

Frequency dependence of amplitude scintillation

Citation for published version (APA):

Kamp, van de, M. M. J. L., Riva, C., Tervonen, J. K., & Salonen, E. T. (1999). Frequency dependence of amplitude scintillation. *IEEE Transactions on Antennas and Propagation*, 47(1), 77-85.
<https://doi.org/10.1109/8.752997>

DOI:

[10.1109/8.752997](https://doi.org/10.1109/8.752997)

Document status and date:

Published: 01/01/1999

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Frequency Dependence of Amplitude Scintillation

Max M. J. L. van de Kamp, Carlo Riva, Jouni K. Tervonen, and Erkki T. Salonen

Abstract—In the prediction models of tropospheric scintillation on earth-satellite paths from Karasawa, Yamada, and Allnutt and ITU-R, the frequency dependence of scintillation is expressed as a power law with a different exponent for each model. In this paper, this is verified using a collection of measurement results from different satellite links in Europe, the U.S., and Japan at frequencies from 4 to 50 GHz and elevation angles from 2.5 to 52°. It shows that the exponent of the power law varies widely among the results from the different sites. Possible explanations of this are: 1) the frequency dependence of scintillation due to cloudy turbulence is different from that due to clear-sky turbulence and this kind of scintillation may be present to different extents in the various databases due to climatic differences and different clear-sky selection procedures or 2) angle-of-arrival fluctuations due to turbulence have a different frequency dependence and this effect may have some impact on the measured scintillation at some of the sites.

Index Terms—Electromagnetic propagation, microwave propagation, millimeter-wave propagation, scintillation, terrestrial atmosphere.

I. INTRODUCTION

SCINTILLATION is the fast fluctuations of signal amplitude and phase caused by atmospheric turbulence. This effect is due to turbulent irregularities in temperature, humidity, and pressure, which translate into small-scale variations in refractive index. An electromagnetic wave passing through this medium will then encounter various refraction and scattering effects, which result in a multipath effect. In the microwave region, the result is random degradation and enhancement in signal amplitude and phase received on a satellite-earth link, as well as degradation in performance of large antennas, which can also be noticed in synthetic-aperture radars.

In general, the impact of rain attenuation on communication signals is predominant. Scintillation, however, becomes important for low-fade margin systems operating at high frequencies and low elevation angles. It has been observed that at high frequencies ($\geq \approx 10$ GHz) and low elevation angles ($\leq \approx$

15°), scintillation may contribute as much as rain or even more to the total fade measured, especially for time percentages larger than 1% and, therefore, for low-fade margin systems.

For the prediction of scintillation effects, a few prediction models are currently known. At the time of publication of those, not many measurement results were yet available to verify these models. Nowadays many more measurements have been carried out at various sites. In this paper, the frequency dependence of scintillation is examined using measurement results from several different sites in different continents.

II. PREDICTION MODELS

Both from theory and from various experiments, it has been found that signal-level fluctuations due to turbulence (in decibels) on a short-term basis (up to several minutes) can be described by a distribution around the mean signal level. This is why they can be completely characterized by the variance σ^2 . On a long term basis, correlation between this variance and meteorological parameters is generally observed.

In the prediction models presented by Karasawa *et al.* [1] and ITU-R [2], the long term scintillation variance is expressed as related to the wet term of the ground refractivity N_{wet} , which is a function of relative humidity and temperature measured at ground level [1]. Both models can be written in the following form:

$$\sigma^2 = f^a g^2(D_e) \sin^q \varepsilon (b + dN_{wet}) \quad (1)$$

where f = frequency (GHz) and ε = elevation angle. All of the constants a, q, b , and d have different values for the two models. $g^2(D_e)$ is an aperture averaging function, as given by Haddon and Vilar [3]

$$\begin{aligned} g^2(D_e) &= 3.8637(x^2 + 1)^{11/12} \\ &\quad \cdot \sin \left[\frac{11}{6} \arctan \frac{1}{x} \right] - 7.0835x^{5/6} \\ &\approx 1 - 7.0835x^{5/6} \quad \text{for } x \ll 1 \end{aligned} \quad (2)$$

where $x = 0.0584kD_e^2/L$ is a measure of the ratio between the effective antenna diameter D_e and the Fresnel zone size ($\sqrt{2\pi L/k}$), k is the radio wave number and D_e can be calculated from the geometrical antenna diameter D and the antenna efficiency η as

$$D_e = D\sqrt{\eta}. \quad (3)$$

The length L of the turbulent path can be calculated from the height h of the turbulence as

$$L = \frac{2h}{\sqrt{\sin^2 \varepsilon + 2h/a_e + \sin \varepsilon}} \quad (4)$$

Manuscript received June 4, 1997; revised June 30, 1998. This work has been supported in part under ESA/ESTEC Contract No. 10827/94/NL/NB(SC).

