Long-Term Measurements of Tropospheric Scintillation at Very Low Elevation Angles – Initial Analysis

Martin Rytir[1]
[1]Norwegian Defence Research Establishment, FFI, N-2027 Kjeller, Norway, Martin.Rytir@ffi.no

***Abstract*— Four years of scintillation measurements at very low elevation angles at Kjeller, Norway are analyzed and compared with the ITU-R model. One year is at Ka band with an elevation angle of 3º, and three years are of simultaneous measurements at Ka and X band with an elevation angle of 4.2º. The measured scintillation is highly asymmetrical with more than 40 dB fades recorded at Ka band. In agreement with previous results, the scintillation spectra for low elevation angles have a low corner frequency. Compared with the ITU-R model, the measurements highlight issues with uncertainty of input parameters, as well as accuracy of the deep-fading part of the model. The model predicts the measured scintillation well for high percentages of the time, but poorly for low percentages of the time. The deep-fading part of the model significantly overestimates fades at X band, highlighting a previously observed issue with frequency scaling.**

***Index Terms*—Electromagnetic propagation, scintillation, measurements.**

I. Introduction

Tropospheric scintillation, causing rapid signal variations, affects satellite communication links as well as links to airborne platforms. The severity of these variations increases with increasing frequency, becoming significant at frequencies over a few GHz, as well as for low elevation angles that lead to longer path through troposphere. At very low elevation angles (<5º) multipath propagation also starts affecting the link [1].

Very low elevation angles are common for satellite links with geostationary satellites from high latitudes, as well as for long-range links to airborne platforms. Furthermore, use of very low elevation angles can significantly increase contact time with satellites in low earth orbit, for example those used for earth observation.

Current long-term modelling of scintillation at very low elevation angles in ITU-R P. 618 [2] is based on few measurements mostly done many years ago in Canada [3][4], UK [5][6] and Norway [7]. The multipath part of the model uses old refractivity index gradient maps only available in printed form [8]. Recent measurements show that these models have limited accuracy [9][10]. It has also been observed that scintillation spectra behave differently at very low elevation angles [11]-[13], which likely affects the frequency scaling.

This paper analyzes initial results from a long-term measurement campaign at elevation angles of 3 and 4.2 degrees at Kjeller, Norway. The total measurement period analyzed is four years, out of which three years compromise simultaneous measurements at X band (7.6 GHz) and Ka band (20.7 GHz) towards the same satellite.

The rest of the paper is organized as follows: Section II summarizes the modelling issues. Section III describes the measurement setup. Section IV shows examples of a few measurements. In Section V long-term results are plotted and compared with the ITU-R model, and Section VI draws conclusions.

II. Scintillation Modelling Issues

A. Long-Term Prediction Model

The existing ITU-R long-term prediction model for elevation angles <5º compromises of three parts [2]:

- Prediction of scintillation fading amplitude at elevation angle of 5º, using the wet part of the surface refractivity (N_{wet}) as the only climate input parameter.
- Prediction of scintillation fading amplitudes for fades with multipath character and amplitude ≥25 dB, using refractivity gradient statistics value p_L as main input, but also depending on the actual elevation angle.
- Prediction that interpolates between the two above results as introduced by [14].

As mentioned in the introduction, the value of p_L (percentage of time with refractivity gradient over 100 m lower than -100 N-unit/km) is only given in printed maps with limited resolution. Furthermore, the maps were calculated using climatologic data from the middle of the 20th century. It is therefore likely that different values should be used for the current climate. Furthermore, recent measurement have shown issues with fit of the interpolated part of the model [9].

The model frequency scaling exponent for fading amplitude is 0.583 (7/12) for the model for elevation angles of 5º and higher, based on scintillation theory [15]. The deep fading part has a frequency exponent of 0.4.

B. Scintillation Properties at Very Low Elevation Angles

Spectral analysis done in [12][13] has shown that for very low elevation angles, the size of the first Fresnel zone might become larger than the outer scale of turbulence L_0.

This was observed by comparing the lower than expected scintillation corner frequency with transversal windspeed and comparing it with scintillation theory [15]. In this case the frequency exponent of fading amplitude should be 1, which is much higher than in both parts of the current model.

III. Measurements

A. Measurement Location

The new measurements analyzed in this work were conducted at Kjeller, Norway (59.97ºN, 11.04ºE, 110 m AMSL). One year of data was collected using the Ka band beacon from the Inmarsat-5 F2 satellite at 20.68 GHz. Three years of data were subsequently collected using the X band (7.6 GHz) and Ka band (20.7 GHz) beacons from a WGS (Wideband Global Satcom) satellite. The link geometry is shown in Fig. 1.

