Variability of Gaseous Attenuation at Very Low Elevation Angle Slant Paths; Measurements and Modelling

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***Abstract*—Gaseous attenuation variability for a 3.2º elevation angle satellite link operating at 20 GHz in the Norwegian Arctic is analyzed and compared with different models. At a very low elevation link like this one, gaseous attenuation reaches high values and has significant temporal variation over short periods of time. 5 months of measured data are compared with a model based on measured ground meteorological data and two different numerical weather prediction (NWP) models. The simplified model based on ground data gives lower values than the measured levels and is unable to model the observed fast variations. Both the NWP model based on predictions and the one based on re-analysis of past data are able to model most of the fast variations. When cloud attenuation is included in the NWP models both show excellent agreement with the measured data, without a clear difference in accuracy between them.**

***Index Terms*—propagation, measurement, satellite, Numerical Weather Prediction.**

I. Introduction

Frequencies over 15 GHz are increasingly being used for satellite as well as aeronautical communications. The trend is dictated by congestion at the lower frequency bands used for satellite communications, both from satellite systems and also from terrestrial networks. Higher frequencies offer larger available bandwidth and therefore capacity, as well as higher antenna directivity. However, electromagnetic waves at higher frequencies are increasingly affected by atmospheric propagation impairments [1].

While attenuation due to precipitation is usually the most significant impairment, it occurs only during limited periods of time and has limited spatial extent. Due to this short term character it can be partly compensated for by fade mitigation techniques such as adaptive coding and modulation (ACM) [1]. Clear-air impairments such as gaseous attenuation and scintillation are, on the other hand, always present on the links. Some level of cloud attenuation can also be present at the links for long periods of time.

Slant paths at low elevation angles occur for geostationary satellites from locations at high latitudes, for low/medium earth orbit satellites or for airborne vehicles. The path length trough the troposphere can be quite long, leading to significant gaseous attenuation [2]. High levels of non-rainy attenuation were also recently measured at a very low elevation angle link at Isfjord Radio on Svalbard, Norway over the course of three years [3]. While gaseous attenuation is often regarded as relatively constant and only slowly changing, the values measured in [3] were changing relatively fast over the course of a few hours, prompting an investigation of the cause. Recently, high resolution numerical weather prediction (NWP) data are becoming available for general use and have been demonstrated to relatively accurately predict non-rainy attenuation at moderate elevation angle [4].

In this paper, multiple methods are used to model gaseous attenuation for a very low elevation angle link at Isfjord Radio and results compared with measured data. Both simplified methods using ground meteorological measurements as well as models using high resolution NWPs are used. The comparison is complemented by modelling of cloud attenuation. Sections II and III describe the measurement and gas attenuation models used, Section IV compares the obtained results from gaseous attenuation models, Section V investigates the additional effect of cloud attenuation, and finally Section VI draws conclusions.

II. Measurement

A. Location and Setup

A satellite beacon transmitted at 19.68 GHz from the Eutelsat KaSat satellite was measured at Isfjord Radio (78.1 ºN 13.6 ºE) on the Svalbard archipelago which is part of Norway. The 1.8 m diameter antenna was located on the coastline about 5 m above the sea level and the geometric elevation angle towards the satellite was 3.2º. The main lobe (-3 dB) beamwidth was 0.6º. Beacon data was collected using a spectrum analyzer controlled by beacon receiver software at a rate of 10 samples per second. The measurement setup had a dynamic range of about 40 dB. Meteorological data was collected using Vaisala WXT520 weather station and Lambrecht 1518 H3 tipping bucked. In addition surface meteorological data from an independent meteorological station operated by the Norwegian Meteorological Institute located at the same site were also used. More details about the measurement setup can be found in [5].

B. Data Processing

For the purpose of analyzing gaseous attenuation, events with attenuation over 4 dB and lasting less than 6 hours

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caused by rain and heavy clouds were first removed from the beacon time series and replaced by linear interpolation. Clouds are, however, present at Svalbard about 67–88% of the time and some effects from clouds will remain in the time series [6]. The resulting data were filtered using a low pass filter with a cut off frequency of $2.3 \cdot 10^{-5}$ Hz, which corresponds to a moving average filter of approximately 320 minutes. Finally the data were downsampled to 1 sample per hour for comparison with the models. The resulting data is not calibrated and hence cannot give total attenuation values, but it gives information about time-varying gaseous and cloud attenuation.