M. M. J. L. van de Kamp was with Helsinki University of Technology, Espoo, Finland. He is now with Eindhoven University of Technology, Radiocommunications Group, Eindhoven, 5600 MB, The Netherlands.

C. Riva is with Politecnico di Milano, Dipartimento di Elettronica e Informazione, Milano, 20133 Italy.

J. K. Tervonen is with the Helsinki University of Technology, Radio Laboratory, Espoo, 02015 HUT, Finland.

E. T. Salonen was with Helsinki University of Technology. He is now with University of Oulu, Telecommunications Laboratory, Oulu, 90571, Finland.

Publisher Item Identifier S 0018-926X(99)02214-0.

where a_e is the effective radius of the earth including refraction, which is dependent on station height and at sea level becomes 8.5×10^6 m. A value of the height h of the turbulence of 1000 m is suggested by ITU-R [2] and 2000 m by Karasawa *et al.*

The ratio of the variances σ_1^2 at f_1 and σ_2^2 at f_2 , measured at the same site and with a common elevation angle follows from (1)

$$\frac{\sigma_1^2}{\sigma_2^2} = \frac{g^2(D_e, f_1)}{g^2(D_e, f_2)} \times \left(\frac{f_1}{f_2}\right)^a. \quad (5)$$

The frequency exponent a has in the ITU-R model [2] a value of 7/6, which comes directly from Tatarski's theory [4]. Karasawa *et al.* [1] derived a significantly lower value of 0.9 from their measurements at 11.5 and 14.2 GHz.

It should be noted that, instead of the antenna averaging function $g^2(D_e)$ from Haddon and Vilar [3], Karasawa *et al.* [1] use a function that is a piecewise linear approximation. However, for the calculation of ratios [as in (5)] this function is less suitable due to the corners between the pieces. The function itself is accurate enough, but ratios of function values get unstable near the corners. Therefore, the function of Haddon and Vilar [3] will be used for all analyses in this paper.

III. MEASUREMENT RESULTS FROM KIRKKONUMMI

A. Measurement Setup at Kirkkonummi

Helsinki University of Technology, Espoo, Finland, has been involved in the Olympus project in which various propagation effects have been studied using measurements of the beacon signals transmitted by the Olympus satellite. The signals at 19.77 GHz, both quasi-vertically and quasi-horizontally polarized, and at 29.66 GHz, quasi-vertically polarized, were received at Kirkkonummi (60.22°N; 24.40°E, about 30 km west of Helsinki) with a Cassegrain antenna with a diameter of 1.8 m. Only the results for quasi-vertical polarization are presented here. The antenna efficiency is 0.63 at 19.77 GHz and 0.38 at 29.66 GHz, and the apparent elevation angle of Olympus seen from Kirkkonummi is 12.7°.

For the analysis of frequency dependence of scintillation, it is advantageous to have such a small antenna and low elevation angle since due to this, the ratio of aperture averaging functions in (5) hardly depends on the height of the turbulent layer. In general, this height is a very uncertain parameter of the aperture averaging factor. Some estimations of this quantity can be made using meteorological measurements as the height profiles of temperature and humidity or by spectral analysis of scintillation measurements, but still very little is known certainly about it. Usually, the height is assumed to be 1000 m or taken as an extra unknown parameter [5]. In Kirkkonummi, however, if the turbulent layer height varies from 500 to 5000 m (which are very extreme values) the ratio $g^2(D_e, f_1)/g^2(D_e, f_2)$ varies less than 1%. This dependence would be stronger for a larger antenna or a larger elevation angle. Here, however, the aperture averaging function ratio can be taken as a constant and the study can concentrate on the

