Results of a Ka Band Campaign for the Characterisation of Propagation Conditions for SatCom Systems at High Latitudes

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***Abstract*—Satellite services in the High North are utilized extensively for both communication purposes and for earth and climate observations. This paper presents results of two year measurements at 20 GHz and co-sited meteorological data. The results suggest that with 7-8 dB margin, services can be provided with 99 % availability for systems with elevation angles as low as 3.2° and 3 dB for elevation angles above 10.1°. Measured attenuation distributions support International Telecommunication Union prediction methods within 3 to 4 dB for 99.99 % of the time. However, scintillation and multipath are not well predicted at the lowest elevation angle.**

***Index Terms*—propagation, measurement, satellite.**

I. Introduction

Measurement data are important to secure good planning and operation of satellite communication (SatCom) systems. The quality of link prediction is judged against measured data. Often such data are also actively used in developing and revising prediction methods, for example to find optimum parameters. For satellite links there are quite a few measurement campaign data available, also at 20 GHz. However, this has not been the case for Norway and high north maritime latitudes in general.

Telenor Satellite is leading a project funded by European Space Agency (ESA) performing a measurement campaign at 5 locations. In addition a Norwegian Defence and Research Establishment (FFI) project adds measurements from two other locations. The measurement campaign was launched in response to a request for better information to deploy Ka-band high capacity satellite systems in the high north regions. So far the result is a two-year propagation data set and one half-year of telecom data.

The paper has 5 sections including introduction and conclusion. Section II gives information on the experiment campaign; Section III covers measured data along with predictions; discussion of results is in Section IV.

II. Measurement Campaign

Three measurement stations are located in maritime climates along the coast of main-land Norway and one station is located at Svalbard. In addition there are three measurement locations in the inland Oslo-region. The latter stations also provide suitable data for practical site-diversity set-ups. The telecom experiment performed in the north of Norway, in Vadsø, provided results of importance for satellite link channels with respect to spectrum efficiency.

Until end of September 2016 the 20 GHz propagation and concurrent meteorological data have been collected at all 7 stations. This paper presents an overview of the first two-year propagation data set covering November 2013 - October 2015. The telecom station in Vadsø measured additional data for half a year from two-way test traffic; July-December 2015.Table I lists the geographical coordinates, altitude above sea level, and elevation angle towards Ka-Sat at 9°E in the geostationary orbit. The telecom measurement was carried out using the Thor 7 at 1°W.

TABLE I. Measurement locations, altitude, and elevation angles towards Ka-SAT and Thor 7 in addtion for Vadsø

Location	**Latitude (°N)**	**Longitude (°E)**	**Altitude (m)**	**Elevation angle (°)***
Nittedal	60.1	10.8	200	21.8
Eggemoen	60.2	10.3	200	21.7
Røst	67.5	12.1	10	14.1
Vadsø	70.1	29.7	30	10.1
", telecom	"	"	"	8.4
Isfjord radio	78.1	13.6	5	3.2
Kjeller	59.98	11.05	110	22.0
Haakonsvern	60.34	5.23	30	21.5

*) Geometrical calculated angles

The range of elevation angles results in a propagation path through the atmosphere being more than 6 times longer for the most northern station compared with the most southern location, although somewhat reduced due to the lower height of the troposphere in the north.

Details of the most northern locations, Røst, Vadsø and Isfjord radio (Svalbard) were provided in [1]. More information about the measurement site Kjeller, in the Oslo-

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region and close to Nittedal and Eggemoen, is found in [2], and about Haakonsvern, close to Bergen, in [3].

A. Measurement Stations

A block diagram of the propagation terminal is given in [1] along with a description of the procedures used to calculate the signal strength from the spectrum analyser data taken every 0.1 s. The set-up gives a dynamic detection range of about 40 dB at all stations. The same measurement method was used for the Kjeller and Haakonsvern stations. The meteorological data are collected every 10 s, but once per minute at Kjeller and Haakonsvern. At the latter two stations only the compact WXT weather station was available, and not the tipping bucket to measure rain rate as used as well by the other stations. The tipping bucket is measuring the time between each tip. Apart for rain rate the meteorological data include air temperature, pressure, and humidity, and wind speed and direction.