III. Gas Attenuation Modelling

Three different models were used for calculation of gaseous attenuation for the purpose of comparison with measurement data. All models originated from ITU-R Rec. P. 676-12 [7] but differed both in complexity and type of input data.

A. *Simplified Method Based on Surface Measurement*

Approximate estimate of gaseous attenuation was calculated using the method described in Annex 2 of Rec. P. 676-12 that used actual meteorological data measured at the site. Since the humidity data measured by the WXT520 weather station showed incorrect values around the freezing point, the data measured by the meteorological institute was used instead. Nevertheless the observed difference between mean results from these two datasets was approximately 0.13 dB. Note that the method is not recommended for elevation angles below 5º, but a comparison with a stochastic model of water vapor in [2] did not show large errors even for 3º at 19.5 GHz for Spino d'Adda, Italy.

B. *AROME Arctic*

High resolution NWP data from the AROME Arctic prediction model by the Norwegian Meteorological Institute were used as input to the line-by-line method from Annex 1 of [7]. AROME Arctic has a resolution of 2.5 km and uses 65 vertical model levels for the first 30 km of the atmosphere. The model is calculated every 6 hours with predictions for the next 66 hours. In this work data predicted from 6 to 11 hours ahead were used. The temporal resolution is 1 hour. The model covers high-latitude areas around Svalbard, for more details see [8]. The data is freely available for noncommercial use utilizing a web advanced programming interface (API). Figure 1 shows the grid around Isfjord Radio as well as the path towards the satellite in relation to the model grid.

The actual apparent elevation angle towards the satellite was found by calculating the ray bending due to refraction trough 800 thin layers of the first 30 km of the atmosphere as given in [7] and then adjusting the starting angle until the resulting ray hit the satellite. The mean result was 3.4748º which is close to the value of 3.499º calculated by the approximate formula from [9]. The variation of the apparent elevation angle over the period of available data was ±0.0013º which is much smaller than the antenna beamwidth. Refraction above 30 km of altitude was tested as insignificant.

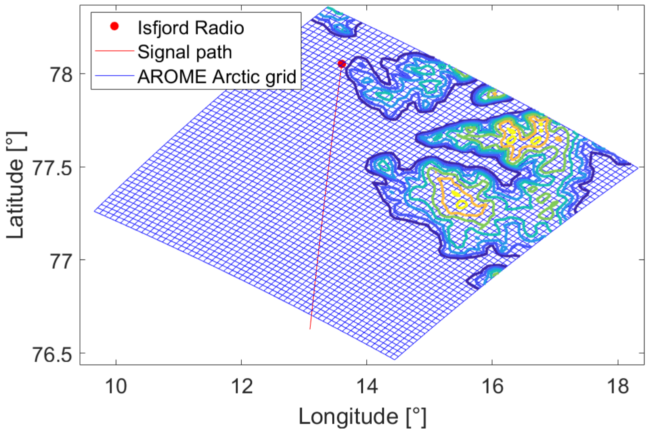

Fig. 1. Path towards the satellite and the part of AROME Arctic grid around Isfjord Radio that was used in the study.

To obtain values along the path for each point crossing the 800 layers defined by [7], the AROME Arctic data were interpolated by using Barycentric interpolation of the 3 nearest points at the model level above and below the point and then linear interpolation between these two values, repeating the procedure used in [10].

The used AROME Arctic horizontal grid was limited to the first 150 km of the signal path, corresponding to an altitude of 10 km. Between 10 and 30 km the signal path used values from vertical profile at the last point of the horizontal grid. The variety of modelled gas attenuation above 10 km altitude was negligible within the grid, which made the simplification acceptable.

C. *Atmospheric Numerical Simulator (ANS)*

The French Aerospace Lab (ONERA) provided gaseous and cloud attenuation data from the Atmospheric Numerical Simulator (ANS). The ANS uses data from European Center for Medium-Range Weather Forecast (ECMWF) ERA-Interim re-analysis database for input and for boundary conditions of NWP model WRF-ARW [11]. ERA-Interim provides meteorological parameters every 6 hours with a 0.75º resolution. The WRF model then uses three nested domains to increase the resolution down to 2 km and 5 minutes. For more details see [12] and the references within. Successively the gas attenuation is calculated using the line-by-line method of Annex 1 of Rec. P. 676-11 which is the same as 676-12 [7].

