract*— With the move of satellite systems towards Ka and Q/V bands, the Alphasat TDP5 Aldo Paraboni scientific experiment aims to characterize atmospheric attenuation in those bands. However, during the retrieval of the attenuation from the measured beacon signal, the clear-sky contribution to attenuation is lost. Microwave radiometers give the clear sky absolute reference level, but these are costly and not always available. This paper proposes Numerical Weather Prediction models as an alternative source of clear-sky attenuation. Three months of beacon and radiometric data from Spino d'Adda Alphasat receiving station are used as benchmark for the validation of the method. A preliminary conclusion is that gaseous attenuation is well predicted, but cloud attenuation is underestimated.**

***Index Terms*—Alphasat, clear-sky attenuation, microwave radiometer, Numerical Weather Prediction model, radiowave propagation.**

I. Introduction

Earth-space downlinks for communication or Earth observation satellites are constantly pushed towards more applications and better data rates. The use of higher frequencies, in the Ka and Q/V bands, is expected to help satisfying those needs thanks to the increase of bandwidths, antenna gains, etc. with frequency. At those frequencies however, radio-propagation is heavily impaired by rain, clouds, turbulence, and even gases.

Propagation measurement campaigns aim to characterize the tropospheric impairments to provide guidelines for the design satellite hardware and coding schemes needed to maintain a high data throughput. A propagation campaign consists of ground stations measuring the signal from single-frequency beacons available on-board of a satellite.

The Alphasat TDP5 Aldo Paraboni scientific experiment [1] has two beacons at two frequencies with a coverage over Europe and North Africa:

- 19.701 GHz, linear vertical polarization, boresight at (32.5°N, 20°E);
- 39.402 GHz, linear 45° polarization, boresight at (45.4°N, 9.5°E).

Alphasat (25°E) is a geosynchronous satellite (inclined equatorial orbit) so that a tracking system is needed to receive its signal. In this work, copolar beacon measurements from the Spino d'Adda station [2], [3] are used. This station is located at the 39.402 GHz boresight (~159° azimuth, ~36° elevation), and measures co-polar signals for both frequencies, and the 39.402 GHz cross-polar, though only the co-polar is used here. Spino station also benefits from its ancillary equipment:

- a microwave radiometer inclined at the link elevation, for brightness temperature measurements;
- a tipping-bucket rain gauge, for rain rate measurements;
- a ground meteorological station, for pressure, temperature and humidity measurements.

As detailed in Sec. II, the atmospheric attenuation extracted from the beacon signal alone is called "in excess" and does not include the contribution of the clear-sky (gases). The "clear sky" attenuation is due to the absorption by gases, accurately retrieved from microwave radiometers (MWR), following a procedure such as the one given in [4]. The expected accuracy on clear-sky attenuation retrieved by this method is about 0.1 dB at the frequencies of interest [5].

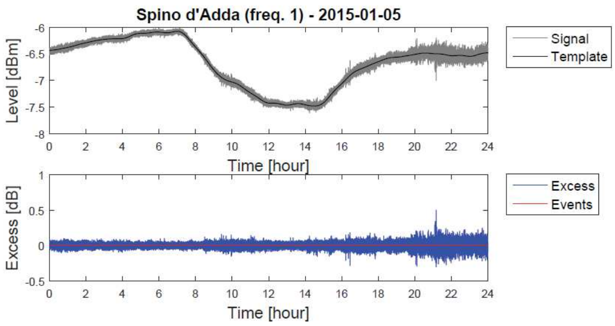
Not all the experimenters have a radiometer, so there is an interest in other ways to generate clear-sky attenuation time series. For example, the experimenters of the ASALASCA consortium measure Alphasat signals but do not have radiometers [6], [7]. The use of GNSS zenith tropospheric delays has been investigated as an alternative to, or a validation tool for radiometers [5]. This paper presents an approach based on Numerical Weather Prediction (NWP) models.