The telecom terminal is similar to the propagation terminal described in [1], but with a modem included for two-way communication.

B. Data Collection Network

All data are collected and stored locally, while also sent through the network for central storage and pre-processing. These processes are automated to minimize the time needed for manual interventions. The DataMiner tool is used to collect data at the ESA-project stations. It allows 24/7 surveillance with alarms created in case of operator intervention should be needed.

III. MEASURED DATA AND PREDICTIONS

After data pre-processing, time series have been manually visually screened and classified into events, such as events caused by rain. Also non-valid data periods are marked. The resulting set is the used to calculate excess attenuation, scintillation and fade duration statistics shown below. For the two latter the data time series have been resampled to 0.1 s sampling period. This is also the typical sampling period for the measured data, but with some small variability. Also other first- and second order statistics have been estimated, but results are not included in this paper.

A. Measured and predicted attenuation

Establishing excess attenuation requires a reference for no fading. For all stations except Isfjord radio, the reference is set per event by a line through signal strength values in dB, from before to after. For Isfjord radio it is not possible to identify events this way and a fixed reference is used corresponding to signal strength for clear sky days. Per year it was set to the signal level received during a few dry days in November. In the event-based analyses the data in between events are set to no fading.

Fig. 1 shows the measured attenuation distribution of all 7 locations. All measured data points have equal weight and the 100 % value corresponds to the total number of observations. Here this is interpreted as a two-year average estimate of the cumulative distribution. The corresponding concurrent rain rate distributions are provided in Fig. 2.

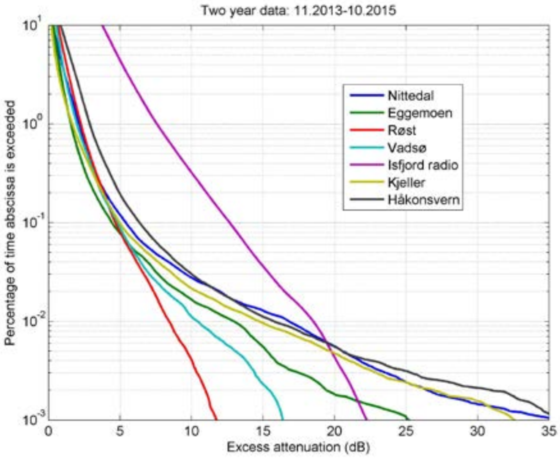

Fig. 1. Attenuation distributions.

The lowest rain rate, and also driest area, is the most northern station at Isfjord radio. Then the rain rate values increase with lower latitudes to the highest observed values at the most southern stations. See the next section for discussion of these observations and effect on attenuation.

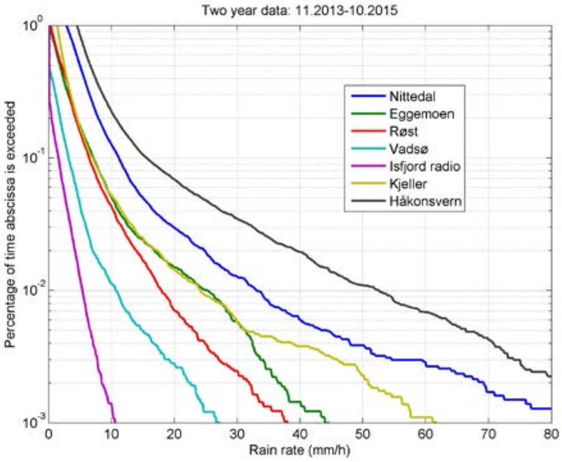

Fig. 2. Measured con-current rain rate distributions.