B. Measurement Setup

The beacon measurement setup is based on the one used in [9] and compromises of a 1.2 m (Ka band) and 1.8 m (X band) antenna with an Orbital Research commercial LNB (Low Noise Block downconverter). The X and Ka band antennas are placed next to each other. The downconverted signal is fed to a spectrum analyzer (Keysight EXA) controlled by a computer program that saves the data. For the combined X and Ka band measurement, the same computer controls two separate spectrum analyzers and saves data from both. The sampling rate is 10 samples/s and the clear sky SNR with the available beacon is between 43 and 47 dB. Meteorological data were collected using a Vaisala WXT520 weather station. The main parameters are summarized in Table I, note that elevation angles are without refraction.

TABLE I. Main parameters of the three measurements

Satellite	***Elevation Angle [°]***	***Azimuth [°]***	***Frequency [GHz]***	***Antenna Diameter [m]***	***SNR [dB]***
Inmarsat-5 F2	3.06	249	20.68	1.2	47
WGS	4.22	247	20.7	1.2	43
			7.6	1.8	47

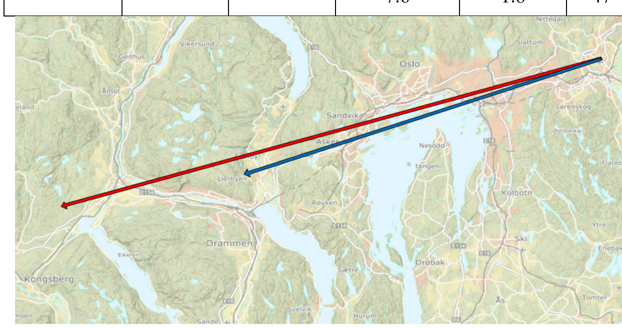

Fig. 1. Propagation path towards the two satellites according to the definition in ITU-R P.618 § 2.4.2. For Inmarsat-5 F2 (red) this gives 77 km and for WGS (blue) 51 km, this correspond approximately to a path length up to a height of 4.5 km.

C. Data Processing and Availability

Invalid beacon data were removed by a combination of automatic and manual checks. All data with rain, cloud and gaseous attenuation higher than 15 dB were removed. This attenuation level corresponds to approximately 30 dB SNR, depending on the measurement. The cause of the attenuation was identified by using weather data as well as monitoring of the increase of the noise floor over 7.5 kHz bandwidth recorded by the receiver.

To separate scintillation from other impairments, a high-pass 6th order Butterworth filter is used. The cut-off frequency used by the filter is 2 mHz for clear-air situations and 10 mHz for periods with attenuation that are manually identified. These filtering frequencies were chosen by spectral analysis of all three datasets using the method described in [9]. As was also shown in [9] the precise value used for the cutoff is not very critical and the data with attenuation represents only a small part of total measurement time.

For the 3º link to Inmarsat-5 F2, the measurement period was July 2016 to June 2017 with 96.5% availability of valid scintillation data. For the 4.2º degree links to the WGS satellite, the measurement period was October 2017 to September 2020 with availability of valid scintillation data of 99.54% for Ka band and 99.57% for X band.

IV. Results

A. Sample Results and Spectra

Sample time series and spectra in Fig. 2 show a good match with the -80/3 dB/decade slope of scintillation for both frequencies, both during periods of strong and weak scintillation. The scintillation corner frequencies indicated in the examples show a clear difference between X and Ka band values, just as expected from scintillation theory [12][13], and confirmed for higher elevation angles in [16]. Since the precise scaling factor between the corner frequencies should be different for cases when the outer scale of turbulence is smaller and larger than the first Fresnel zone, it might be possible to use the estimated values for detailed analysis that identifies which case is valid at a given time. These results could then be compared with frequency scaling values from the comparison of scintillation amplitudes.

Fig. 3 shows a detail of the scintillation time series from same day as Fig. 2 after a high-pass filter was used to separate other effects. Two distinct types of behavior can be observed. During periods of weaker scintillation in the first half of the example, the two frequencies are well correlated both in time and amplitude. In the second part of the example with multipath-like behavior, the correlation is seemingly much worse, notably the deep fades do not match well in time, and in general the scaling factor appears larger. This seems to further support the idea that the frequency scaling factor varies during different conditions for same link geometry.

