AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE
10.1002/2013RS005338

Special Section:
URSI Symposium on Radiowave Propagation and Remote Sensing, 2013

Key Points:
- The impact of wet snow on wave propagation
- The unavailability of radio link communication due to weather conditions

Correspondence to:
I. Henne,
ingvar.henne@hib.no

Citation:
Thorvaldsen, P., and I. Henne (2014), Propagation measurements on a line-of-sight over-water radio link in Norway, *Radio Sci.*, *49*, 531–548, doi:10.1002/2013RS005338.

Received 12 NOV 2013
Accepted 13 JUN 2014
Accepted article online 17 JUN 2014
Published online 23 JUL 2014

Propagation measurements on a line-of-sight over-water radio link in Norway

Per Thorvaldsen[1] **and Ingvar Henne**[1]

[1]Department of Electrical Engineering, Bergen University College, Bergen, Norway

Abstract Propagation measurements have been carried out on a 43 km long 13 GHz 128 QAM (quadrature amplitude modulation) over-water path in the coastal regions of Norway. The measurements lasted for 18 months. The intention with the measurements on this in-service radio link was to compare results with models given by the (Recommendation International Telecommunication Union) Rec. ITU-R P. 530-15. The attenuation due to combined rain and wet snow was of special interest, since the radio link is situated in an area —Trondheimsfjorden—that has a significant amount of wet snow in winter. The radio link experienced outages due to multipath, rain and wet snow, where the latter were the predominant outage cause. The fading due to combined rain and wet snow resembled the shape of the model given in Rec. ITU-R P. 530-15, but the model underpredicts the amount of fading. In addition to outages (performance degradation and unavailability) and fading, various other parameters such as fading speed, enhancement, average fade duration, and number of fade events have been measured and compared to Rec. ITU-R P. 530-15. The radio link activity has also been compared to the weather conditions at the time for the most severe fading incidents.

1. Introduction

In line-of-sight radio relay system planning it is crucial to have reliable prediction methods in order to estimate performance and availability. The (Recommendation International Telecommunication Union) Rec. ITU-R P.530-15 [*International Telecommunication Union (ITU)*, 2013a] and its predecessors have offered well-tested models for prediction of fading due to multipath and rain based on measurements on radio links from all parts of the world.

A combined method for predicting fading due to rain and wet snow was introduced by ITU-R in Recommendation P.530-12 [*ITU*, 2007]. Since the coastal region of Norway experiences wet snow during the winter season, and there are relatively few measurements on radio links having combined rain and wet snow fading [*Tjelta and Bacon*, 2010], it was decided to perform propagation measurements over the Trondheimsfjord in Sør-Trøndelag.

In fact, there was an existing path Kopparn-Fillheia in the area which had significantly more outage than had been predicted using pre-P.530-12 [*ITU*, 2007] models that takes only multipath and rain fading into consideration. It was therefore decided to do in-service measurements on that particular radio link to see if combined rain and wet snow fading could explain the excessive outage. The measurements were made in the same region where *Tjelta and Bacon* [2010] had reported that the combined rain and wet snow model in P.530-12 [*ITU*, 2007] is underpredicted.

Propagation measurements performed in Bergen, farther south in Norway, have been performed earlier and reported in *Thorvaldsen and Kvicera* [2002] and *Thorvaldsen* [2000, 1996]. However, apart from one single incident in February 2000 [*Thorvaldsen*, 2000], these measurements did not reveal much fading due to combined rain and wet snow.

Section 2 of this paper presents the measurement setup which consists of radio link and weather data collection. Section 3 describes the relationship between the various fading types and the weather. Sections 4 shows in detail the predictions, based on Rec. ITU-R P.530-13 [*ITU*, 2009] and P.530-15 [*ITU*, 2013a], of the path Kopparn-Fillheia. Section 5 compares predictions with measurements and presents various distributions for both combined rain and wet snow and multipath, and compares them with the Rec. ITU-R P.530 [*ITU*, 2013a, 2009] models.

2. Measurement Setup

2.1. The Path

For the current study, a 43.3 km long, over-water path stretching from Kopparn (N 63°48′25″ E 9°44′18″) to Fillheia (N63°36′48″ E8°58′43″) was selected for the measurements, see Figure 1. A relatively long over-

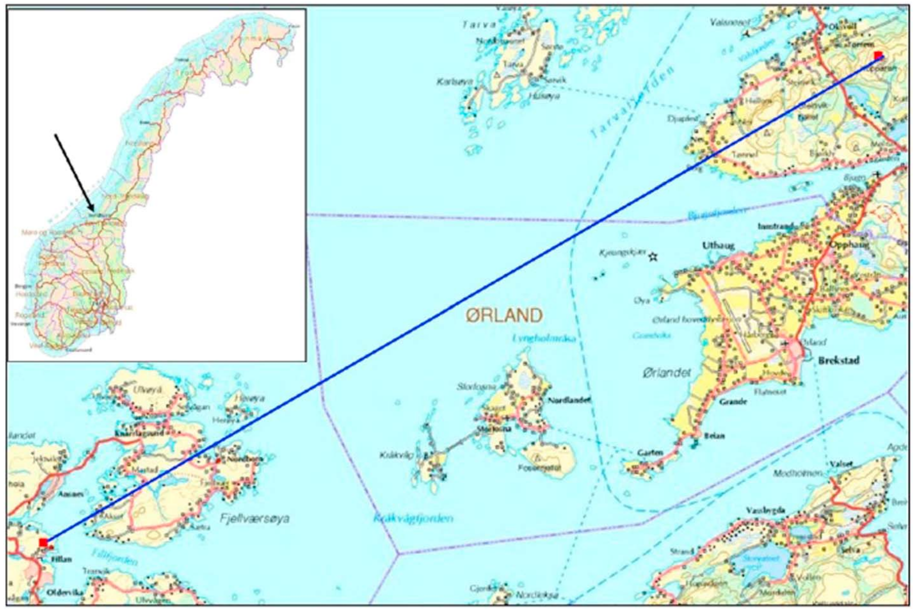

Figure 1. The Fillheia-Kopparn path (straight blue line). Inset: approximate test location indicated by the arrow.

water path was chosen in order to get more experience with over-water multipath events. The path is an in-service radio link which is part of TrønderEnergi's broadband network for the region.

The terrain profile (Figure 2) shows that the radio path has good clearance to the ground. The path is free from specular ground reflections. The antenna height is 475 mamsl (meters above mean sea level) at Kopparn and 95 mamsl at Fillheia.

The path is equipped with a Nera Evolution 128 QAM 155 Mbit/s 1 + 0 radio operating at 13 GHz on vertical polarization. The mode-received input level was found to be −41 dBm, and the radio's SES (Severely Errored Seconds) threshold is −71 dBm. This gives a fading margin of 30 dB.

2.2. Radio Link Measurement

The radio link measurement was performed remotely, using a PC with the Linkmeter software [*Thorvaldsen*, 2010] located in Bergen and polling the radio link at Fillheia through the Internet. The received input level and performance parameters such as SES and UAS (Unavailable Seconds) were monitored at a rate of 0.83 Hz (samples every 1.2 s). The SES and UAS are defined in Rec. ITU-T G.828 [*ITU*, 2000]. SES is a 1 s period which contains 30% or more errored blocks or at least one defect. UAS are periods including 10 or more consecutive seconds of SES. SES measured in UAS periods are subtracted from the overall SES. The accuracy of the received input level measurements was estimated to ±1 dB with a repeatability of ±0.1 dB. It should be noted that the redundant Internet paths to the Fillheia site failed, so the measurements were dependent on the radio link which was measured—i.e., when the signal was below the thresholds for the radios, the contact was lost. However, the SES and UAS accumulated at Fillheia preserved both the performance and unavailability data during the outages.

The radio link measurements started on the 14 December 2009 and lasted until 28 July 2011. Figure 3 shows the percentage of time that the measurements were performed in this period. The two significant periods with lack of data in February and April 2011 were caused by maintenance and PC-crash during Easter. The SES and UAS which are accumulated in the radio link showed that there had been no outages in the periods February and April 2011 when the measurement PC was not operating.