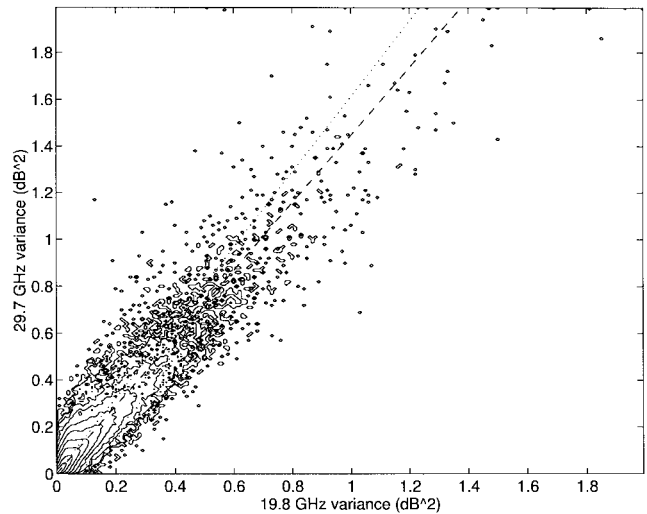


Fig. 1. Contour plot of the joint distribution of variances of 19.77 and 29.66 GHz for the whole measured period in Kirkkonummi. The values of the contour lines are logarithmically spaced. Also included are the theoretical curves according to ITU-R (.....) and Karasawa (---).

frequency exponent a in (5). For a height of 2000 m, and $f_1 = 19.77$ GHz and $f_2 = 29.66$ GHz, $g^2(D_e, f_1)/g^2(D_e, f_2) = 0.996$.

For this study, the data received from January to December 1990 and from June to October 1992 have been used. The data cover the entire period, except for some intervals of several days due to technical problems of the receiver. The received signal amplitude has been sampled at a rate of 20 Hz, high-pass filtered with a cutoff frequency of 2 MHz, and the variance has been calculated over each minute. No separation of rainy and nonrainy scintillation data has been made in this analysis, however, it has been checked that the inclusion or exclusion of rainy data did not influence the resulting statistics significantly.

B. Calculation of the Frequency Exponent

In Fig. 1, a contour plot is shown of the joint distribution of σ_1^2 at 19.77 GHz and σ_2^2 at 29.66 GHz, for the whole measured period. If the average variance ratio σ_1^2/σ_2^2 is calculated from this distribution at once, the result will be determined mainly by the very lowest variance values since for those values the distribution is highest, while the calculation of the ratio is most inaccurate. In order to regulate the relative importance of different parts of the distribution, the data points are first collected in bins in the direction of the expected curve fit, using the parameter r

$$r = \sigma_1^2 + 0.7\sigma_2^2. \quad (6)$$

The value 0.7 in this equation has been chosen to match the expected variance ratio. Each bin contains the data points for which r is in an interval between r_1 and $r_1 + \Delta r$ so that in Fig. 1, the bins have a thin dimension in the direction of the expected curve fit and an infinite length perpendicular to this. To compensate for the effect that the intervals for high variances will be sparse, the values r_1 between the intervals are chosen logarithmically so that the intervals will increase in

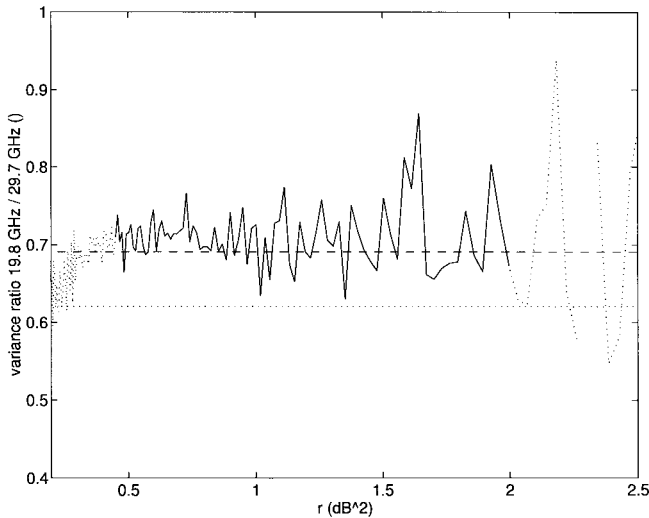


Fig. 2. The average ratio σ_1^2/σ_2^2 in Kirkkonummi as a function of r . The solid line is the part over which is averaged afterwards. Also included are the theoretical curves according to ITU-R (.....) and Karasawa (---).

TABLE I
VARIANCE RATIO AVERAGED OVER THE CURVE OF FIG. 2 FOR
DIFFERENT VALUES OF THE LOWER AND UPPER THRESHOLDS

lower threshold (dB ²)	upper threshold (dB ²)	variance ratio
0.40	2.0	0.7099
0.45	2.0	0.7102
0.50	2.0	0.7103
0.45	1.8	0.7096
0.45	1.9	0.7092
0.45	2.0	0.7102
0.45	2.1	0.7082
0.45	2.2	0.7115

size with increasing r . The average variance ratio is calculated for every bin.