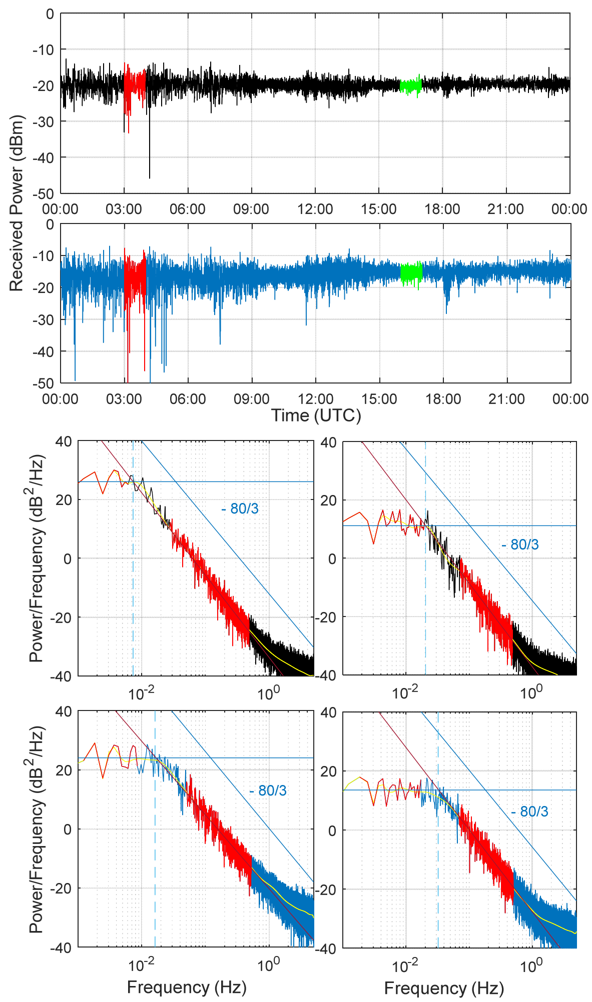

Fig. 2. Measured WGS beacon signal (top) on 08/08/2020 with calculated spectra and estimated scintillation corner frequencies for the marked 1-hour periods, red period on the left side, green on the right side. X band in black, Ka band in blue.

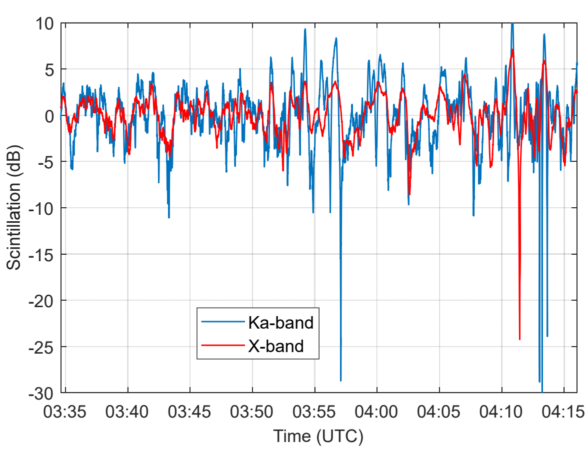

Fig. 3. Scintillation time series example from 08/08/2020.

B. *Long-Term Statistics and Variability*

The measured long-term statistics for Kjeller are plotted in Fig. 4 and compared with a recent 3-year measurement at Isfjord Radio in the Arctic at similar elevation angle [9]. As observed before, the scintillation distribution is highly asymmetrical for amplitudes above 4–5 dB. All four measured fading distributions show a clear multipath-like Rayleigh slope for deep fades below approximately 15 dB.

Note that while very low percentages of time are typically not considered statistically stable for propagation studies with duration of only a few years, this is mainly due to the characteristics of rain attenuation. Rain attenuation causes very few high-attenuation events that last a few minutes each year. For scintillation the high fading statistics are composed of a much larger number of events lasting a few seconds or less. Fig. 5 shows very little difference between the statistics for the 3 years of measurement at Kjeller.