2.3. Meteorological Measurements

All the meteorological data have been collected by the Norwegian Meteorological Institute (NMI). In order to check the causes of fading, weather data from Ørlandet weather station (N 63°42′ E 9°37′, 20 mamsl—close to the Kopparn site and the Fillheia-Kopparn path) was used. The ground-based measurements gave

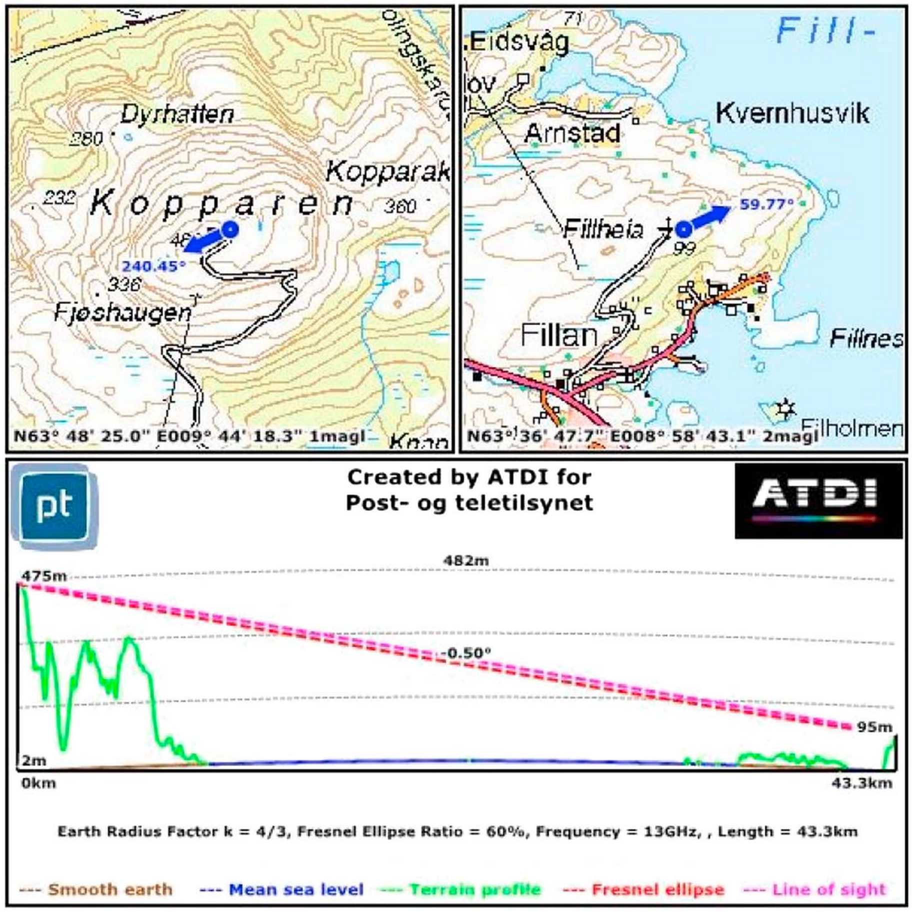

Figure 2. Path profile (dotted lines indicate line of sight and 0.6 Fresnel zone).

temperature, pressure, wind direction, wind speed, cloud cover, snow depth, and weather observation on an hourly basis. The rain was measured with an integration time of 12 h with a standard precipitation gauge of Swedish type with wind shield. In addition to the usual ground-based measurements, the Ørlandet station provided radiosonde data for pressure, dewpoint, and temperature. The radiosonde data have been used to calculate the radio refractivity [*ITU*, 2012b] of the atmosphere as a function of height, and hence to determine if ducts are present during fading.

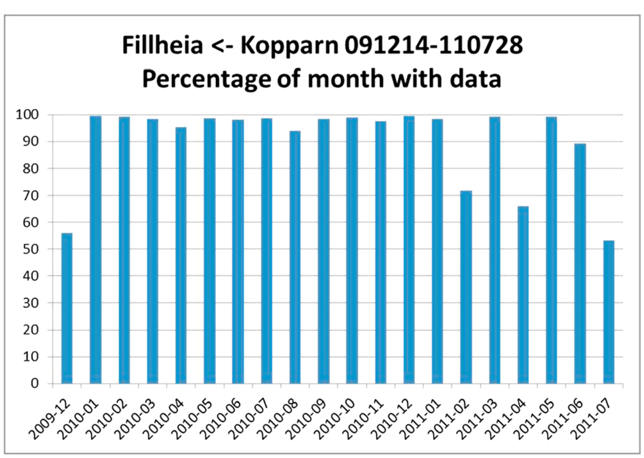

Figure 3. Actual percentage of received level input data per month. (Please observe that the date format in all figure headings is "yymmdd.")

The weather radar at Olsøyheia (N63°41′26″ E10°12′14″) covers the whole path Fillheia-Kopparn with a rate of 4 samples/h, and has been used to check the presence and spatial structure of precipitation during deep fades that has caused the observed outages.

Since Ørlandet weather station lacks information about rain rate exceeded for 0.01% of the time, values from Trondheim (N 63°24′ E 10°25′) have been used. Trondheim is located about

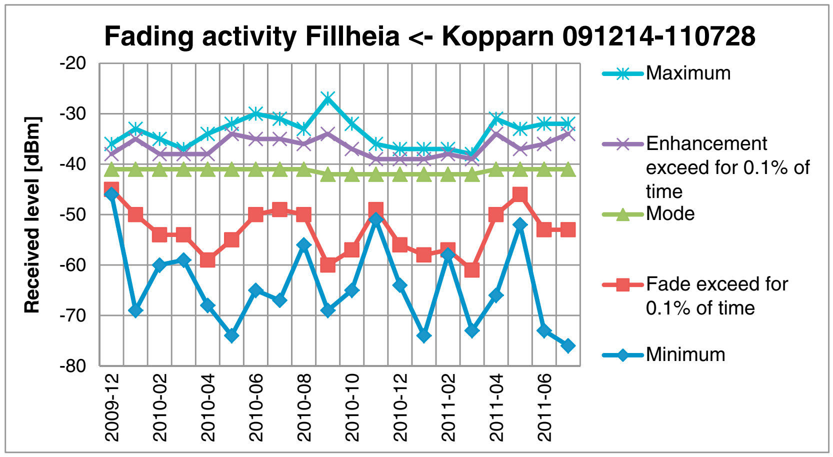

Figure 4. Fading activity in the measurement period.

60 km southeast of the path Kopparn-Fillheia. The Trondheim precipitation gauge is a tipping-bucket pluviometer that records the time for each 0.1 mm of accumulated precipitation. During the winter season the funnel is heated for melting solid precipitation. The algorithm used when transforming from number of tips to precipitation (*rr*) in mm is $rr = A \cdot iv + B \cdot iv^2$, where *iv* is the number of tips and $A = 0.0995$ and $B = 0.0006$ for the Lambrecht sensor. The accumulation time in minutes is well defined when $iv > 1$.

3. Fading and Weather

The expected causes of fading on the Kopparn-Fillheia path were wet snow, hail, rain, and multipath. There was no hail observed at Ørlandet weather station over the measurement period. The path has suffered from fading due to wet snow, rain, and multipath. Multipath fading and rain and wet snow fading are usually mutually exclusive phenomena. Multipath is caused by layering of the atmosphere and seldom occurs during precipitation.

The actual cause of all fades below 10 dB has been identified by looking at the time series of the received input level together with weather data from Ørlandet such as temperature, precipitation, precipitation type, and radio ducts. In addition, weather radar data have been checked for precipitation when fades caused severe outage.

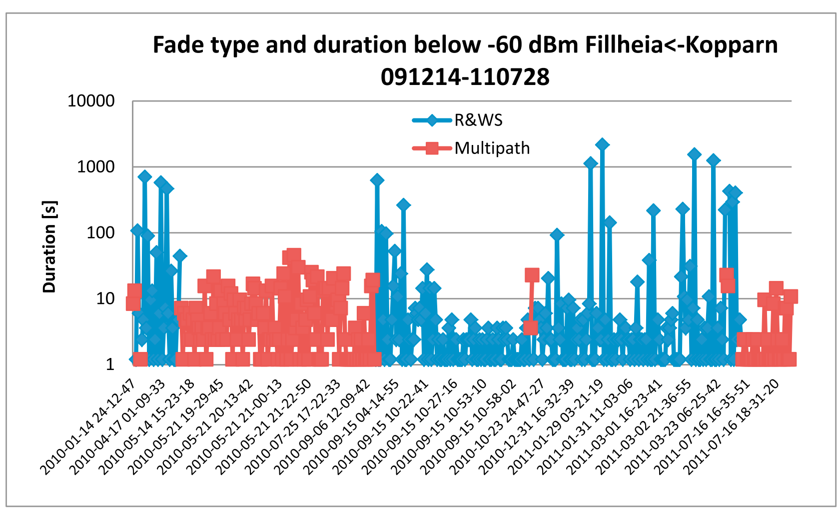

Figure 5. Fade types and duration for fades below −60 dBm.

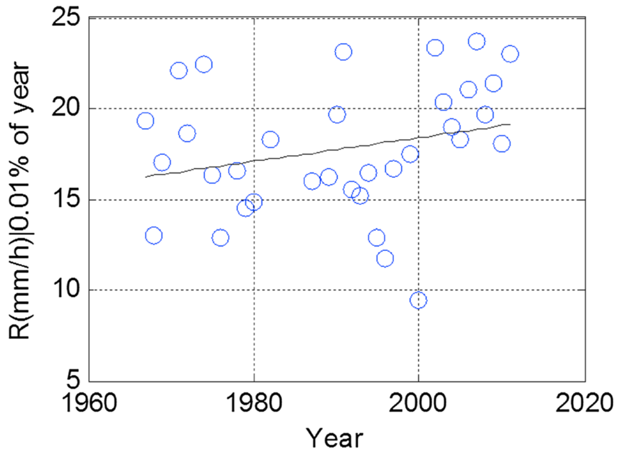

Figure 6. Measurements of rain rate exceeded for 0.01% of the time in Trondheim. Source: T. Tjelta and J. Mamen (Climate trends and variability of rain rate derived from long-term measurements in Norway, private communication, 2014).

According to Figure 4 the fading activity exhibits monthly variations over the measurement period. The figure shows the mode value, fades, and enhancements exceeded for 0.1% of the month and extremal values of the received input level. The figure may also be used to quickly identify the predominant fading type in a given month. When there is no enhancement, but fading, the cause is either rain, wet snow, or a combination. If both enhancements and fading are observed in the same month, the cause is multipath fading, but there can also be additional rain and wet snow fading.