IV. Gas Attenuation Results

Full resolution AROME Arctic data was first available from February 2016 giving 8 months of overlap with the measurement data until the measurement period stopped at the end of September. Crucially, this period covers both a period of cold months as well as the warm summer period.

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ANS data was obtained for comparison for the period from April to September resulting in 5 months overlap.

A. Reference Level Setting

Since the measured beacon data is not calibrated it is not possible to retrieve total attenuation time series, but rather an estimate of the varying component of gaseous attenuation. The comparison with model data therefore suffers some level of inaccuracy, but is nevertheless interesting for analyzing the temporal variation. The reference level for gaseous attenuation is set using at a reference time without clouds and with as low gaseous attenuation as possible. The measured time series is then adjusted to the modelled one at this point. Available web camera-pictures from Isfjord Radio, weather observations and cloud coverage predicted by NWP were used to ensure cloud free conditions at the reference time of 08. March 2016 12:00 UTC.

B. Temporal Variation and Comparison

As can be seen from the time series comparison shown in Figure 2, there is quite a good agreement between the measured attenuation and the gaseous attenuation predicted by the high-resolution AROME Arctic and ANS models. Some discrepancy is to be expected since the measured time series also include some cloud attenuation. The ANS values of gaseous attenuation are consistently higher than those predicted using the AROME Arctic model. Note that the reference level for the measured data was set using AROME Arctic values.

The attenuation values modelled using actual measured surface meteorological data and the simplified method from Annex 2 of [7] do not follow the measured fast changes observed by the beacon and modelled by the line-by-line method as was the case in [2].

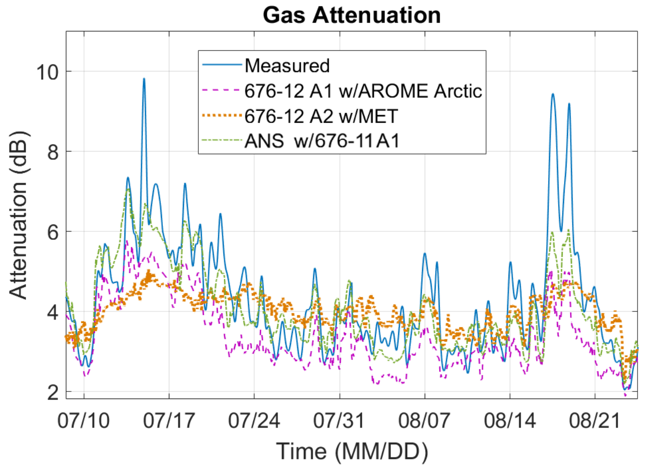

Fig. 2. Example comparison of the measured attenuation with time series from the three gas attenuation models.

C. Long-term Statistics

Comparison complementary cumulative distribution functions (CCDFs) of the measured data and the three different models are shown in Figure 3. As noted before ANS values are higher than those using AROME Arctic. Both NWP models deviate significantly from the simplified model based on actual on site ground meteorological parameters already from the 10 % exceedance level, reaching a difference of between 1 and 2 dB at the 1 % level. All gaseous attenuation models show values that are much lower than the measured time series that includes some cloud attenuation.

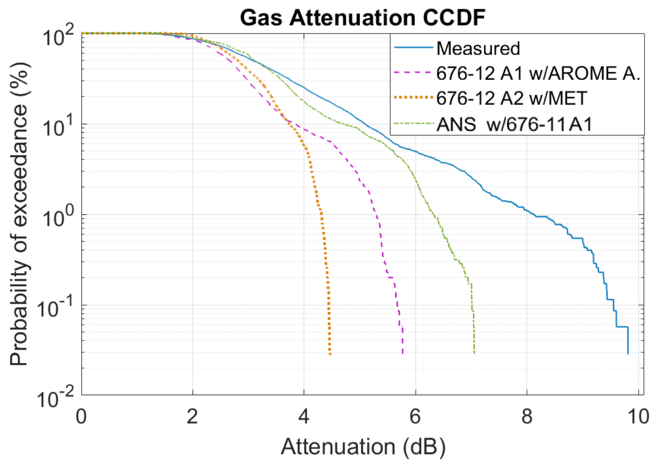

Fig. 3. CCDF of modelled gas attenuation compared with measured attenuation for 5 months (April–August 2016).