NWP models have already been included in simulators providing time series of attenuation for various applications related to data downlink from satellites [8]–[10] and Deep-Space missions [11], [12]. In this work, the Weather Research and Forecasting (WRF) model [13], [14], is run with input data from the European Center for Medium-range Weather Forecasts (ECMWF) [15] to get three months of 3D meteorological data around Spino d'Adda in 2015, in order to compare with the available measured data. As explained in Sec. III, the output of NWP models are used for the production of clear-sky attenuation time series. Total attenuation is obtained by adding the estimated clear-sky attenuation from NWP or MWR, to the measured excess attenuation. The comparison of both methods is given in Sec. IV.

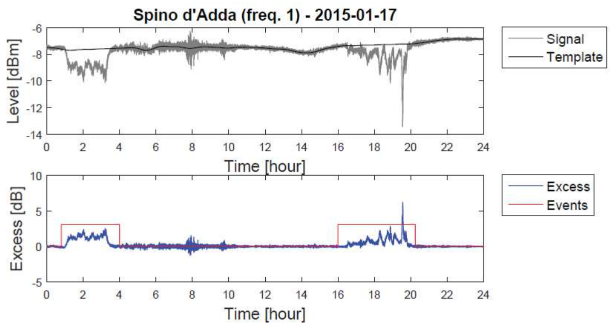
II. Excess attenuation extraction from propagation beacon signal power level

Measurements of the power level of the signal emitted by a propagation beacon onboard a satellite are affected by the accuracy of the tracking, as well as other effects such as temperature variations of the equipment, etc. Collectively, all those effects are unpredictable. In order to remove them and obtain a metric of atmospheric impairments alone, the strategy is to subtract from the power signal (often called “raw data”), a slow-varying template computed over a few days. This template excludes all the attenuation events (rain and clouds), identified as such by the experimenter, with dedicated procedures to flag them out. The template is then extracted from the measured power level, without the flagged events. The result of the whole operation is the excess attenuation time series, containing the flagged events (mostly rain) and the fast-varying attenuation due to scintillation. This “excess attenuation” does not contain the contribution of the clear-sky, which is indistinguishable from the other slow-varying effects, and is removed with the template. This procedure has been implemented in the Propagation Data Processing System (PDPS) developed in the frame of an ESA contract [16], [17].

As an example, Fig. 1a shows the extraction of the excess attenuation from one day with no events; the mean value of the excess attenuation is clearly around 0 dB. Fig. 1b presents another day with two events. The template is extracted without the flagged events.



(a) 05/01/2015 (no event)



(b) 17/01/2015 (2 events)

Fig. 1. Excess attenuation extraction procedure from the Alphasat 19.701 GHz signal at Spino d’Adda

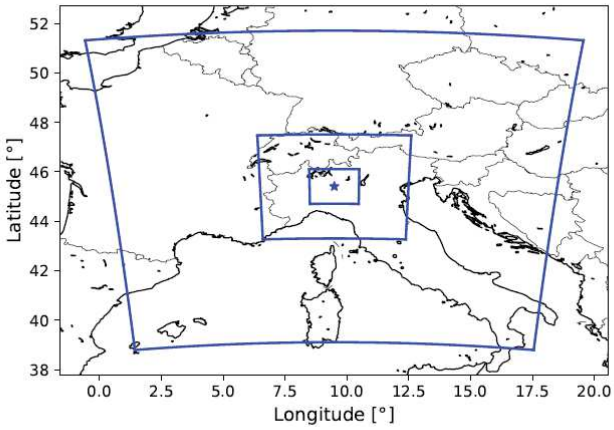


Fig. 2. WRF nested 79x79 Lambert conformal conic domains at 18 km, 6 km and 2 km around Spino d’Adda (45.41°N, 9.49°E)

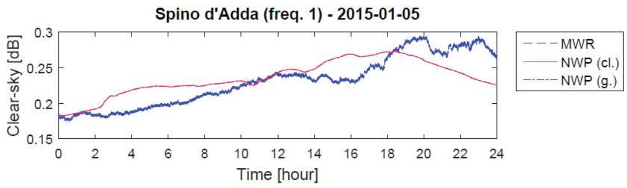
The purpose of this paper is to evaluate a new data source for clear-sky attenuation, that can be added to the measured excess attenuation and provide the total attenuation due to the troposphere. The total attenuation calculated by Politecnico di Milano, using a radiometer [2], [3], is used as a reference. The beacon power level is reprocessed with the PDPS software [18] for the need of the comparison, and clear sky attenuation calculated from NWP model is added.