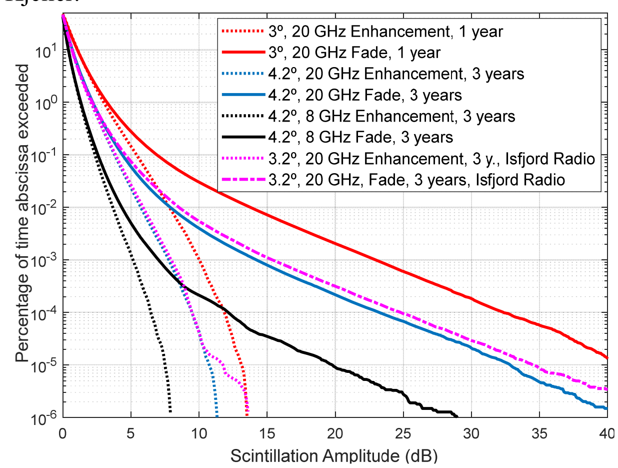

Fig. 4. Measured yearly scintillation statistics at Kjeller, compared with measurement from Isfjord Radio.

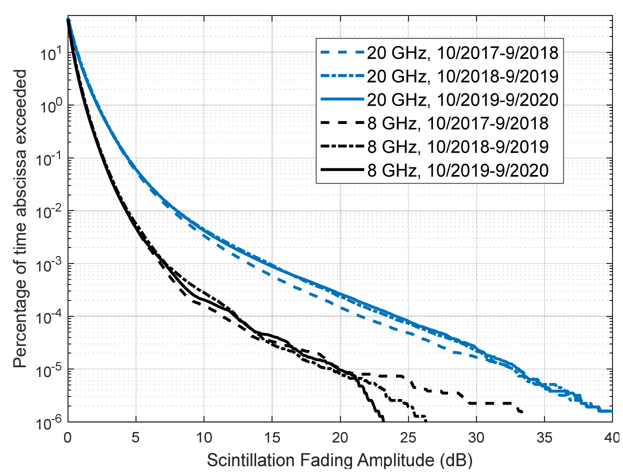

Fig. 5. Measured scintillation fading statistic at 4.2º for each of the three years.

C. Comparison with Model

The ITU-R model in Rec. P.618 only gives predictions for fading and only for average year (AY) and worst month WM). (Figs. 6–8 compare the model with slightly different input values with the measurements.

The three main climatic input values are N_{wet}, p_L and C_0. N_{wet} affects mostly the first part of the prediction (high probability values). ITU-R maps [10] give the value for Kjeller at 34.6 ppm. Concurrent measurement by local meteorological instruments give 33.4 for the first year and 32.6 for the following three, these difference have negligible effect on the predictions.

The other two parameters affect the deep fading part of the distribution. As was mentioned p_L is given in [9] only in plotted maps based on old data, the most likely value that should be used is 2 %, but 1 % was included for comparison. The coefficient C_0 depends on the proximity of the propagation path to large bodies of water. The later versions of Rec. P.618 lack the definition of propagation path. For consistency with the original model, the last published definition from Rec. P.618-10 was used, giving path lengths of approximately 77 and 55 km plotted in Fig. 1. Based on these, C_0 values of 79 (for the 3º link) and 80 (for the 4.2º link) were used. Predictions using maximum value of 82 (link entirely near large bodies of water) were also added.

For high-percentages of time, the model shows good fit for all links. Rest of the model shows best fit for the 3º link, which is similar in geometry and climate to the main location used in development of the model (Goonhilly, UK) [14]. There is some difference in the deep-fading part but overall the fit is relatively good.

For both 4.2 º links, the middle "interpolating" part of the model starts to have issues replicating the shape of the curve, similarly as previously observed for the link at Isfjord Radio [9]. The deep fading part of the ITU- R model shows a very large difference compared with measured values at X band, which then subsequently affects rest of the model. Similar scaling issues were also observed at Isfjord Radio when scaling from an old measurement at Ku band [9].

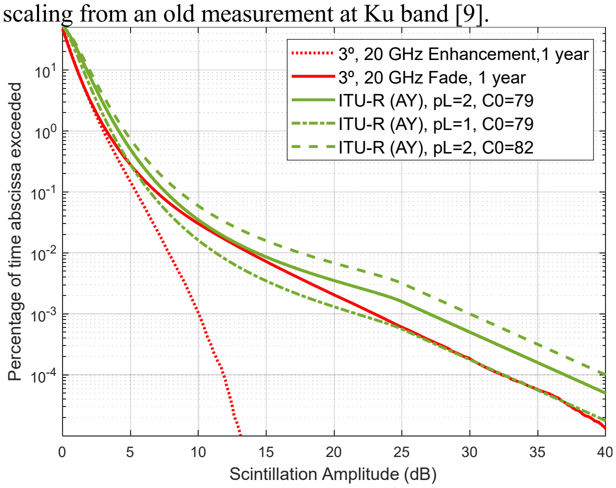

Fig. 6. Model comparison for Ka-band link at 3º at Kjeller.