It should be noted that the 5 ESA-stations all measure with a tipping bucket rain gauge instrument, while the FFI-stations use a compact weather instrument deploying an electro-acoustic method [1].

The signal variation is significantly different at Isfjord radio compared to the other stations. In the deep fading tail it indicates a Rayleigh-fading slope of 10 dB/decade, as also shown in [4] covering the first year measurement.

The event-based excess attenuation distributions have been compared with the ITU-R rain attenuation prediction method [6] assuming that only precipitation contributes to the additional attenuation. The measured distribution for Isfjord radio based on a fixed non-fading clear sky, has been compared with a combined prediction method taking all effects, such as precipitation, scintillation and multipath, cloud attenuation, and gaseous attenuation into account, except including only the wet part of the gaseous attenuation. For methods only valid for elevation angle larger than 5°, the value for 5° was used, and not the real elevation angle of 3.2°. The prediction errors for the ITU-R methods are shown in Fig. 3 using methods in P. 618 [6]. The errors are within -3 dB to 4 dB for up to 99.997 % of an average year.

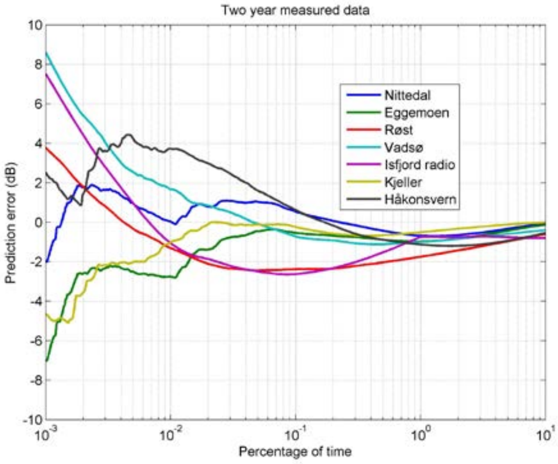

Fig. 3. Attenuation prediction error at various percentages of time.

B. *Measured and predicted scintillation/multipath*

The data were resampled before analyses of scintillation and fade duration. For the amplitude scintillation analyses the time series data have been filtered with a zero-phase 6th order Butterworth filter. See [4] for information on setting the cut-off frequencies needed clear-sky and attenuated periods Fig. 4 shows resulting distributions.

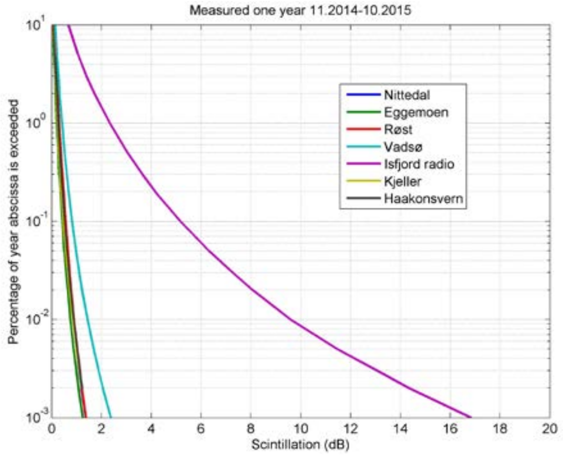

Fig. 4. Measured scintillation and multipath.

The ITU-R method prediction errors are in Fig. 5. The under-prediction of scintillation and multipath at Isfjord radio is significant. At the other stations the absolute values of errors are small, but the relative errors are considerable and at the same level as for Isfjord radio, all over-predicted.