Finally, the resulting values are averaged. For this, a lower threshold of r is considered in order to leave out the inaccurate lowest points. Also an upper threshold is used since, as can be seen from Fig. 1, for high-variance values, σ_2^2 moves out of the range of 2 dB² (implied by the software) so that the distributions in the highest intervals are not representative.

Fig. 2 shows the average ratio σ_1^2/σ_2^2 as a function of r . The solid part of this curve is an example of the part between thresholds of 0.45 and 2.0 dB². The average value of this curve for different values of the upper and lower thresholds is shown in Table I. It can be seen that the result varies slightly with the thresholds used. The average of all these resulting values, given 0.7098, is accepted as the average ratio σ_1^2/σ_2^2 .

An uncertainty evaluation of this calculation is performed as follows. The rms error of a mean value, which is calculated from a distribution of samples of a stochastic variable, is equal to its standard deviation and given by [6]

$$\sigma_{\bar{x}} = \sigma_x / \sqrt{N} \quad (7)$$

where $\sigma_{\bar{x}}$ is the standard deviation of the mean value, σ_x is the standard deviation of the variable itself that can be found from the distribution of samples, and N is the number of samples in the distribution. Applying this formula successively

to both steps of the procedure described above, gives that the root mean square (rms) error in the calculated mean ratio is smaller than 0.0065.

To the resulting ratio σ_1^2/σ_2^2 , (5) can be applied in the reverse direction in order to calculate the frequency exponent a , which results in a value of 0.835 (with a rms error of 0.023). This value is lower than both the exponents proposed by ITU-R and Karasawa *et al.*, though close to the latter one. This difference could be explained by the frequencies used, which are both higher than the frequency range for which both models have been validated. However, more measurements at different frequencies are needed in order to draw more quantitative conclusions.

IV. MEASUREMENT RESULTS FROM SPINO D'ADDA

A. Measurement Setup at Spino d'Adda

Politecnico di Milano has been involved in a propagation measurement campaign using the Olympus and Italsat satellites. Scintillation measurements at 12.50 and 19.77 GHz (vertically polarized) were carried out at Spino d'Adda (45.4°N; 9.5°E, 21.5 km east of Milano) in a 30.6° slant path to the satellite Olympus with a Cassegrain antenna having a diameter of 3.5 m and an antenna efficiency of 0.64. The observation period is restricted to July 1993. The scintillation signal was also observed on a 37.8° slant path to the satellite Italsat at 18.69, 39.59, and 49.49 GHz, with a similar Cassegrain antenna of 3.5-m diameter during the summer of 1993 (from June 1–August 31).

Only time series recorded during clear-sky were considered, which was defined as the data with attenuation values smaller than 2 dB at 18.69 GHz. The considered period is larger than 80% of the total time for every month and every beacon. The signal was sampled at a rate of 1 Hz and slowly varying signal contributions were removed by high-pass filtering with a cutoff frequency of 0.008 Hz. The standard deviation was calculated over every minute.

B. Calculation of the Frequency Exponent

From joint distributions of 1-min standard deviations for each frequency pair, the frequency scaling ratios, hereafter referred to as “short-term ratios,” were obtained as the slopes of the best fitting straight lines for standard deviations larger than a threshold of 0.1 dB for the 19.77-GHz beacon and scaled for the other beacons. The offset of each fitted line was very close to zero; a forced zero offset would have resulted in similar slopes. For the Italsat measurements, the resulting ratios for the three months were averaged for each frequency pair. From (2) and (5), the frequency exponent a was calculated for each frequency pair of the Olympus and Italsat beacons. The values of a , shown in Table II, are substantially higher than those proposed by ITU-R (7/6) and Karasawa *et al.* (0.9), especially for the higher frequencies of the Italsat pairs.