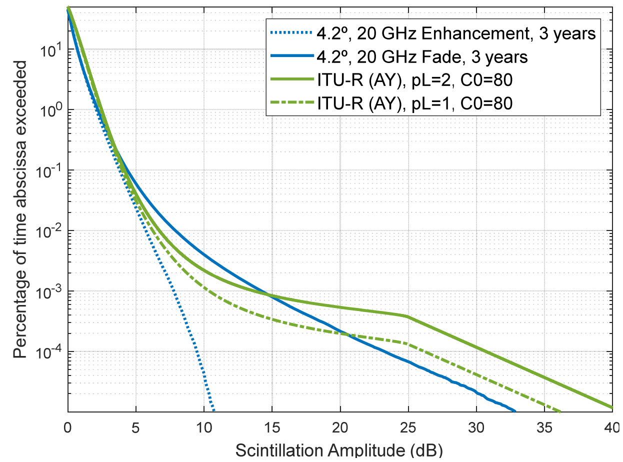

Fig. 7. Model comparison for Ka-band link at 4.2º at Kjeller.

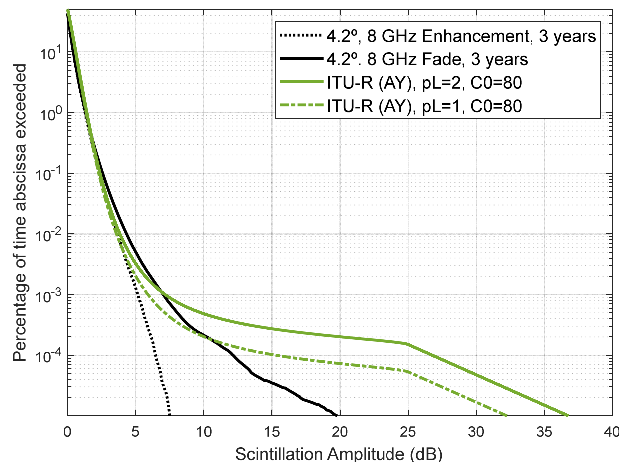

Fig. 8. Model comparison for X-band link at 4.2º at Kjeller.

Since the ITU-R model only gives AY and WM predictions, it does not model the measured large monthly variations shown in Fig. 9 at all, further reducing the usefulness of the model. The measured scintillation fading levels at 0.01% of time change from a minimum value of 3 dB to as much as 12 dB during the summer.

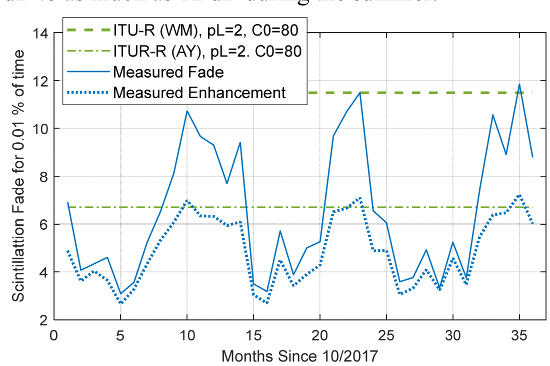

Fig. 9. Monthly variability of scintillation for the 4.2º, 20 GHz link at 0.01 % level, compared with model predictions.

V. Conclusions and Future Work

This paper presented an initial analysis of results from long-term measurements of scintillation at very low elevation angles. The measured data exhibit large differences between signal enhancement and fading, with fading values down to 40 dB for the Ka band links. The deep-fading statistics follow a Rayleigh fading slope.

The current ITU-R model predicts the measured values well for high percentages of time. For low percentage of time, the Ka band predictions of the model are sensitive to climatic parameters, which are either obsolete or hard to define, and the X band predictions are rather inaccurate. When examining the time series it appears that the frequency scaling factor between the two frequencies changes during different conditions. This is somewhat consistent with recent studies on scintillation theory [12][13].

In addition to providing a new large dataset, this paper also identified a number of interesting areas for future work.