All fades below −60 dBm and their duration for the whole measurement period are shown in Figure 5. This figure clearly shows the seasonality in the fading and its duration. Multipath occurs mostly in the summer, and rain and wet snow fading are predominant in autumn (heavy rain) and winter (wet snow and rain). For fades below −60 dBm, no multipath incident has lasted longer than 45 s, whereas rain and wet snow can last more than 1000 s.

In order to make valid assumptions on the outage caused by rain and wet snow, the measurement period must be sufficiently long to account for the large variability of precipitation. The measurement period was 18 months and short, relative to the long-term measurements on many radio links which the Rec. ITU-R P.530-15 [*ITU*, 2013a] rain and wet snow models are based on. Nevertheless, the measurement period benefitted from having two winter seasons. Since Rec. ITU-R P.530-15 [*ITU*, 2013a] rain and wet snow models are annual, two measurement periods, 2010 and July 2010 to June 2011, have been chosen to indicate year-to-year variability. In order to compare measurement results with the rain and wet snow models, the rain rate exceeded for 0.01% of the time must be known. Ideally, this value should have been known at the middle of the path Kopparn-Fillheia. However, such information is not available,

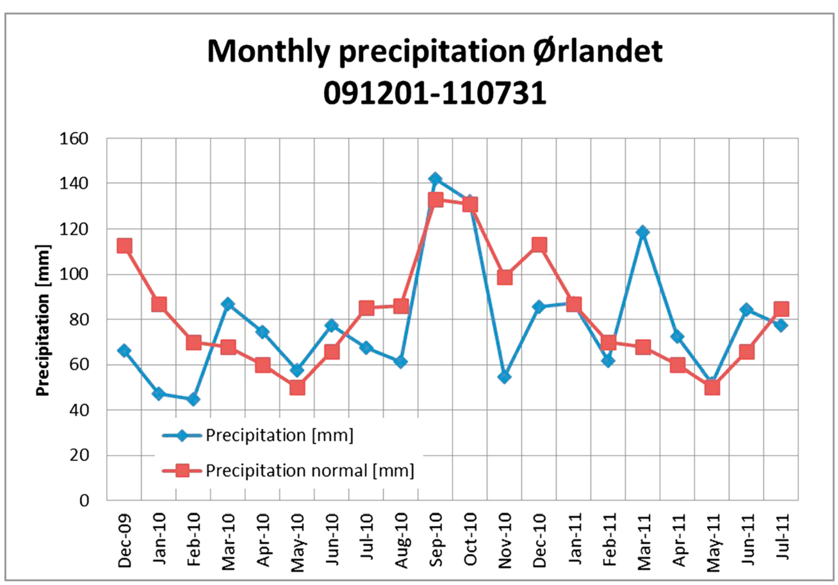

Figure 7. Monthly precipitation for Ørlandet weather station.

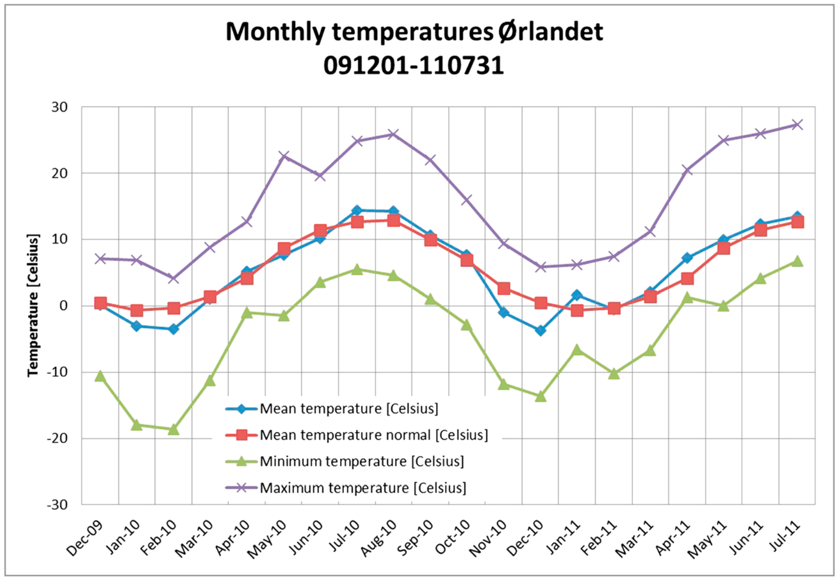

Figure 8. Monthly temperatures for Ørlandet weather station.

and measurements from Trondheim have been used. This is a limitation when comparing models with measurements, but it is better to use actual measured values in the vicinity of the path than to use the annual average found in Rec. ITU-R P.837-6 [*ITU*, 2012a]. The rain rate exceeded for 0.01% of the time in Trondheim was 23 mm/h in 2010 and close to measured annual average value as shown in Figure 6.

The precipitation statistics for Ørlandet weather station on a monthly basis are given in Figure 7. The actual precipitation follows the normal (standard normal period 1961–1990—average over 30 years) quite closely apart from March 2011 which was unusually wet. The figure shows that rain fading should be expected in the autumn, which corresponds to the actual measurements.

Figure 8 shows the temperature in the measurement period. It is interesting to observe that the temperature in the winter of 2011 was slightly higher than that in 2010. This fact, combined with more precipitation in March 2011, gave more wet snow and rain outage in the latter year.

Table 1. Outage Incidents

#	Date[a] and Time	SES	UAS	Fading Type
1	2010/01/14, 00:21:06	2		Multipath
2	2010/05/21, 16:53:02–21:26:25	43	10	Multipath
3	2010/05/22, 00:54:59	2		Multipath
4	2010/06/11, 00:16:30–00:44:17	5		Multipath
5	2010/07/24, 15:25:56	2		Multipath
6	2010/07/25, 14:40:26	1		Multipath
7	2010/08/24, 13:52:23–14:04:45		245	No fading activity
8	2010/09/06, 10:51:34–18:06:27	22		Multipath
9	2011/01/29, 03:31:29–03:50:55	21	888	Wet snow/rain
10	2011/03/04, 11:40:09–11:46:11	1	333	Wet snow/rain
11	2011/03/22, 08:43:38–08:55:47	1	711	Wet snow/rain
12	2011/06/09, 18:11:5–18:21:45		340	Rain
13	2011/07/16, 16:15:03–18:58:48	19		Multipath
14	2011/07/19, 04:47:08	1		Multipath
15	2011/07/21, 10:14:23	2		No fading activity

[a]Dates are formatted as year/month/day.

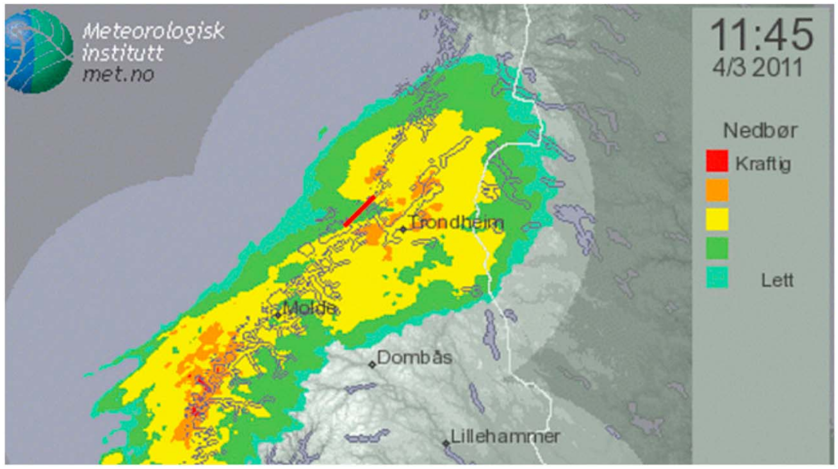

Figure 9. Screenshot from www.met.no weather radar in Trøndelag. Nedbør = Precipitation, Kraftig = Heavy, and Lett = Light.

There were 15 incidents that resulted in outages during the measurement period. Table 1 shows the particular incidents, their duration and cause. The largest numbers of outages were caused by multipath, but outages due to wet snow and rain lasted much longer and dominated the overall outage. The cause of each incident was found by using weather data such as precipitation and temperature at ground level and radiosonde data at Ørlandet weather station. In addition, data from the weather radar at Olsøyheia for the time of the incidents were inspected.

As an example, the wet snow and rain fading event of 4 March 2011 is presented. Figure 9 shows precipitation along the whole path at the time of fading, and Figure 10 shows the accompanying time plot of the event.

At Ørlandet, between 11:00 and 12:00, the wind turned from southwest to northwest, the temperature dropped from 5.5 to 2.2°C, and the weather observed changed from Moderate rain (WW SYNOP CODE 63)

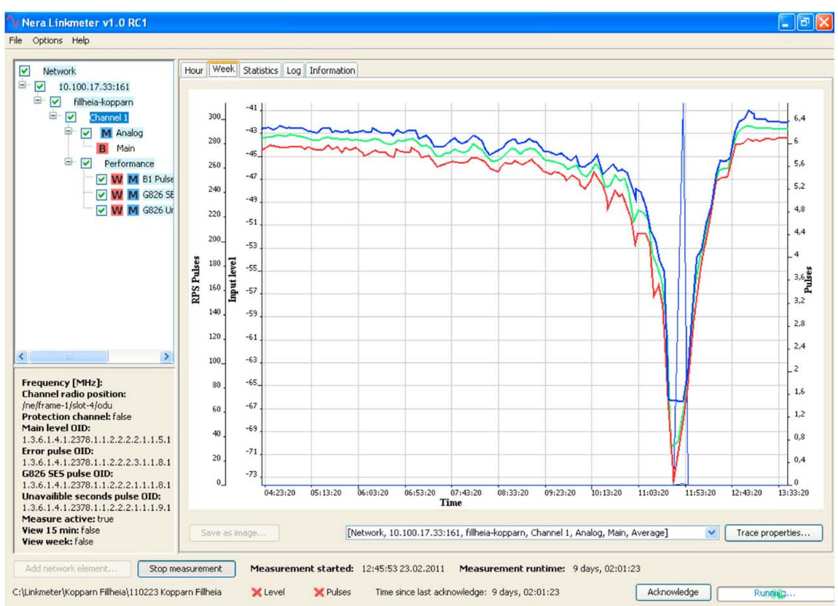

Figure 10. The rain and wet snow fade incident at 11:45 on 4 March 2011. The event caused 313 s of UAS. The measurements are presented with 5 min resolution, and the blue line indicates the highest received input level in the 5 min period, the red one the lowest, and green the average. The blue spike indicates measured errors.