A procedure to evaluate the uncertainty of the slope of a least-square fitted line is described by Taylor [7]. Following this method, the rms errors of the averaged ratios were calculated to be smaller than 0.003 for all frequency pairs

TABLE II
EXPERIMENTAL RESULTS (SHORT-TERM FREQUENCY SCALING)
MEASURED σ -RATIOS, AND EXPONENTS a CALCULATED FROM
THE AVERAGE RATIOS, FOR ALL THE FREQUENCY PAIRS OF THE
OLYMPUS AND ITALSAT EXPERIMENTS IN SPINO D'ADDA

Frequency pair	Measured short-term ratios				a
	June 93	July 93	Aug. 93	average	
$\sigma_{12.5}/\sigma_{19.77}$ (Olympus)	0.78	0.78	0.78	0.78	1.25
$\sigma_{18.7}/\sigma_{39.6}$ (Italsat)	0.51	0.55	0.57	0.54	1.90
$\sigma_{18.7}/\sigma_{49.5}$ (Italsat)	0.42	0.44	0.47	0.44	1.96
$\sigma_{39.6}/\sigma_{49.5}$ (Italsat)	0.85	0.81	0.83	0.83	2.04

of the Italsat measurements and smaller than 0.005 for the Olympus measurements. This leads to a rms error in the exponent a of smaller than 0.028, 0.015, 0.014, and 0.032, for $\sigma_{12.5}/\sigma_{19.77}$, $\sigma_{18.7}/\sigma_{39.6}$, $\sigma_{18.7}/\sigma_{49.5}$, and $\sigma_{39.6}/\sigma_{49.5}$, respectively.

For the Italsat data, the cumulative distribution of standard deviation of scintillation at each frequency was also calculated. In Fig. 3 the cumulative distributions over the period June–August 1993 is shown. From the ratio of the values of scintillation standard deviation at the same probability level, the so-called “long-term frequency scaling ratios” were obtained as a function of probability and then were averaged over the probability range. The ratios and the frequency exponents a , calculated from (2) and (5), are shown in Table III (left side). The uncertainty of these “long-term” results are hard to determine, but they can be expected to be smaller than those of the short-term results. Comparing Table III with Table II, it shows that the long-term ratios are more stable than the short-term ones, and the exponents a are lower. Especially for the frequency pair 39.59/49.49 GHz, the result of a is much lower than from the short-term method. Thus, it shows that the statistical (‘long term’) ratio of scintillation variance at two frequencies can be different from the instantaneous (‘short term’) ratio.

The three months averaged σ -ratios for the short-term and the long-term analyses have been averaged and a has been calculated from this; these results are also shown in Table III (right side). These values then represent an average between statistical and instantaneous behavior. Here, the exponent is similar for the three frequency pairs. These are the values which will be used in further analyses in this paper.

V. COMPARISON WITH OTHER SITES

The frequency exponents of scintillation calculated from measurements in Kirkkonummi and in Spino d'Adda are quite different, one being lower than both theoretical values and the other significantly higher. We could now try to use these results to refine the existing prediction models of scintillation by relating the frequency dependence to one of the climatic or system parameters that are different between the sites of Kirkkonummi and Spino d'Adda. However, if we expect this “refined” model to be globally applicable, it is better to first compare our results to those of other experimenters.

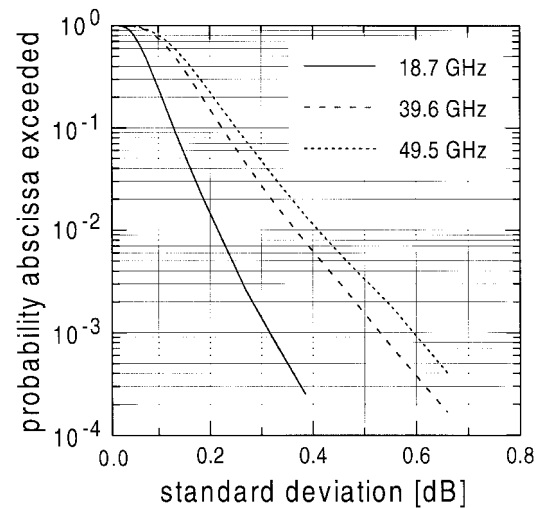


Fig. 3. Cumulative distributions of scintillation standard deviation for the Italsat beacons at 18.69, 39.59, and 49.49 GHz (Spino d'Adda, June–Aug. 1993).