The deep-fading part of the model should be modified for the use of a more up-to-date and readily available climatic data. From the statistical comparison of X and Ka band, it seems that the frequency dependence of this effect is not well modelled. Further study of this effect can be conducted using several approaches. Instantaneous/short-term frequency scaling could be combined with an approach based on spectral analysis of the time series. This spectral analysis could also be helpful in further improving the ITU-R model by taking into account a better understanding of the applicability limits of the scintillation theory.

Acknowledgment

Jostein Sander and Terje Mjelde from FFI helped set up and run the measurements. Lars Bråten from FFI and Terje Tjelta from the University of Oslo were instrumental in setting up the preceding propagation campaign as well as designing the original measurement setup.

References

[1] D. V. Rogers, "Clear-air transmission impairments at low path elevation angles," *In Proc. 4th European Conference on Antennas and Propagation (EuCap)*, Barcelona, April 2010.

[2] ITU-R Recommendation P.618-13, "Propagation data and prediction methods required for the design of Earth-space telecommunication systems," International Telecommunication Union, Geneva, Switzerland, 2017.

[3] J. I. Strickland, R.L. Olsen, and H.L. Westiuk, "Measurements of low-angle fading in the Canadian Arctic," *Ann. Télécommunic.,* vol. 32, pp. 530-535, Nov-Dec 1977.

[4] W. I. Lam, "Low angle signal fading at 38 GHz in the high arctic," *IEEE Trans. Ant. Prop.,* vol. 35, pp. 1495-1499, Dec 1987.

[5] E. C. Johnston, D. L. Bryant, D. Maiti and J. E. Allnutt, "Results of Low elevation angle 11GHz satellite beacon measurements at Goonhilly," *7th International Conference on Antennas and Propagation (ICAP)*, vol. 1, pp. 366-369, 1991

[6] M. M. B. Mohd Yusuff, N. Sengupta, C. Alder, I. A. Glover, P. A. Watson, R. G. Howell and D. L. Bryant, "Evidence for the Presence of Turbulent Attenuation on Low-Elevation Angle Earth-Space Paths – Part I: Comparison of CCIR Recommendation an Scintillation Observations on a 3.3° Path," IEEE Trans. Ant. Prop., vol. 45, no. 1, pp. 73-84, January 1997.

[7] O. Gutteberg, "Low elevation propagation in high-latitude regions," Final Report on ESTEC/Contract no. 5032/82 NL GM(SC), Norwegian Telecom, Kjeller, Norway, April 1983.

[8] ITU-R Recommendation P.453-14, "The radio refractive index: its formula and refractivity data," International Telecommunication Union, Geneva, Switzerland, 2019.

[9] M. Rytir, "Clear-Air Scintillation and Multipath for Low-Elevation High-Latitude Satellite Communication Links," *In Proc. 9th European Conference on Antennas and Propagation (EuCap)*, Lisbon, pp. 1-5, April 2015.

[10] T. Tjelta, M. Rytir, L. E. Bråten, P. A. Grotthing , M. Cheffena and J. E. Håkegård, "Results of a Ka band campaign for the characterisation of propagation conditions for SatCom systems at high latitudes," *In Proc. 11th European Conference on Antennas and Propagation (EuCap*), Paris, pp. 1481-1485, March 2017.

[11] P. T. Thompson and B. G. Evans, "Results of Simultaneous Very Low Elevation Ku-Band Propagation Measurements at Two Sites in Southern England," *30th AIAA International Communications Satellite System Conference (ICSSC)*, Ottawa, September 2012.

[12] E. Vilar and J. R. Larsen, "Elevation Dependence of Amplitude Scintillations on Low Elevation Earth Space Paths," *6th International Conference on Antennas and Propagation (ICAP)*, vol. 2, pp. 150-154, 1989.

[13] M. Rytir, C. Riva. D. Vanhoenacker-Janvier and T. Tjelta, "Tropospheric Scintillation Spectra and Transversal Wind Speed for Satellite Links at Very Low Elevation Angles," *In Proc. 11th European Conference on Antennas and Propagation (EuCap)*, Paris, March 2017.

[14] C. H. Lee, K-M. Cheung and C. Ho, "A Unified Low-Elevation-Angle Scintillation Model," *IPN Progress Report 42-185*, May 15, 2011.

[15] V. I. Tatarski, "Wave Propagation in a Turbulent Medium" McGraw-Hill, New York, 1961.

[16] C. Riva. L. Luini, J. Nessel and M. Rytir, "Wind intensity inferred from the Alphasat Ka- and Q-band beacon measurements," *In Proc. 10th European Conference on Antennas and Propagation (EuCap)*, Davos, April 2016.