Mean absolute error (MAE), relative mean square error (RMSE), and correlation for the gas attenuation models relative to the measured data for the 5 month period are shown in Table 1. Correlation is high for all models, with highest values for the line by line methods. The measured time series include some cloud effects which are reflected in the high RMSE values. Although the simplified model (Annex 2) has lower absolute RMSE, the line by line method (used by Annex 1 and ANS) describes the variations better, shown both in the relative RMSE and correlation values.

TABLE I. GASEOUS ATTENUATION ERROR

	MAE (dB)	RMSE (dB) [%]	Corr.
676-12 A1 w/AROME	0.66	0.97 [20.88]	0.87
676-12 A2 w/MET	0.65	0.91 [25.52]	0.81
ANS Gas w/676-11 A1	0.48	0.67 [17.23]	0.88

V. CLOUD ATTENUATION

Results from the previous section indicate that data processing and filtering of the measured beacon level time series did not remove a significant part of long-term cloud attenuation. Cloud attenuation model data were therefore added to the gaseous attenuation values for comparison.

A. Cloud Attenuation Modelling

For both AROME Arctic and ANS data cloud attenuation was modelled using the Rayleigh scattering approximation (1) from Annex 1 of ITU-R Rec P. 840-8 (AROME) [13] and 840-7 (ANS), to calculate specific attenuation within

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the cloud. The respective high resolution NWP data of each model were used to directly give the water content of the cloud. The resulting modelled time series of gaseous and cloud attenuation were filtered using the same low-pass filter as the measured attenuation time series.

B. Combined Gaseous and Cloud Attenuation Results

An example of the resulting (filtered) combined gaseous and cloud attenuation time series is given in Figure 4, showing excellent agreement with the measured data for both models. The same excellent agreement is also present in the CCDF in Figure 5, with the ANS values being slightly higher than the measured ones as well as those modelled by AROME Arctic. Again it is worth noting that the reference level for the measured data was set using the AROME Arctic model. The difference between ANS and AROME Arctic is much lower than for the gaseous-only attenuation in the previous chapter. The reduced difference comes from ANS predicting higher gaseous attenuation than AROME Arctic and at the same time lower levels of cloud attenuation.

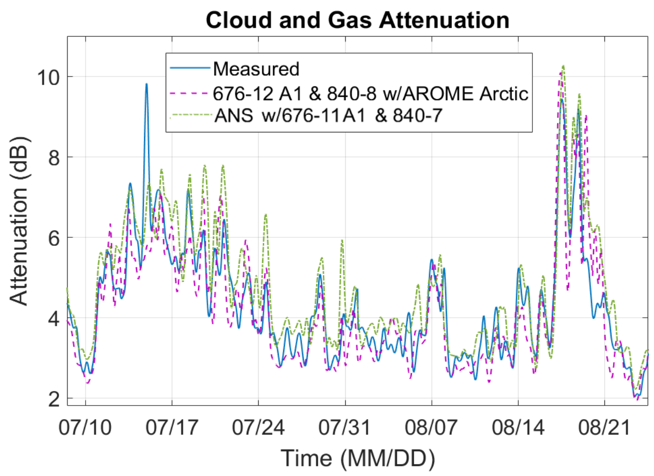

Fig. 4. Example comparison of the measured attenuation with time series of gas and cloud attenuation from the AROME Arctic and ANS models.

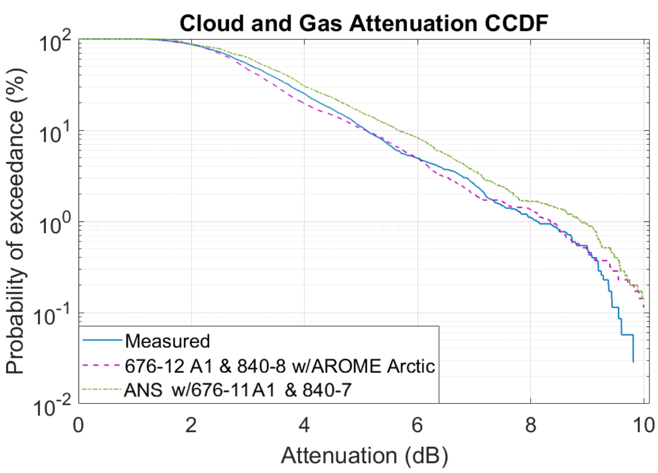

Fig. 5. CCDF of modelled gaseous and cloud attenuation compared with measured attenuation for 5 months (April–August 2016).