TABLE III
EXPERIMENTAL RESULTS (LONG-TERM FREQUENCY SCALING) FOR ALL
THE FREQUENCY PAIRS OF THE ITALSAT EXPERIMENT IN SPINO
D'ADDA: MEASURED σ -RATIOS, EXPONENTS a CALCULATED FROM
THE AVERAGE LONG-TERM RATIOS, AVERAGES OF THE SHORT-
AND LONG-TERM RATIOS, AND a CALCULATED FROM THESE

Frequency pair	Measured long-term ratios				a	average short- + long-term ratios	a
	June 93	July 93	Aug. 93	average			
$\sigma_{18.7}/\sigma_{39.6}$ (Italsat)	0.57	0.59	0.59	0.58	1.71	0.56	1.80
$\sigma_{18.7}/\sigma_{49.5}$ (Italsat)	0.52	0.53	0.53	0.53	1.61	0.49	1.78
$\sigma_{39.6}/\sigma_{49.5}$ (Italsat)	0.90	0.89	0.88	0.89	1.41	0.86	1.72

Analysis of the measurement results from one site is useful for validating existing prediction models. However, in order to develop new globally applicable prediction models, these will have to be validated with global data. Here, we will compare the results of frequency dependence analyses from many sites in different continents where scintillation measurements have been performed at different frequencies simultaneously. For this comparison, results concerning the frequency dependence of scintillation have been extracted from various publications. These published results are usually presented in graphs. The data have been extracted from these by enlarging the paper copies, which were scanned by hand. This way, an estimated accuracy of $\approx 0.1\%$ of the maximum range of the graphs could be reached.

The site parameters relevant for further analysis are summarized in Table IV. Some details on the data processing at the different measurement sites include the following.

- In **Blacksburg, VA** [8], in the Virginia Tech Olympus propagation experiment, scintillation at all three Olympus frequencies (12.50, 19.77, and 29.66 GHz), was measured during several 1 h clear air scintillation events in May and September 1991. The standard deviation was computed over every minute. Only the results from two events, on September 14 and on May 10 are reported.

TABLE IV
SITE PARAMETERS. STATION NAMES, GEOGRAPHICAL COORDINATES (LATITUDE AND LONGITUDE), FREQUENCIES f , ELEVATION ANGLES ε , ANTENNA DIAMETERS D , APERTURE EFFICIENCIES η , AND SATELLITE NAMES. IF η IS NOT INDICATED, IT IS NOT MENTIONED IN THE REFERENCE

Ground station	coordinates	f (GHz)	ε (°)	D (m)	η ()	Satellite
Blacksburg	37.23 - 279.60	12.50	14	4		Olympus
		19.77		1.5		
		29.66		1.2		
Crawford Hill	40.39 - 285.81	19.04 28.56	38.6	7	0.73	Comstar
Darmstadt	49.87 - 8.63	12.50	27	1.8	0.5	Olympus
		19.77		3.7	0.5	
		29.66		3.7	0.5	
Eindhoven	51.45 - 5.49	12.50	26.8	5.5	0.92	Olympus
		19.77		0.78		
		29.66		0.44		
Fairbanks	212.18 - 64.86	20.19 27.51	7.9	1.22	0.56	ACTS
Fort Collins	255.3 - 40.4	20.19 27.51	43.1	1.22	0.56	ACTS
Kirkkonummi	60.22 - 24.40	19.77 29.66	12.7	1.8	0.63 0.38	Olympus
Lessive	50.22 - 5.25	12.50 19.77	27.8	1.8	0.6	Olympus
Louvain	50.67 - 4.62	12.50 29.66	27.6	1.8	0.6	Olympus
Martlesham	52.06 - 1.29	≈11 14.27	≈10	6.1		Intelsat-V (≈60°)
Martlesham	52.06 - 1.29	12.50 29.66	27.5	1.8 6.1		Olympus
Norman	263 - 35	20.19 27.51	49.1	1.22	0.56	ACTS
Spino d'Adda	45.40 - 9.49	12.50 19.77	30.6	3.5	0.64	Olympus
Spino d'Adda	45.40 - 9.49	18.69 39.59 49.49	37.8	3.5	0.64	Italsat
Tampa	278 - 28	20.19 27.51	52.0	1.22	0.56	ACTS
Tokyo	35.6 - 139.7	4.17 6.39	5.5	22		Cas A
Upolu	20.27 - 204.13	9.55	2.5	2.7		Mt. Haleakala
		19.1		2.7		
		22.2		2.7		
		25.4		2.7		
		33.3		2.0		
Yamaguchi	34.18 - 131.55	11.45 14.27	6.5	7.6		Intelsat-V (60°)

The scaling ratios were obtained as the slopes of the forced zero intercept best fit lines of the scattergrams of standard deviation for each two frequencies. The results from the two events are significantly different for which two possible explanations are mentioned: a difference in average scintillation intensity between the two events causing a different sensitivity to noise or a difference in the turbulent layer height. Here, the results from the two events have been averaged.