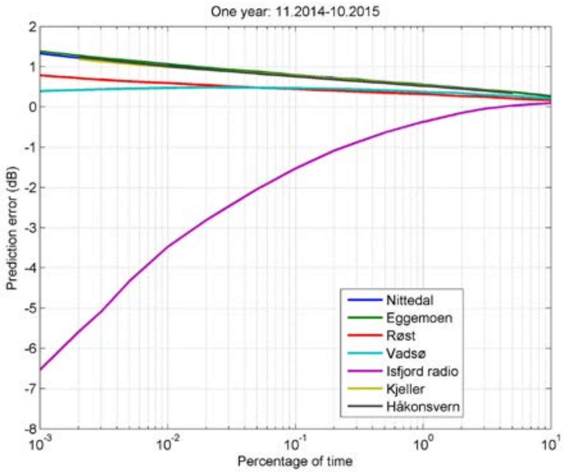

Fig. 5. Prediction error of scintillation and multipath.

C. *Fade duration*

Fig. 6 presents fade duration results as number of fades below a set of thresholds. For each station the numbers are visualised drawing a line between each observed number. Taking the threshold of 5 dB and 10 dB, for example, all stations but Isfjord radio, have about 1000 and 100 events, respectively. Isfjord radio has more than 100 times these numbers at the same thresholds showing a much more dynamically changing signal.

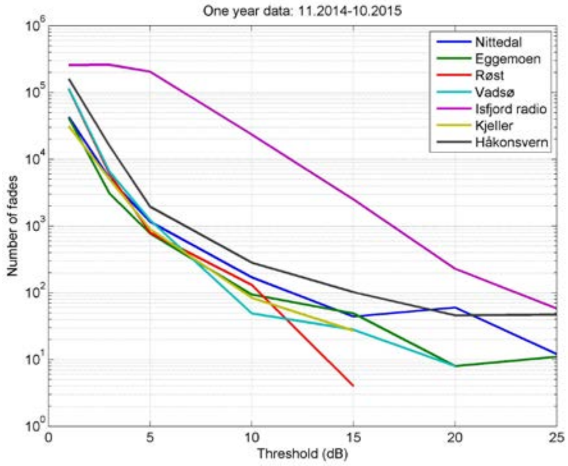

Fig. 6. Measured number of fades.

D. *Telecom Experiment*

The telecom measurement terminal iDirect Velocity was set up in Vadsø and connected to the Telenor Satellite's high throughput satellite Thor 7. The modem platform uses time division multiplex (TDM) DVB-S2 carrier on forward and multi-frequency time division multiplex access (TDMA) on the return link. The forward link utilises adaptive coding and modulation (ACM) with modulation codes (MODCODs) ranging from QPSK 1/4 to 16 APSK 8/9, while the return link is operated in an adaptive TDMA. The return link uses QPSK and 8 PSK, and forward error correction (FEC) ratios from 1/2 to 6/7.

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The telecom set-up had two parallel measurements: i) continuous logging of the broadband spectrum on Ka-band downlink (45 Msps over 54 MHz) and ii) an on-line Ka-band terminal providing access to physical layer statistics from the iDirect Velocity VSAT HUB.

The overall idea was to monitor the broadband spectrum and identify the impact of frequency selective propagation effects e.g., multipath over low elevation angles over sea. And if such events were present, the modem data could be used to address the impact of multipath on a communication link.

The raised cosine shaped spectrum was measured continuously at 0.1 s sampling rate. Fig. 7 top shows the mean power of the in-band spectrum and the out-of-band power. This subplot shows any malfunction of the equipment causing no signal reception or increased out-of-band noise. In addition, signal attenuation over the entire signal bandwidth caused by precipitation becomes very apparent, as the example with one detected rain event.

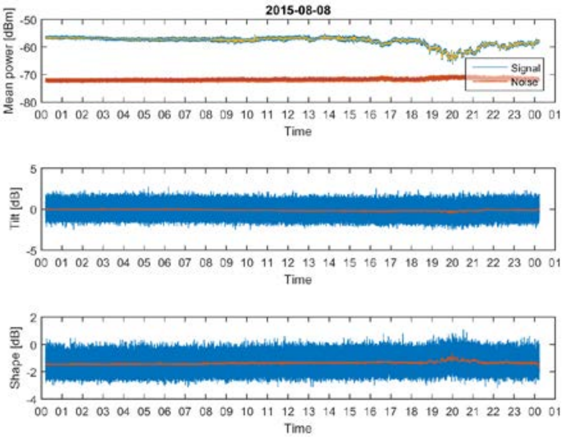

Fig. 7. Example of signal and noise level, spectrum tilt and shape.