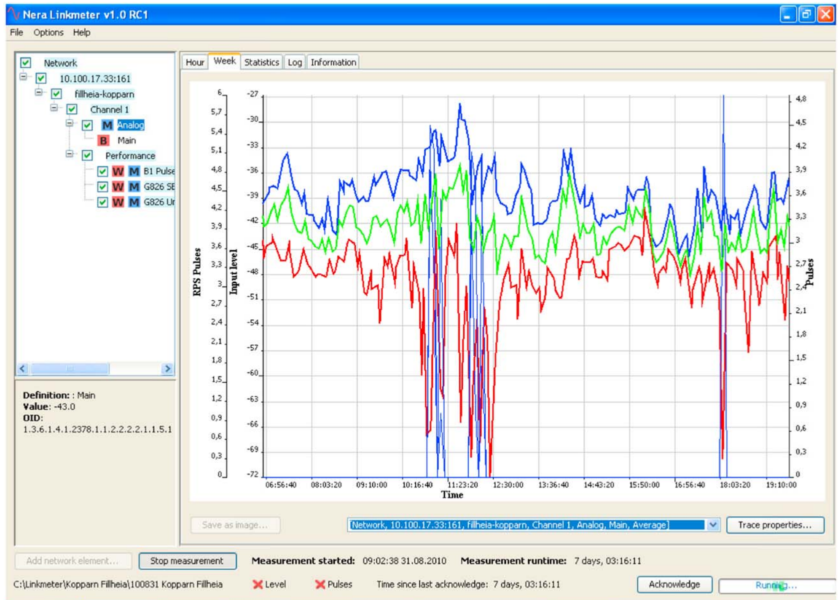

Figure 11. Multipath fading 6 September 2010 giving 22 s of SES.

to Light wet snow (sleet) (WW SYNOP CODE 68). The incidents of 29 January 2011 and 22 March 2011 occurred under similar weather conditions. By comparing weather radar data for the path Kopparn-Fillheia and Trondheim, where accurate rain measurements have been performed, the rain rate during the combined wet snow and rain events is estimated to about 10 mm/h. The rain rate was close to 70 mm/h at the incident with rain only on 9 June 2011. Combined rain and wet snow gives longer outages at lower rain rates. This has also been observed by others as reviewed by *Tjelta and Bacon* [2010].

In addition to fading due to rain and wet snow, the path also experienced over-water multipath fading. A typical scenario is shown in Figure 11. It starts with rapid variations in the received input level which are deep enough to cause errors, and then some hours after there is heavier fading, giving more errors.

If Figure 11 is compared to weather measurements from Ørlandet shown in Figure 12, it becomes apparent that this was a day favorable for multipath fading. The fading activity is highest when the temperature has its most rapid changes.

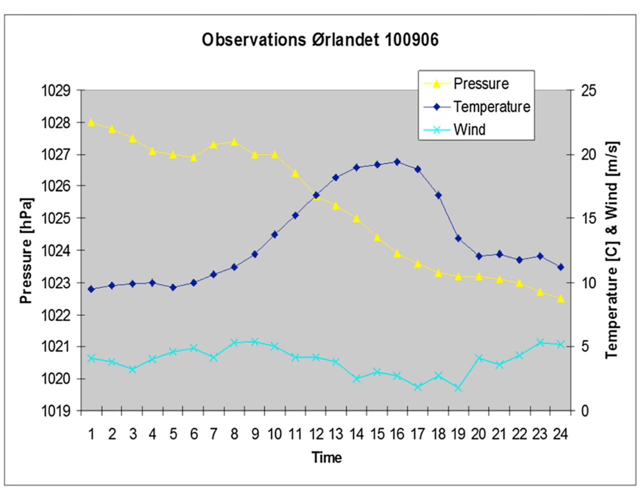

Figure 12. Measured weather at Ørlandet 6 September 2010.

The radiosonde data recorded at Ørlandet on 6 September 13:00 (the dark blue line in Figure 13) shows the presence of a radio duct between 200 m and 400 m up in the air which cause the multipath fading experienced that day. The additional purple line shows the drop in N in a normal standard atmosphere (−40 N/km) where no multipath occur.

All the incidents in Table 1, which have been classified as multipath, coincide with radiosonde measurements that show ducts in the lower part of the atmosphere. It is also interesting to observe that the heaviest multipath fading occurs during daytime. This

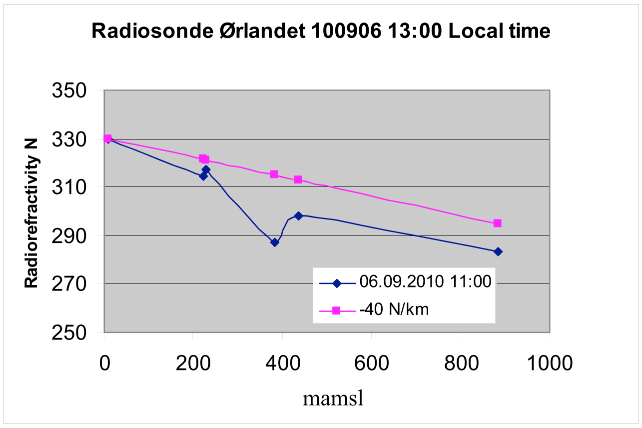

Figure 13. Radiosonde data from Ørlandet 6 September 2010.

observation is quite different from those typical for inland paths, were multipath usually is a night and/or morning phenomena.

4. Predictions

The predictions are based on the Rec. ITU-R P.530-15 [*ITU*, 2013a].

4.1. Rain

The applied rain rate exceeded for 0.01% of the time is 23 mm/h, as measured in Trondheim in 2010. The specific rain attenuation at $R = 23$ mm/h for the path on vertical polarization is $\gamma_r = kR^{\alpha} = 1.0$ dB/km and was calculated using the methods in ITU-R P.838-3 [*ITU*, 2005b]. The distance factor r is given by

$$r = \frac{1}{0.477d^{0.633}R_{0.01}^{0.073\alpha}f^{0.123} - 10.579(1 - \exp(-0.024d))} \tag{1}$$

where f (GHz) is the frequency, d (km) is the path length, and α is the exponent in the specific attenuation model. The estimated path attenuation for 0.01% of the time is $A_{0.01} = \gamma_R d_{\text{eff}} = \gamma_R dr = 1.0 \cdot 18.93$ dB. The attenuation for other percentages of the time p in the range 0.001% to 1% is deduced from

$$\frac{A_p}{A_{0.01}} = C_1 p^{-(C_2 + C_3 \log_{10} p)} \tag{2}$$

For $f = 13$ GHz, $C_1 = 0.11$, $C_2 = 0.59$, and $C_3 = 0.058$. The estimated yearly outage due to rain with the 30 dB fading margin is 0.002428% (755 s = 12.6 min). If the old rain model is used Rec. ITU-R P.530-13 [*ITU*, 2009], some of the parameters will be slightly different, $d_{\text{eff}} = 15.7$ km, $C_1 = 0.12$, $C_2 = 0.546$, and $C_3 = 0.043$, resulting in less predicted attenuation and the estimated yearly outage is 0.001467% (456 s = 7.6 min).

4.2. Combined Rain and Wet Snow

The median rain height H_{rainm} was obtained from Rec. ITU-R P.839-4 [*ITU*, 2013b] where Figure 1 in this recommendation shows $h_0 = 1$ km yearly average for the 0°C isotherm height above mean sea level (km) where the path is located. $H_{\text{rainm}} = h_0 + 0.36$ km = 1.360 km. Then the rain height at the center of the link path H_{link} is calculated.

$$h_{\text{link}} = 0.5(h_1 + h_2) - \left(\frac{d^2}{17}\right) \text{mamsl} \tag{3}$$

The height of the link terminals are $h_1 = 475$ mamsl and $h_2 = 95$ mamsl, and d is the path length in km. The rain and wet snow attenuation A_{rs} as a function of A_p can be found following the iterative procedure given in Rec. ITU-R P.530-15 [*ITU*, 2013a]. For the path Kopparn-Fillheia the relationship is given by

$$A_{\text{RS}} = 1.26 \cdot A_p \tag{4}$$

The estimated yearly outage due to rain and wet snow with the 30 dB fading margin is 0.005127% (1595 s = 26.6 min). If the old rain model is used Rec. ITU-R P.530-13 [*ITU*, 2009], some of the parameters will be slightly different, $d_{\text{eff}} = 15.7$ km, $C_1 = 0.12$, $C_2 = 0.546$, and $C_3 = 0.043$, resulting in less predicted attenuation and the estimated yearly outage is 0.003053% (950 s = 15.8 min).