- In **Crawford Hill**, NJ [9], the orbital signal sources were the 19.04- and 28.56-GHz beacons of the COMSTAR satellites, and the measurements were made with the Bell Laboratories Receiving Facility. The data sampling rate was 4 Hz. Results are reported for the months of July and August of the years 1978 and 1979. Only “dry” scintillation events (i.e., in the absence of significant attenuation) were used for this analysis, the classification of which was performed by hand. The frequency scaling ratio was obtained in two ways: for every value of signal level deviation at 19 GHz, the median occurrence of 28-GHz signal level was calculated and also an equiprobable exceedance relation for signal level at both frequencies was derived. To both resulting relations, straight lines

were fitted, which both gave equal slopes. This is the result for the frequency scaling ratio.

- In **Darmstadt**, Germany [5], all three Olympus beacon signals have been received at the Research Institute of Deutsche Bundespost Telekom (current name: Research Centre of Deutsche Telekom AG) with two antennas of different sizes. The receiver outputs were sampled at a rate of 80 Hz and averaged on-line over every second. Slowly varying signal contributions caused by attenuation due to gases, clouds, and rain were removed from the signal by a suitable hardware high-pass filter. Cumulative distributions of 1-min standard deviations over a period of one year were produced. The frequency scaling factors have been derived from these distributions on an equiprobability basis.
- In **Eindhoven**, Netherlands [10], the three Olympus beacons were received at Eindhoven University of Technology with one Cassegrain antenna with a frequency-dependent aperture efficiency. The signal was sampled at a rate of 3 Hz. Five clear-sky scintillation events of 23 min each are reported, all occurring in June 1992; the scintillation standard deviation was calculated over each event. The frequency scaling factors were obtained for each event and each frequency pair as the ratio of these event standard deviations between the two frequencies. The resulting frequency scaling factors vary from event to event, which is stated to be mainly due to the variability of, e.g., the turbulent layer height. Here, these five event values have been averaged for each frequency pair.
- In **Fairbanks**, AK, **Fort Collins**, CO, **Norman**, OK, and **Tampa**, FL, [11], scintillation was measured in a propagation experiment using the 20.16- and 27.51-GHz beacons received from the ACTS satellite. Beacon measurements were sampled at 20 Hz during 6–10 min of each hour for periods of 2–4 months (depending on the site) between June and September 1996. From each of these measurement intervals, power spectra were derived by fast Fourier transform (FFT). The variances were calculated from the spectra after correction for receiver noise. This noise variance was taken as the minimum observed variance value in the data for each site. Frequency scaling factors were obtained by fitting lines to scatterplots of the variances for the two frequencies.
- In **Kirkkonummi**, Finland, the frequency scaling ratio was calculated from the joint distribution of the two signals, as described earlier in this paper.
- In **Lessive** and **Louvain-la-Neuve**, Belgium [12], Olympus measurements have been performed by the Université Catholique de Louvain. Two years of scintillation measurements have been analyzed: one year (1990) has been collected in Lessive at 12.50 and 19.77 GHz and the other (1992) in Louvain-la-Neuve at 12.50 and 29.66 GHz. The scintillation amplitude was calculated as the difference in decibels between the measured signal level and the mean level, obtained using a 30-s moving average filter. The variance of this scintillation amplitude was calculated in a sliding way over 1 min and sampled at a rate of 1 Hz. From concurrent measurements of scintillation variances,

equiprobability plots were made for each frequency pair. The statistics only account for clear weather scintillation, which was achieved by using only the data for 19.77-GHz attenuation being less than 1 dB. The frequency scaling ratios are best fit values to these equiprobability relations for probabilities larger than 1%.