III. Clear-sky attenuation from NWP data

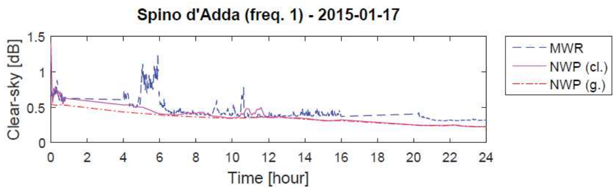
The NWP data used for the estimation of clear-sky attenuation is produced by running the Weather Research and Forecast (WRF) software [13], [14]. The model is run over three nested domains around Spino d’Adda ground station to reach a resolution of 2 km (see Fig. 2). Initialization of WRF uses the ECMWF’s operational analysis data every 6 h [15]. The three months of interest are divided into daily runs with 12 h of spin-up time of the model. Most parametrization options are default or recommended. For the microphysics, the WSM6 scheme is used. For the cumulus physics, the Tiedtke scheme is used but deactivated at 2 km, as cumulus are assumed to be resolved. From the runs, 3D information on the pressure, temperature, water vapor and cloud liquid water are produced every 5 min.

The conversion of NWP data into the desired propagation parameters is carried out similarly to [9], [10]. Gases and cloud specific attenuations are computed according to the ITU-R Recommendations [19], [20], i.e. line-by-line absorption for gases and Rayleigh scattering for clouds. The specific attenuation is then integrated along the path.

In Fig. 3, time series of clear-sky attenuation from NWP and MWR data are compared. Fig. 3a shows an agreement within 0.1 dB during clear sky, in the absence of clouds (the two NWP derived curves overlap). Fig. 3b shows that the NWP data do not accurately represent the cloud attenuation with the parametrization chosen for WRF. The two rain events, visible in Fig 1b, are discarded for the radiometer in Fig 3b due to scattering during rain.



(a) 05/01/2015 (no event)



(b) 17/01/2015 (2 events)

Fig. 3. Clear-sky attenuation estimation for Alphasat 19.701 GHz signal at Spino d'Adda. The estimation uses a radiometer (MWR), or a weather model (NWP) including the clouds (cl.) or only the gases (g.).

IV. Comparison of Total Attenuation Statistics with Clear-Sky Added from Radiometric or NWP Data

The Complementary Cumulative Distribution Functions (CCDF) of three months considered as representative of the climate are chosen to validate the use of WRF (see Fig. 4).

The total attenuation curves considered as the reference are the one provided by Politecnico di Milano (PoLiMi: VI + MWR). The data were processed using a radiometer (MWR), with a definition of events based on visual inspection (VI).

The PDPS is used for the calculation of the three other curves. The events are detected automatically with a threshold on the rain rate (RR > 0.1 mm/h). Consequently the PDPS cannot detect the clouds automatically. The "PDPS: RR+MWR" curve uses the excess attenuation from the PDPS with the clear sky attenuation from the radiometer data of Politecnico di Milano. This test indicates the accuracy of the automatic events selection procedure used in the PDPS. The curves denoted "PDPS: RR + NWP" use the NWP model for the calculation of the clear sky attenuation using only the gases (w/o clouds) or the gases and the clouds (w/ clouds).