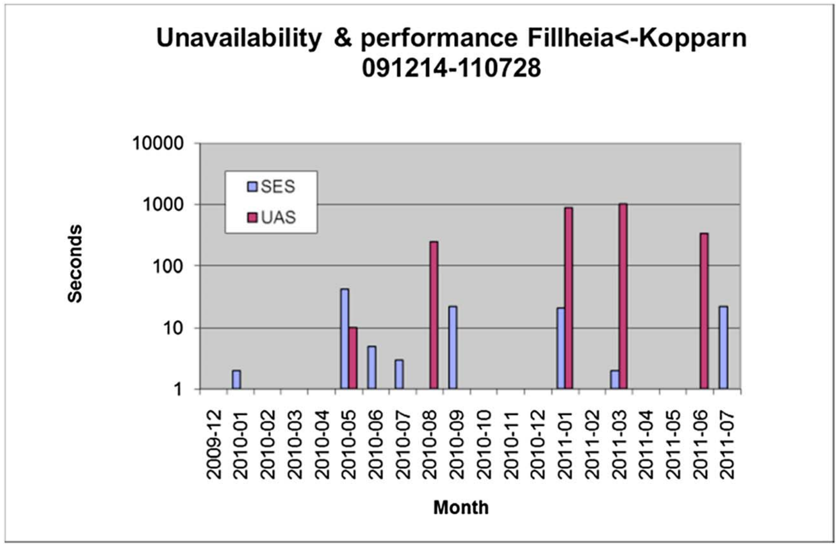

Figure 14. Measured unavailability and performance from month to month.

4.3. Multipath

Multipath fading consists of flat and selective fading due to layering of the atmosphere. To calculate the amount of flat fading the method for small percentages of the time given in Rec. ITU-R P.530-15 [*ITU*, 2013a] is used. This method starts with estimating the geoclimatic factor K for the average worst month.

$$K = 10^{-4.4-0.0027dN_1}(10 + s_a)^{-0.46} \tag{5}$$

dN_1 which is the point refractivity in the lowest 65 m of the atmosphere not exceeded for 1% of an average year, has been found in Rec. ITU-R P.453-10 [*ITU*, 2012b] to have a value of −400 at the path. The parameter s_a is the standard deviation of terrain heights (m) within a 110 km × 110 km area with 30 s resolution. The value $s_a = 116.8$ (64 N, 9.5 E) for the path was found using the map available from ITU-R Study Group 3 Web site. This gives $K = 5.15 \cdot 10^{-5}$.

The path inclination is $|\varepsilon_p| = \frac{|h_r - h_e|}{d} = \frac{|475-95|}{43.3} = 8.76$ mrad. h_r and h_e are antenna heights in mamsl, and d is the path length in km. The percentage of time p_w when the fade depth A (dB) is exceeded in the average worst month is

$$p_w = Kd^{3.4}(1 + |\varepsilon_p|)^{-1.03} f^{0.8} \cdot 10^{-0.00076h_L - \frac{A}{10}} \tag{6}$$

where f is frequency (GHz) and h_L is the altitude of the lower antenna.

The selective outage probability in percent is found using

$$P = 4.3 \cdot 10^{-1} \eta \cdot sf \cdot \frac{{\tau_m}^2}{\tau_0} \tag{7}$$

Where $\eta = 1 - \exp\left(-0.2 \cdot \left(\frac{P_0}{100}\right)^{0.75}\right)$ and $\tau_m = 0.7 \cdot \left(\frac{d}{50}\right)^{1.3}$. P_0 is the value of p_w at $A = 0$. The radio link signature factor is measured by the manufacturer to be $1.2 \cdot 10^{-3}$ using $\tau_0 = 6.3$ ns.

Table 2. Measured Outage Compared to Rec. ITU-R P.530 Models

	Prediction (s)	May 2010 Measurement (s)	2010 Measurement (s)	July 2010 to June 2011 Measurement (s)
Worst month multipath	61,8	53		
P.530-15 combined rain and wet snow	1595		0	2295
P.530-13 combined rain and wet snow	950		0	2295

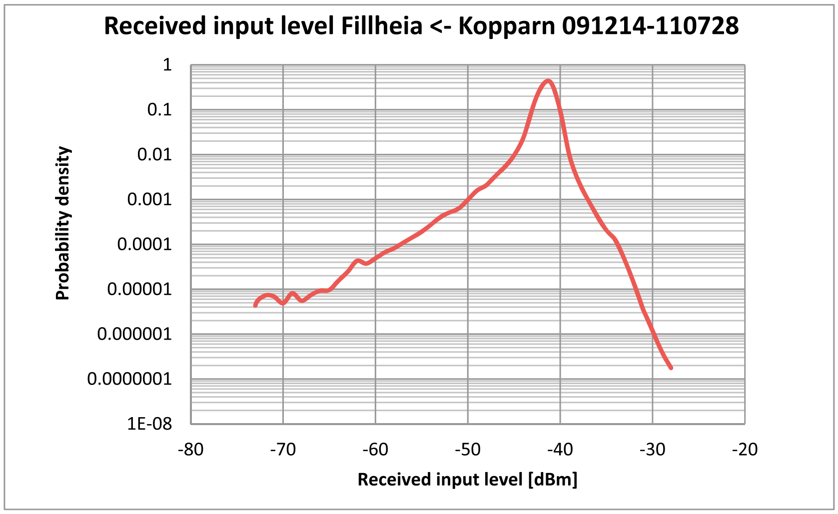

Figure 15. Received input level distribution.

The predicted outage due to multipath flat fading with the fading margin of 30 dB is 0.002065% (54 s). The outage due to selective multipath fading is $3.0 \cdot 10^{-4}$% (7.8 s). For this path the flat part of the multipath fading is dominant.

5. Measurement Results

5.1. Measured Unavailability and Performance

The performance of the radio link varied from month to month and from one year to another as expected due to the statistical nature of fading. The paramount fading was due to rain and wet snow.

As seen from Figure 14, March 2011 was the month with most fading activity. The figure also shows that the winter of 2011 had much more fading activity than the winter of 2010. This underlines the importance of measuring more than one winter in order to get an indication of the year-to-year variation.

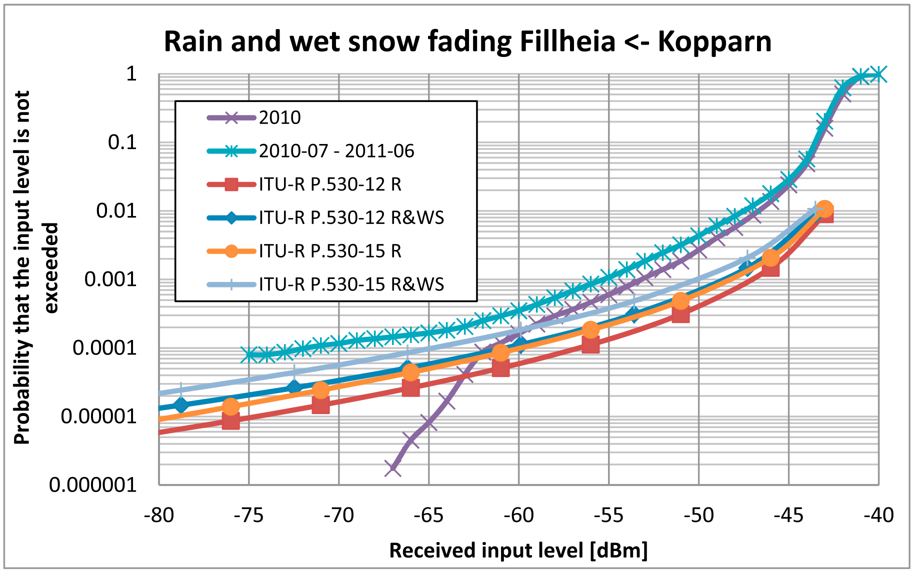

Figure 16. Rain and wet snow received input level distribution.

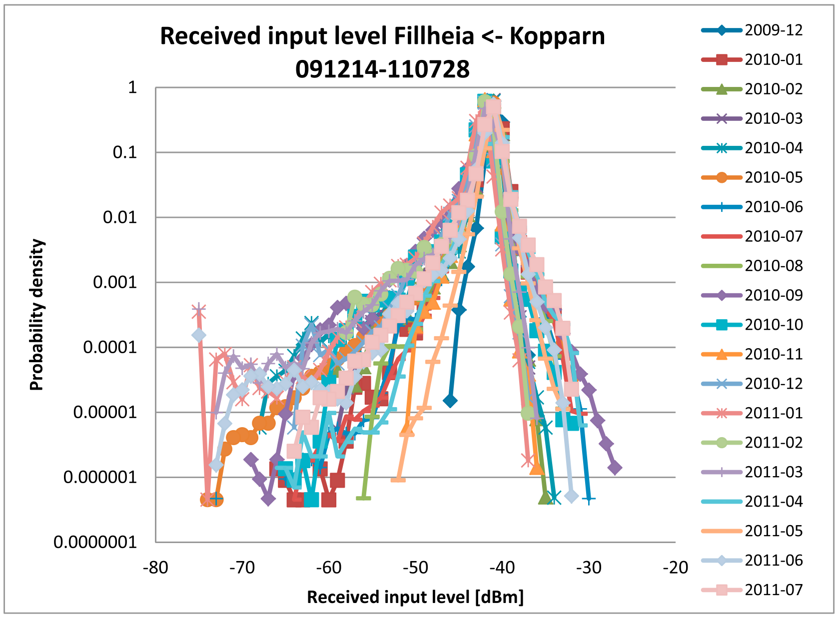

Figure 17. Monthly received input level distribution.