The in-band spectrum is divided into 10 bins, and the mean signal power within each bin is calculated. Fig. 7 middle shows the difference in level in dB between the first bin and the last bin, giving information about the tilt of the spectrum. If the tilt varies or is far from zero, it may be an indication of frequency selective fading.

The difference in signal power in dB between the edge bins and the one bin among the eight remaining bins with lowest power, shown in Fig. 7 bottom, gives an estimate of the shape of the spectrum. Under normal conditions, the spectrum has a shape as a 'U' turned upside down so that the result is negative. If the result is positive, there is a dip somewhere within the signal bandwidth, indicating frequency selective fading.

The analysis of data from July and August 2016 showed no frequency selective effects. The telecom terminal in Vadsø was an important test location used to verify the overall system performance on Thor 7. Due to the results obtained in Vadsø and in other locations, the nominal spectral efficiencies on forward and return were improved.

IV. DISCUSSION OF RESULTS

The measured attenuation distributions show that most fading is observed at Isfjord radio. Taking the low elevation angle into account and the corresponding mean slant path lengths through the atmosphere, it is to be expected that long link lengths experiences a significant amount of fading activity. The mean slant path lengths, L, given in Table 2 are calculated utilising the rain height, which is 360 m above the height of zero temperature, h_0, from [7] and given in Table 2, the station height and elevation angle provided in Table 1. The mean link lengths are applicable when estimating rain attenuation, which is a dominating factor for main-land stations. At Isfjord radio rain is not the dominating factor, but the length for other propagation phenomena, i.e., cloud, scintillation, and multipath, will vary in a similar fashion. Nevertheless, even at Isfjord radio the signal will not fade more than 7-8 dB at 99 % of an average year. For the other locations this figure is 2-3 dB of excess attenuation.

TABLE II. MEASUREMENT LOCATIONS, ZERO-DEGREE HEIGHT (h_0), SLANT PATH LENGTH (BELOW $h0$), AND RAIN RATE INFORMATION

Loc.	**h_0 (km)**	**L (km)**	**Norway $R_{0.01}$ (mm/h)**	**ITU-R $R_{0.01}$ (mm/h)**	**Measured $R_{0.01}$ (mm/h)**	**Error (dB)**
Nitt	2.13	5.63	25.5	28.1	33.0	0.0
Egg	2.15	5.71	19.9	28.0	25.1	-2.8
Røst	0.52	3.53	16.4	41.7	17.9	-1.3
Vads	2.0	13.12	12.7	18.2	10.6	1.7
Isfj	1.03	22.57	-	13.4	5.3	-1.1
Kje	2.10	5.98	24.7	28.3	24.1	-1.0
Haak	1.41	4.67	28.6	51.1	52.6	3.7

Fig. 3 shows the prediction error, excess attenuation for the main-land stations and total attenuation (except oxygen) for the Isfjord radio. The local concurrent observed rain rate data have been used with the attenuation prediction method in P.618 [6] using ITU-R climate information for other parameters, such as rain height.

Table 2 lists the prediction error at 0.01% of the time. In general the prediction errors are small. A deviation can result from an in-correct prediction method, errors in the input parameters such as the point measurement of rainfall rate not fully being representing for the rainfall along the link passing through the atmosphere, and rain height errors. The largest deviations are found at Haakonsvern and Eggemoen.