The performance of the calibration method relying on RR + NWP data is summarized in TABLE I in terms of the error ϵ [dB], which, at a given time step t, is computed as

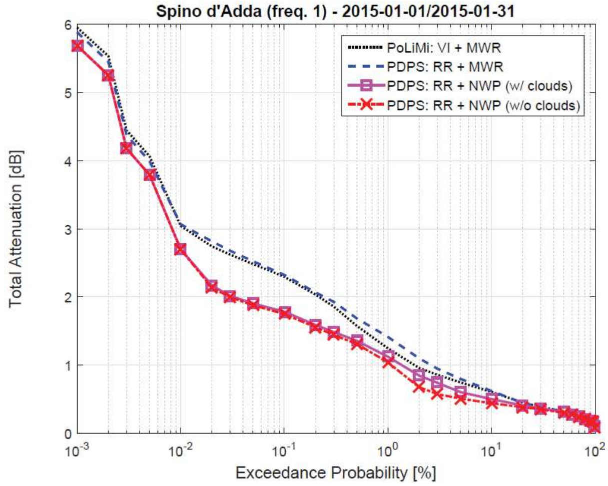
$$\epsilon[t] = A_{tot}^{PDPS:\,RR+NWP}[t] - A_{tot}^{PoLiMi:\,VI+MWR}[t] \quad (1)$$

where $A_{tot}^{PDPS:\,RR+NWP}$ is the total attenuation from the PDPS with RR events detection and NWP clear-sky and $A_{tot}^{PoLiMi:\,VI+MWR}$ is the total attenuation from Politecnico di Milano with VI events detection and MWR clear-sky levels. The mean error (ME) [dB] over N time steps is then

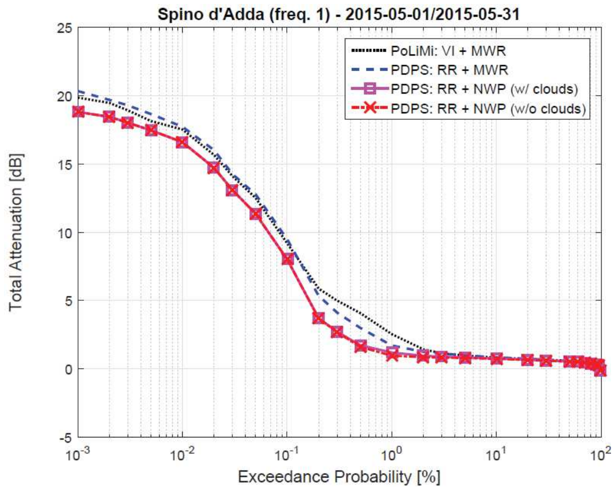
$$ME = \sum_t \epsilon[t]/N \quad (2)$$

and the root mean square error (RMSE) [dB] is

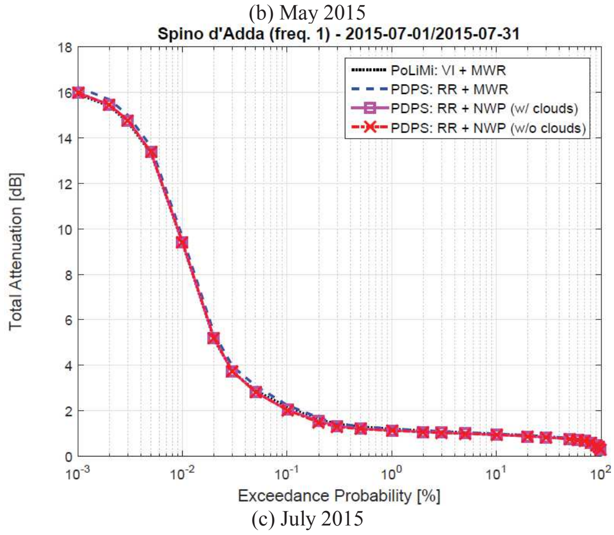
$$RMSE = \sqrt{\sum_t \epsilon^2[t]/N}\,. \quad (3)$$



(a) January 2015



(b) May 2015



(c) July 2015

Fig. 4. Monthly complementary cumulative distribution functions of total attenuation from Alphasat 19.701 GHz signal at Spino d'Adda. Propagation events where flagged by visual inspection (VI) for the reference method of PoLiMi, and with a rain rate threshold (RR) for the PDPS software. Clear-sky attenuation is added either from a radiometer (MWR), or a weather model (NWP) including the clouds or not.