Figure 14 shows large variations from month to month. Little outage due to wet snow activity was measured the first winter. In the spring and autumn there was some outage due to over-water multipath fading effects. The next winter had much more rain and wet snow outage due to higher temperature than the previous winter, see Figure 8. The UAS event in August 2010 was not caused by fading activity. The spring month of May in 2010 was the month with most multipath errors-SES (43 s) and UAS (10 s). Two days with fading during daytime caused these errors. Table 2 shows predicted versus measured outage. As seen from the table, there is large variation in measured outage due to combined rain and wet snow from year to year and the measured values also deviate from the predicted ones. This is to be expected, since outages with the given fading margin occur for small percentages of the time.

5.2. Distributions

In order to compare the measurements with models for rain and wet snow and multipath, the collected received input level samples have been separated when needed. All fades deeper than 10 dB have been identified as either multipath or rain and wet snow. Ten decibels was selected as the limit for practical reasons and the fact that radio link planning is mostly concerned with deep fades.

The received input level distribution for the whole measurement period is shown in Figure 15. It includes fades due to rain, wet snow, and multipath. The measured enhancement is due to multipath only. The mode input level was around −41 dBm, and the signal level varied from lower than −71 dBm to larger than −30 dBm.

Figure 16 presents the measured rain and wet snow level distribution for the two annual periods 2010 and July 2010 to June 2011 of measurements together with the Rec. ITU-R P.530-12 [*ITU*, 2007] and Rec. ITU-R P.530-15 [*ITU*, 2013a] prediction curves for outage due to rain and combined rain and wet snow. Both periods of measurement show more outage than predicted. The measurement graphs diverge for deep fades due to year-to-year variation of combined rain and wet snow. The period July 2010 to June 2011 that has the most rain and wet snow is closest to the rain and wet snow prediction curves for deep fades.

5.3. Distributions From Month to Month

The distributions for the various months in Figure 17 show large variations as expected. The distributions are derived from all samples measured with an interval of 1.2 s. The months experiencing most fading are the winter months January and March 2011. The predominant fading mechanism was rain and wet snow. Most enhancements were seen in June 2010, September 2010, and July 2011.

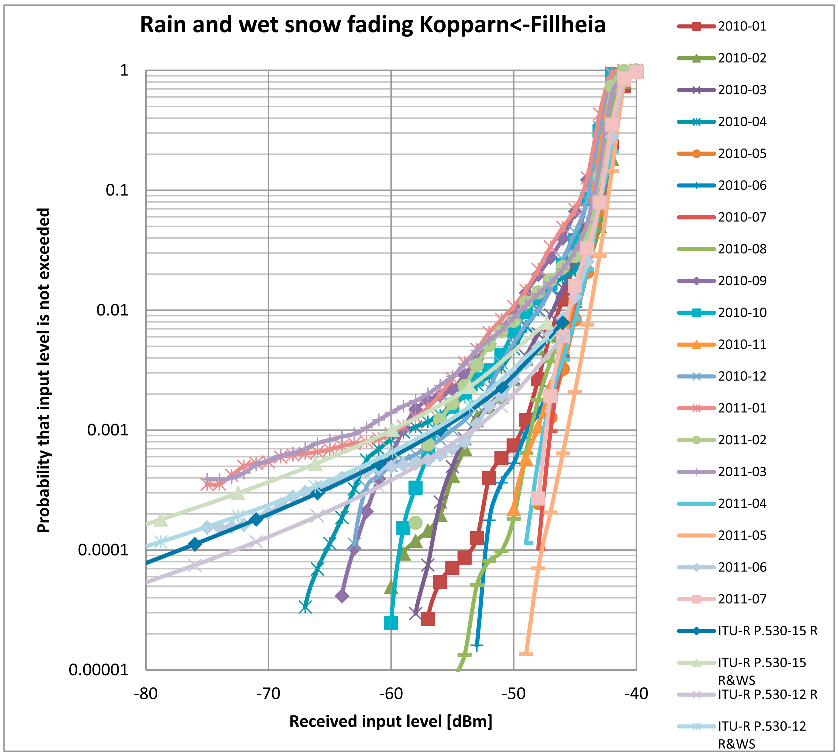

Figure 18. Monthly rain and wet snow received input level distribution and prediction curves.

Figure 18 shows the monthly probability that the input level has been exceeded due to rain and wet snow during the measurement period. The theoretical curves for rain and wet snow are included. The monthly precipitation prediction curves are based on the yearly ones using the conversion formulas given in Rec. ITU-R P.841-4 [*ITU*, 2005a]. There is a resemblance in curve slopes between prediction and actual measurements for the worst months of combined rain and wet snow (January and March 2011), but more fading than predicted is measured. The fading due to rain measured in June 2011 resembles the Rec. ITU-R P.530-15 [*ITU*, 2013a] prediction.

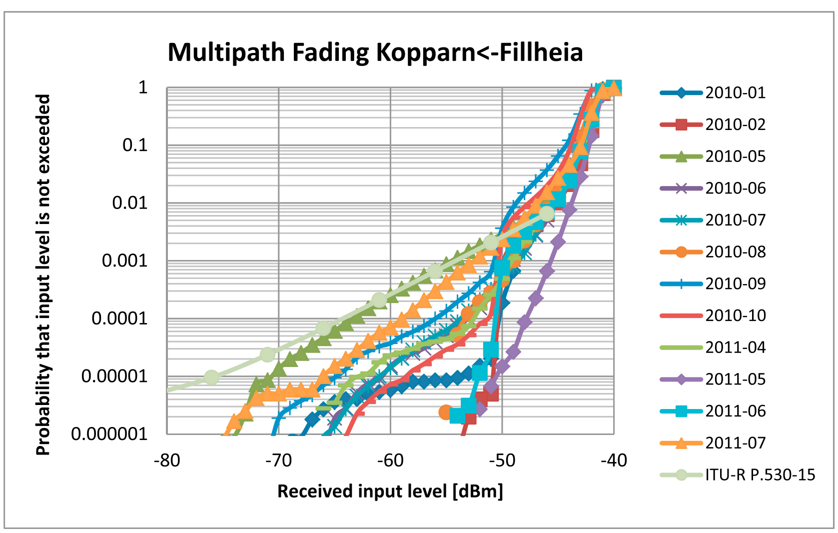

Figure 19. Monthly received multipath input level distribution and prediction curve.

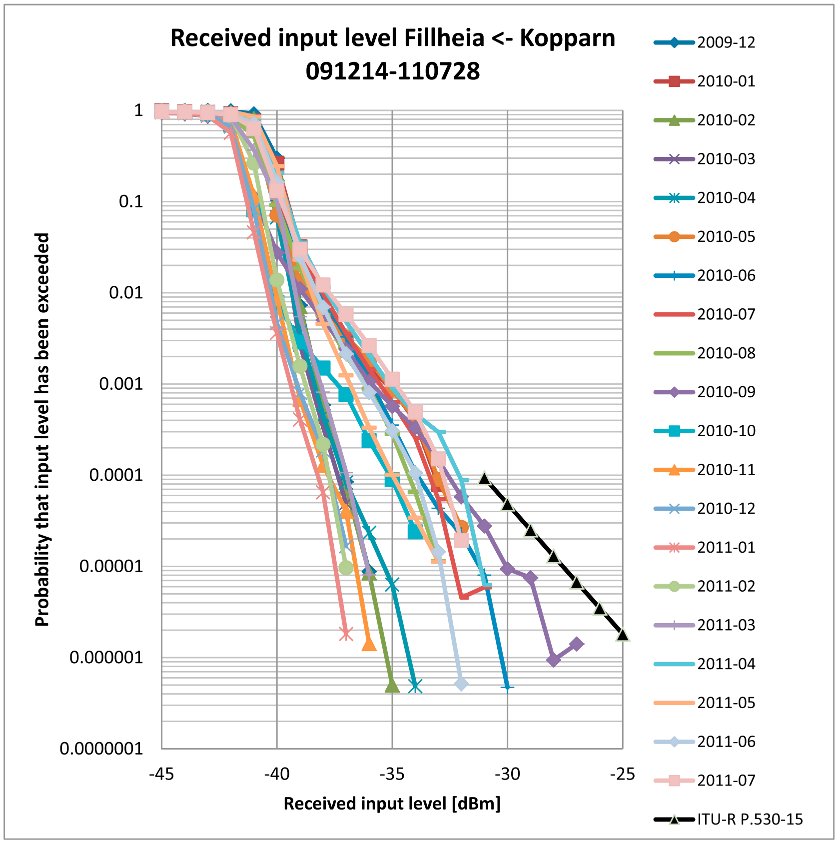

Figure 20. Monthly received enhancement level distribution.

Figure 19 presents the monthly probability that the input level has been exceeded due to multipath activity in the measurement period for months having multipath fades which are deeper than 10 dB. The Rec. ITU-R P.530-15 [*ITU*, 2013a] prediction of worst month multipath is included. The measurement for the worst month (May 2010) is in agreement with the prediction. The odd behavior of the graphs for September and October 2010 are caused by the fact that only rain and wet snow fading larger than 10 dB have been removed.