For the combined cloud and gas attenuation modelling, MAE, RMSE, and correlation are shown in Table 2. The RMSE of the ANS results, that are based on re-analysis data, and the results using AROME predictions, confirm that both models are able to reproduce the actual tropospheric conditions with similar accuracy.

TABLE II. CLOUD AND GASEOUS ATTENUATION ERROR

	MAE (dB)	RMSE (dB) [%]	Corr.
676-12 A1 & 840-8 w/AROME	0.45	0.65 [17.29]	0.89
ANS w/676-11 A1 & 840-7	0.49	0.65 [19.10]	0.92

As can be seen from the full time series comparison shown in Figure 6, both the results from the AROME Arctic predictions and the ANS re-analysis methods show a very good match with the measurements. Figure 6 also shows the RMSE, calculated for every 24 hours. The RMSE of the combined attenuation predicted by the AROME Arctic model decreases in the warm summer months when the predicted attenuation is higher. This corresponds to MAE being similar through the 5 month period. The likely explanation is that the measured values during the summer months are less affected by variations and inaccuracies of the measurement setup. For the ANS results the RMSE is similar through the 5 month period, while MAE is larger during the high attenuation period in the summer. This might be related to ANS giving much higher gaseous attenuation values during the summer months. As explained before this is compensated by lower cloud attenuation values, which are less likely to closely match the measured data in time.

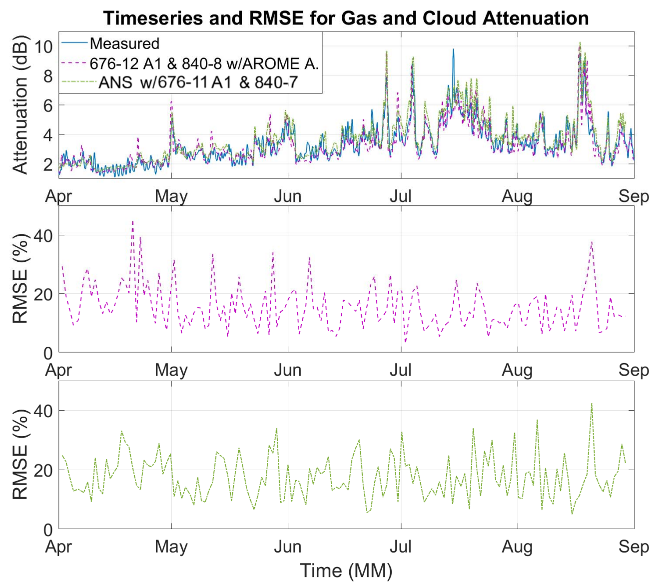

Fig. 6. Time series of measured and modelled attenuation (top) with RMS relative error for gaseous and cloud attenuation relative to measured attenuation for AROME Arctic (center) and ANS (bottom).

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VI. Conclusions

Five months of measured 19.68 GHz satellite beacon data at a (geometric) elevation angle of 3.2º from Isfjord Radio, Svalbard, Norway, were compared with gaseous and cloud attenuation models with the goal of assessing the temporal variability of gaseous attenuation as well as the accuracy of three different models. The measured time series, which includes some additional cloud attenuation, showed up to 8 dB of variation over the course of a few tens of hours.

Comparison with the gaseous attenuation models revealed that changes in water vapor content along the path were responsible for large part of the observed variation. The dynamic range of the simulated gas attenuation was 4.4 dB. The simplified model based on meteorological data measurement at the site was unable to predict not only the absolute value but also the (relatively) fast variation of gaseous attenuation.

After cloud attenuation contribution was added to the NWP-based models, both the AROME Arctic and the ANS models showed excellent agreement with the measurements. Note that while ANS is based on re-analysis data that require additional simulation for increased resolution, AROME Arctic results in this work are based on openly available prediction data for 6–11 hours ahead of the prediction time.

The results show that for very low elevation angle slant paths gaseous attenuation cannot be regarded as being nearly constant. Instead it shows significant temporal variability that should be taken into account in system design and link budget calculation using appropriate modelling.

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