TABLE I. MONTHLY ROOT MEAN SQUARE ERRORS (RMSE) AND MEAN ERRORS (ME) FOR THE TOTAL ATTENUATION OBTAINED FROM SPINO D'ADDA ALPHASAT BEACON DATA (IN JANUARY, MAY AND JULY 2015) PROCESSED BY THE PDPS WITH RAIN RATE (RR) EVENTS DETECTION AND NWP CLEAR-SKY (PDPS: RR + NWP), CONSIDERING THE REFERENCE TOTAL ATTENUATION AS THE ONE FROM POLIMI PROCESSING WITH VISUAL INSPECTION (VI) EVENTS DETECTION AND MWR CLEAR-SKY (POLIMI: VI + MWR)

		19.701 GHz		39.402 GHz	
Month	**Total Attenuation Errors (PDPS: RR + NWP – PoLiMi: VI + MWR)**	**NWP clouds in clear-sky for PDPS: RR + NWP**			
		w/o	***w/***	***w/o***	***w/***
January 2015	RMSE [dB]	0.163	0.149	0.468	0.406
	ME [dB]	-0.057	-0.037	-0.193	-0.121
May 2015	RMSE [dB]	0.360	0.349	1.200	1.152
	ME [dB]	-0.110	-0.096	-0.318	-0.265
July 2015	RMSE [dB]	0.138	0.139	0.229	0.242
	ME [dB]	-0.058	-0.056	-0.072	-0.061

For each of the three months considered, Fig. 4 presents the monthly CCDFs of total attenuation at 19.701 GHz, and TABLE I provides the monthly RMSEs and mean MEs at 19.701 and 39.402 GHz.

In January 2015 (Fig. 4a), there were only a few rain events but the month was cloudy. Indeed, the CCDFs for probabilities of 10 % and lower show differences of up to 1 dB between the NWP gases and the reference CCDF. The CCDF with the NWP clouds slightly improves the situation, also seen in the reduction of the RMSE and ME, but the NWP cloud attenuation appears to be insufficient.

In May 2015 (Fig. 4b), there were many strong rain events. The difference between the MWR and NWP CCDFs reaches 3 to 4 dB at 19.7 GHz. Part of the error is however due to events missed by the automatic detection used in PDPS, as shown by the difference of more than 1 dB between the PoLiMi: VI+MWR and PDPS: RR+MWR curves.

In July 2015 (Fig. 4c), the month was very dry with nearly no clouds and only one strong rain event occurred. The agreement between all the CCDFs is very good. The RMSEs fall within a 0.1-0.2 dB ballpark and, actually, including the NWP clouds does not help.

V. CONCLUSIONS

This paper presents Numerical Weather Prediction models as an option to produce time series of the tropospheric attenuation due to the gases and clouds, a task classically performed by microwave radiometers. Such time series are necessary to obtain the total attenuation on Earth-space links, as direct propagation beacon measurements only produce excess attenuation. From three months of Alphasat beacon signal and radiometric measurements at Spino d'Adda, the performances of NWP-estimated clear-sky attenuations are evaluated. As a conclusion, a target accuracy of 0.1-0.2 dB is obtained for clear-sky including only the gases, but the NWP, with its present parametrization, underestimates the clouds.

In the current situation, the use of NWP data to complete beacon measurements is validated in the absence of clouds. It then relies on the accurate flagging of clouds as events when extracting the excess attenuation. The viability of this approach is under study. A possibility investigated is the change of the cloud parametrization in the model, either by keeping the cloud scheme turned on at the finer resolution or by using a scale-aware scheme. Another possibility that will be tested is an increase in the size of the domains, in order to see if the present size is not too small or if the runs do not suffer from the position of the boundaries. Approaches using cloud detection algorithms, instead of the cloud content directly predicted by the NWP model, will also be examined.

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