Figure 20 displays the monthly received enhancement level distribution. September 2010 was the month with the largest enhancement. In Rec. ITU-R P.530-15 [*ITU*, 2013a], a method for predicting average worst month enhancement is given:

$$p_{\text{enhancement}} = 10^{(-1.7+0.2A_{0.01}-E)} \ \% \quad \text{for } E > 10 \text{ dB} \tag{8}$$

where E (dB) is the enhancement exceeded for $p_{\text{enhancement}}$ (%) of the time and $A_{0.01} = 23$ dB is the predicted deep fade depth using (6). Figure 20 shows that the worst months tend to match the prediction.

5.4. Number, Duration, and Speed of Events

Rec. ITU-R P.530-15 [*ITU*, 2013a] contains formulas for calculating the expected number of fades longer than 10 s for a given fade depth both for rain and multipath.

For rain the formula is given by

$$N_{10s}(A) = 1 + 1313[p(A)]^{0.945} \tag{9}$$

where $p(A)$ is the percentage of time that the rain attenuation A(dB) is exceeded in the average year. Since the path Kopparn-Fillheia also experienced combined rain and wet snow attenuation, the *p(A)* for rain and wet snow is included in Figure 13. This latter prediction of the number of fades comes closest to what was measured.

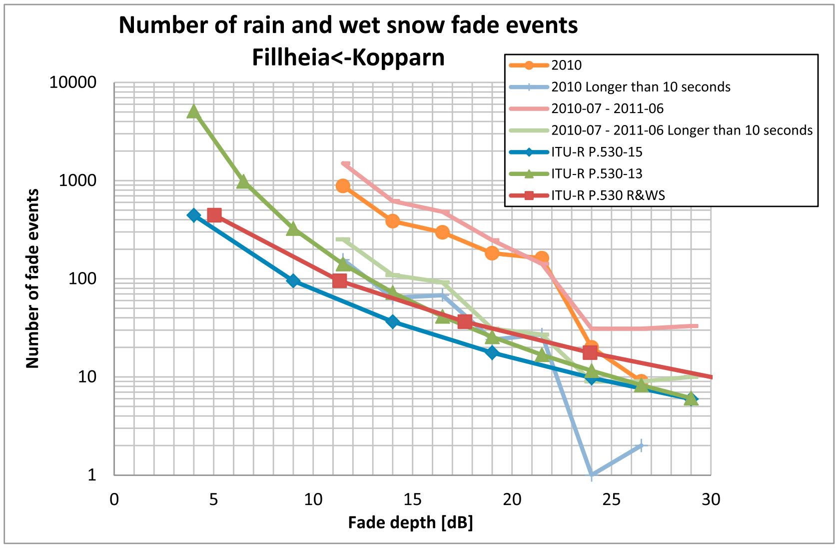

Figure 21. Number of rain and wet snow fade events compared with ITU-R models.

Rec. ITU-R P.530-13 [*ITU*, 2009] has information regarding the duration and number of events due to rain fading. The number of fades (10 s or longer) for this path was given by

$$N_{10s} = aA^b \quad a = 5.7 \times 10^5 \quad b = -3.4 \tag{10}$$

where N_{10s} is the number of fades, A [dB] the fade depth, and a and b are constants. In *Thorvaldsen and Kvicera* [2012], similar results are presented from a 26 GHz path in the Czech Republic. The measurements follow a power law distribution as given in equation (10), but the coefficients were different and the number of fades somewhat higher than in *ITU* [2009].

For the Kopparn-Fillheia path, where there is also substantial fading activity due to combined rain and wet snow, it is interesting to see that the number of fades (Figure 21) resembles the model (10) based on rain fading only. The total number of rain and wet snow fades has also been measured and amounts to roughly 5 times more than the estimated number of fades longer than 10 s.

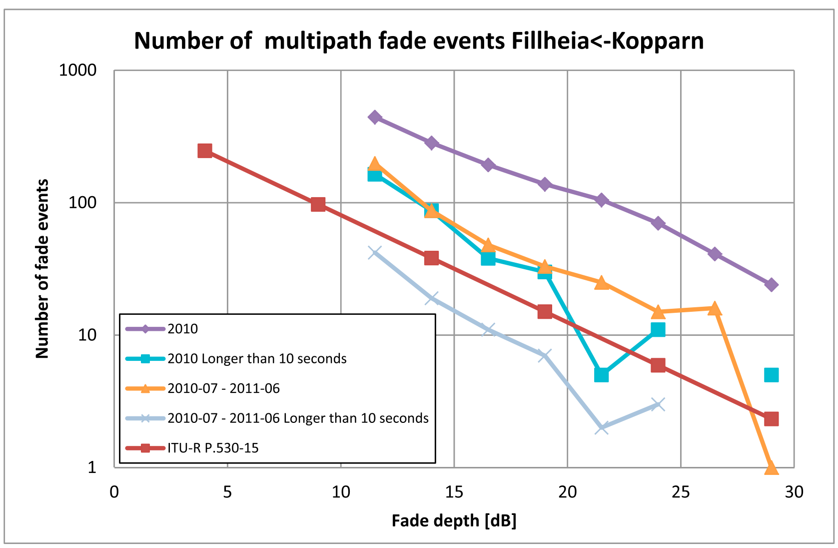

Figure 22. Number of multipath fade events compared with ITU-R model.

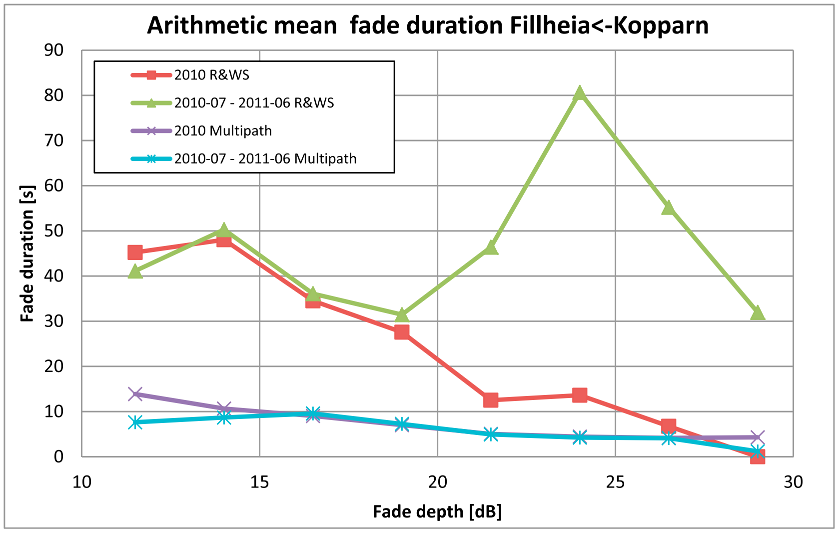

Figure 23. Arithmetic mean fade duration.

Rec. ITU-R P.530-15 [*ITU*, 2013a] has introduced a new formula for calculating the average number of N_{10s} due multipath:

$$N_{10s}(A) = 1425[p(A)]^{0.841} \quad (11)$$

The annual *p*(*A*) is found from the $p_w(A)$ in (6) using the following formulas:

$$p(A) = 10^{-\frac{\Delta G}{10}} p_w(A) \quad (12)$$

$$\Delta G = 10.5 - 5.6 \log\left(1.1 - |\cos 2\xi|^{0.7}\right) - 2.7 \log(d) + 1.7 \log\left(1 + |\varepsilon_p|\right) \quad (13)$$

where ξ is the latitude. For the path Kopparn-Fillheia, $\Delta G = 8.6$. As seen from Figure 22, the model estimate of the number of fades longer than 10 s is less than what was measured in 2010, but more than what was measured in July 2010 to June 2011.

Figure 23 shows the arithmetic mean of fade duration for fade depths in the range of 11.5 to 29 dB. The graphs are not cumulative. The fade duration of combined rain and wet snow is longer than for multipath as

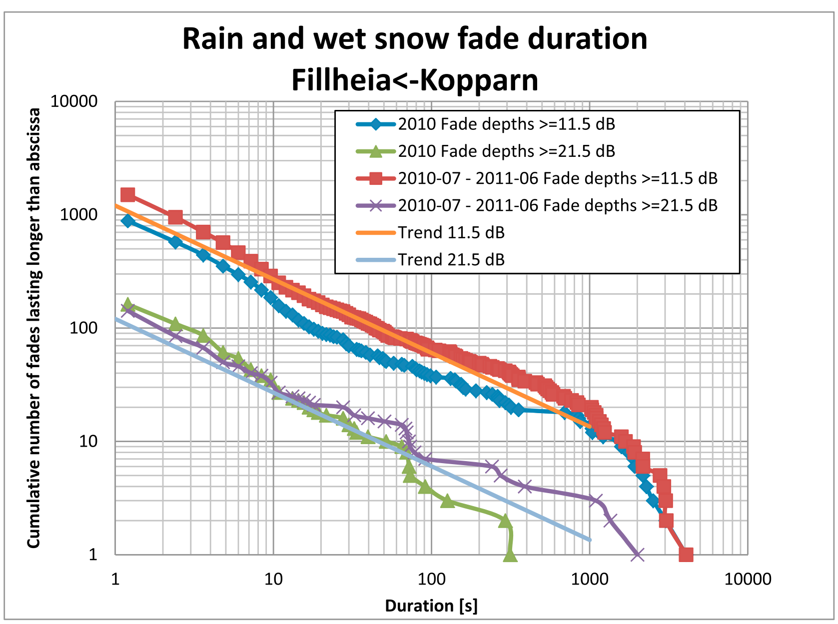

Figure 24. Number of fades and duration due to rain and wet snow.