One important parameter is the rain rate, where the prediction method uses the rain rate exceeded at 0.01 % of the year. Table 2 lists values from the local Norwegian map [5], the ITU-R map [9], and the concurrent observations. Note that the con-current observation is limited to the time when also radio data exist and may therefore not fully be comparable with the other rain rate values subject to concurrent data availability, but it is a more precise parameter to be used in the prediction method when comparing with measurements. The largest deviation at Haakonsvern may indicate that the measured rainfall rate is higher than the true value; a value of 38 mm/h would be needed for no prediction error. The compact sensor, however, reports comparable values at the

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other stations except at Røst. Here the compact sensor shows very much higher values than the tipping bucket located at the same place.

The rain rate trends [8] from Norwegian meteorological office long-period stations in Oslo, at Gardermoen and at Sandsli in the Bergen region have about ±12 mm/h 95 % bounds. The trend value for Sandsli is 33 mm/h. The measured two-year rainfall intensities at 0.01% for these stations are all within these bound except Haakonsvern. The ITU-R rainfall rate maps are comparable with the Norwegian map for in-land Norway, such as the Oslo regions, but shows considerable higher values along the Western Norwegian coast line. The compact WXT instrument shows similar values as the long term estimates of ITU-R at Haakonsvern and Røst; for the latter WXT measured about 50 mm/h compared to 17.9 mm/h by tipping bucket, but the excess attenuation predictions do not support these high rain rate values. An alternative cause of the deviation is the rain height, or zero-degree height, as discussed in [3]. Considering these two important parameters and comparing with the case h_0 = 2 km and $R_{0.01}$ = 35 mm/h for a link with elevation angle 21.5° Fig. 8 illustrates that parameter changes needed versus prediction difference underlining that some change in any of them will create a few dB deviation.

Fig. 5 shows significant under-prediction of scintillation and multipath for Svalbard. Since the over-all under-prediction error in Fig. 3 is more limited it indicates that other mechanisms are covering for the scintillation and multipath effects. Since the multipath model in [6] is based on more than 50 year old climate data information it should be candidate for revision. However, the Rayleigh-distribution tail of 10 dB/decade indicating multipath is confirmed.

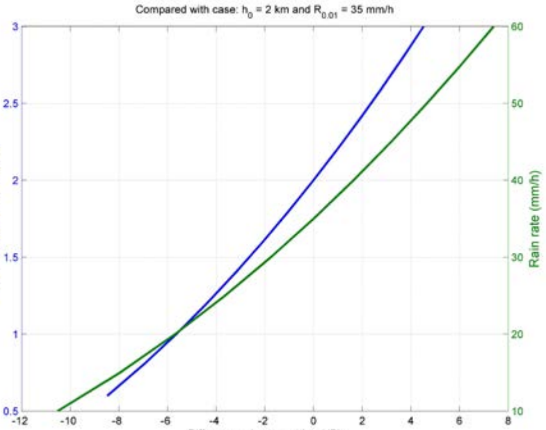

Fig. 8. Sensitivity of predicted rain attenuation at 0.01% of the time compared the case of h_0 = 2 km and $R_{0.01}$ = 35 mm/h

V. CONCLUSION

The paper presents two year measured 19.7 GHz satellite data from 7 locations in Norway with elevation angles from to 3.2° to 21.5°. In addition 6 month telecom data have been collected for one station at 8.4° elevation angle.

At most northern and lowest elevation angle station Isfjord radio, the signal will not fade more than 7-8 dB at 99 % of an average year. The figure is 2-3 dB excess attenuation for the other locations at this availability. The telecom data analysis allowed an improvement of the nominal spectral efficiencies. No frequency selective effects were observed during July and August 2015.

Measured rain attenuation compares fairly well with ITU-R predictions used with local con-current rain rate data. For 99.9 % availability combination rain with gaseous absorption, scintillation and cloud attenuation is needed. At Isfjord radio scintillation and multipath effects dominates.

At elevation angles below 5° the ITU-R methods provide limited guidance. Therefore prediction methods for scintillation and multipath, gaseous absorption, and cloud attenuation need a revision.

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