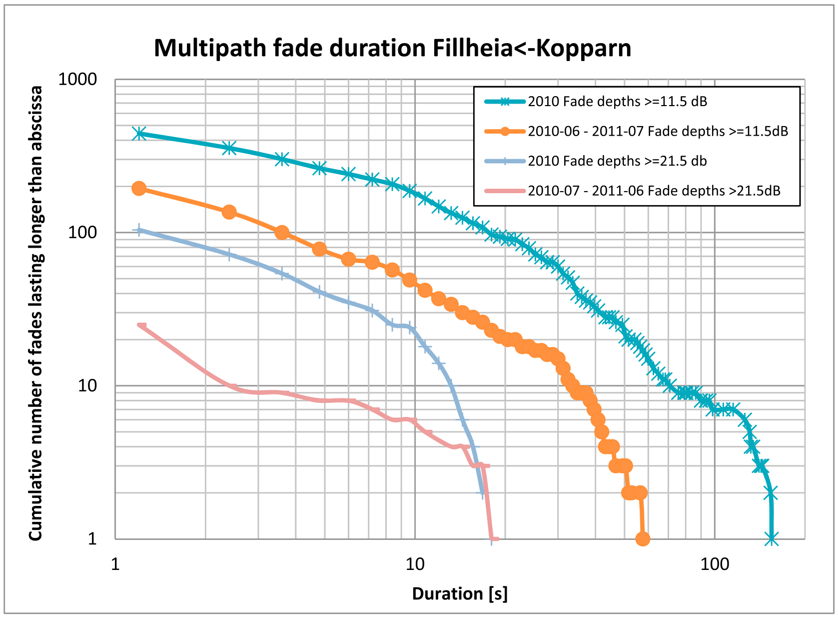

Figure 25. Number of fades and duration due to multipath.

expected due to different causes of the fade types. The large arithmetic mean for large fade depths for combined rain and wet snow in the period July 2010 to June 2011 is a result of having some very long-lasting events.

Figure 24 presents the cumulative number of fades versus the duration for various fade depths for combined rain and wet snow. The graphs show a log-log tendency for cumulative number of fades larger than 10. The graphs for fade depths of 21.5 dB demonstrate the annual variation due to more combined rain and wet snow in the period July 2010 to June 2011. A formula for estimating the trends for the graphs in Figure 24 is as follows:

$$N_{\mathrm{cum}}(A, t) = 17000 \cdot 10^{-A/10} \cdot t^{-0.65} \tag{14}$$

where A is fade depth and t is the fade duration.

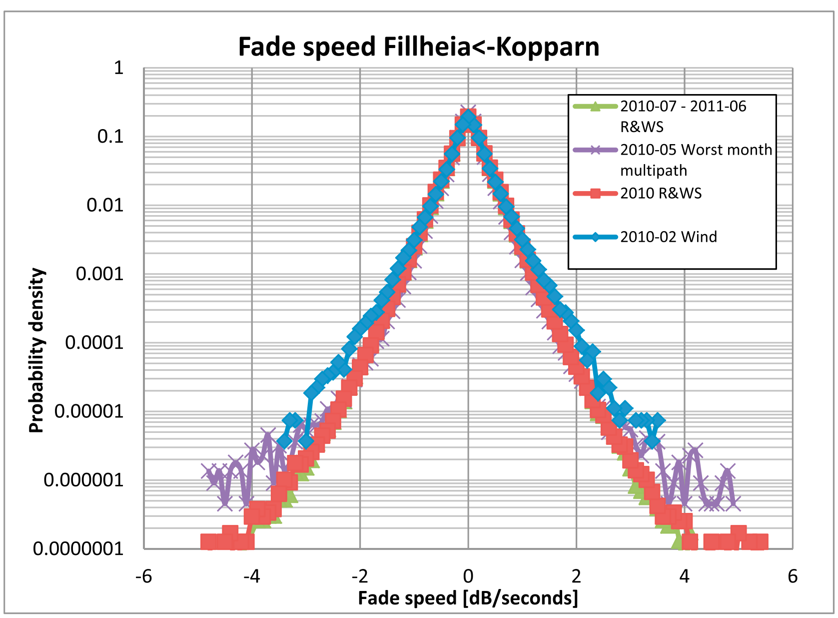

Figure 26. Fade speed.

Figure 25 presents the cumulative number of fades versus duration for various fade depths for annual multipath fades. The number of multipath fade duration was larger in 2010 than in the period July 2010 to June 2011. The large difference in duration of fades between rain/wet snow and multipath can be seen by comparing Figures 24 and 25.

Rain and wet snow fading is a slow process compared to multipath fading. The fading speed is shown in Figure 26 for the two annual periods with combined rain and wet snow and for the worst month with multipath. The higher fade speed measured in February 2010 was due to heavy wind and unwanted movements of the receiving antenna.

6. Conclusion and Further Work

An 18 month long measurement on an in-service radio link was successfully conducted. The path experienced outages due to fading caused by multipath, rain, and wet snow. Outages due to combined rain and wet snow were found to be dominant. The fading due to combined rain and wet snow was found to resemble the shape of the model given in Rec. ITU-R P. 530-15 [*ITU*, 2013a], but the model underpredicts the measurements. The amount of rain and wet snow and its effect on the radio link performance varied from year to year. The last part of the measurement period had the most outage caused by combined rain and wet snow. The mean temperature during the last winter was higher—around the freezing point—than the first winter, and the amount of precipitation was also larger during the last year in the month of excessive fading due to rain and wet snow. Also, the number of rain and wet snow fades longer than 10 s are in accordance with the model based on rain given in Rec. ITU-R P. 530-15 [*ITU*, 2013a]. The multipath fading for the worst month (May 2010) followed the model, and the measured outage was in accordance with the predictions. The number of fades due to multipath was also in accordance with the Rec. ITU-R P.530-15 [*ITU*, 2013a] model. Rec. ITU-R P.530-15 states a lack of information about the number of fades at given fade depths as well as duration distributions. Such distributions have been presented in this paper.

In the further work, radio link data will be compared with weather radar data from Olsøyheia. By correlating the received input level from the radio link to radar reflectivity measurements along the path, more detailed information about precipitation types and spatial attenuation may be found. The radar measurements can also be used to find the vertical precipitation structure and the variation in the 0°C isotherm height above mean sea level. Since the Rec. ITU-R P.530-15 [*ITU*, 2013a] underestimates the amount of combined rain and wet snow fading for the path Kopparn-Fillheia, also other models will be investigated in the future to see if they better match the measurements.

Acknowledgments
The authors would like to thank Nera Networks and Trønderenergi for their kind support during this project. We also thank the former students at Bergen University College Øystein Taskjelle, Espen Steine and Hans-Even Ramsevik Riksem for developing the splendid tool Linkmeter, and Øystein Waage and Erlend Bjerke Gabrielsen for postprocessing software and initial analysis. We are also grateful to Florin Turcu for help on improving the language. Last, but not the least, we would like to thank Jostein Mamen at the Norwegian Meteorological Institute for weather data and kind support.

References

International Telecommunication Union (ITU) (2000), *Error Performance Parameters and Objectives for International, Constant Bit-Rate Synchronous Digital Paths*, Recommendation ITU-T G.828, International Telecommunication Union, Geneva.

International Telecommunication Union (ITU) (2005a), *Conversion of Annual Statistics to Worst-Month Statistics*, Recommendation ITU-R P.841-4, International Telecommunication Union, Geneva.

ITU (2005b), *Specific Attenuation Model for Rain for Use in Prediction Methods*, Recommendation ITU-R P.838-3, International Telecommunication Union, Geneva.

International Telecommunication Union (ITU) (2007), *Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-of-Sight Systems*, Recommendation ITU-R P.530-12, International Telecommunication Union, Geneva.

International Telecommunication Union (ITU) (2009), *Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-of-Sight Systems*, Recommendation ITU-R P.530-13, International Telecommunication Union, Geneva.

International Telecommunication Union (ITU) (2012a), *Characteristics of Precipitation for Propagation Modelling*, Recommendation ITU-R P.837-6, International Telecommunication Union, Geneva.

ITU (2012b), *The Radio Refractive Index: Its Formula and Refractivity Data*, Recommendation ITU-R P.453-10, International Telecommunication Union, Geneva.

International Telecommunication Union (ITU) (2013a), *Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-of-Sight Systems*, Recommendation ITU-R P.530-15, International Telecommunication Union, Geneva.

ITU (2013b), *Rain Height Model for Prediction Methods*, Recommendation ITU-R P.839-4, International Telecommunication Union, Geneva.

Thorvaldsen, P. (1996), Measurement results from a 50 kilometre 15 GHz path, ECRR 96 Fifth European Conference on Fixed Radio Systems and Networks.

Thorvaldsen, P. (2000), Co-channels everywhere, ECRR 2000 Seventh European Conference on Fixed Radio Systems and Networks.

Thorvaldsen, P. (2010), Linkmeter—The Swiss Army Knife of Radio Relay, The Fourth Libyan Arab International Conference.

Thorvaldsen, P., and V. Kvicera (2002), 26 GHz Crosspolar Trial in Prague, Teleinformatika 2002.

Tjelta, T., and D. Bacon (2010), Predicting combined rain and wet snow attenuation on terrestrial links, *IEEE Trans. Antennas Propag.*, *58*(5), 1677–1682.