- In **Martlesham Heath**, U.K. [13], a four-year study of attenuation, depolarization, and scintillation on an INTELSAT-V satellite link was conducted by British Telecom Research Laboratories from June 1983 to May 1987. During the measured period, four different satellites served in succession, which were seen at elevation angles of 10.1°, 8.3°, 11.8°, and 10.1°, respectively. The satellite beacons at 11.45 and 11.20 GHz, right-hand circularly polarized, and a looped-back wave at 11.46 GHz, linearly polarized, which were originally sent out from the ground station at 14.26 GHz, linearly polarized, were received by one Cassegrain antenna. Data were recorded each half second. A high-pass filter algorithm was used to separate the rapidly from the more slowly varying components of the measured attenuation signal. The data were divided into rain-event data, characterized by mean fades ≥ 3 dB together with short pre- and post-event periods, and the remaining data. The standard deviation was calculated over every 10-min block of data. The frequency scaling ratio was obtained as the peak occurrence ratio of the 14/11 GHz standard deviations for the data set containing the data outside of rain events.
- In a later project in **Martlesham Heath**, U.K. [14], Olympus satellite propagation measurements were performed by the University of Surrey between November 1989 and November 1991. The signals at 12.50 and 29.66 GHz were observed using two antennas of different sizes. One scintillation event is reported, from which the variances at both frequencies were calculated over a period of 34.13 min. The frequency scaling ratio is the ratio of these variances. This result is only reported as an example, but it is the only frequency scaling measurement result found in literature from this project.
- In **Spino d'Adda**, Italy, "short-term" and "long-term" frequency scaling ratios have been calculated and the results of these two methods have been averaged for each frequency pair, as described earlier in this paper.
- In **Tokyo**, Japan [15], the transmitter was actually not a satellite, but the star Cas A. The radio waves transmitted by this star were received at 4.17 and 6.39 GHz by one antenna. The two frequencies were coupled simultaneously in linear orthogonal polarizations. The time constant was 1 s. One scintillation event is reported, which occurred on September 3, 1966. The frequency ratio from this event was obtained by performing a curve fit on a joint distribution of signal level of the two frequencies.
- In **Upolu**, HI [16], the transmitter of the slant path was also not really a satellite, but was situated on Mount Haleakala, Maui, at an altitude of 3025 m. The receiver was situated at Upolu point, 64 km away at sea level. Since almost the entire 2.5° elevated path was over open sea, the troposphere up to a height of at least 2500 m had

the same effect on this link as it would on a satellite link with the same elevation. Five different frequencies (9.55, 19.1, 22.2, 25.4, and 33.3 GHz) were used and the data were collected over nine events of 40 min each, all within the period of September 10–14, 1971. For each event, the mean scintillation standard deviation was calculated for every frequency. We calculated the ratio between the mean-event values for five frequency pairs covering all frequencies.

- In **Yamaguchi**, Japan [17], long-term propagation experiments have been carried out using the INTELSAT-V satellite link during the year 1983. A satellite beacon at 11.45 GHz, right-hand circularly polarized, and a looped-back wave at 11.18 GHz, linearly polarized that was originally sent out from the ground station at 14.27 GHz (linearly polarized) were received by one Cassegrain antenna. All data were sampled at 1 Hz. A scattergram was made of the signal level variations of the two frequencies during one scintillation event on August 10, 1983, between 12:00 AM and 13:00, and another of the standard deviations of the two frequencies, calculated over every hour for the whole period of August 1983. Curve fits to both scattergrams gave the same frequency-scaling ratio of scintillation.

In the scintillation prediction models of ITU-R and Karasawa, the frequency dependence lies not only in the power function f^a , but also in the antenna averaging function [see (5)]. When testing the power law, the frequency dependence of the antenna averaging function should be compensated for. This is done using a "normalized variance ratio"

$$\frac{\sigma_1^2}{\sigma_2^2} \Big|_n = \frac{\sigma_1^2}{\sigma_2^2} \frac{g^2(D_e, f_1)}{g^2(D_e, f_2)}. \quad (8)$$

According to the prediction models, this should be equal to

$$\frac{\sigma_1^2}{\sigma_2^2} \Big|_n = \left(\frac{f_1}{f_2} \right)^a \quad (9)$$

with $a = 7/6$ according to ITU-R and $a = 0.9$ according to Karasawa. This normalized variance ratio has been plotted versus the frequency ratio in Fig. 4 for all of the different frequency pairs of all the sites described above. In this plot, the height h of the turbulent layer has been assumed 2000 m and the antenna aperture efficiency η , where it was not indicated in the references, has been assumed 0.75. Where the frequency scaling ratio given was a ratio of signal level or standard deviation, these ratios have been squared. Observations over only one or a few events are indicated with different symbols than observations over longer periods since in the first case, particular turbulence heights could bias the result.

What concerns an uncertainty evaluation of the comparison of Fig. 4: the uncertainties in the other results than those from Kirkkonummi and Spino d'Adda are hard to estimate since for most analyses, neither the spread of the distribution of ratios nor the number of data points used in the calculation is given in the respective publications. However, it can be roughly expected that the "long-term" results ("*" in Fig. 4) have an uncertainty comparable to those of the Kirkkonummi

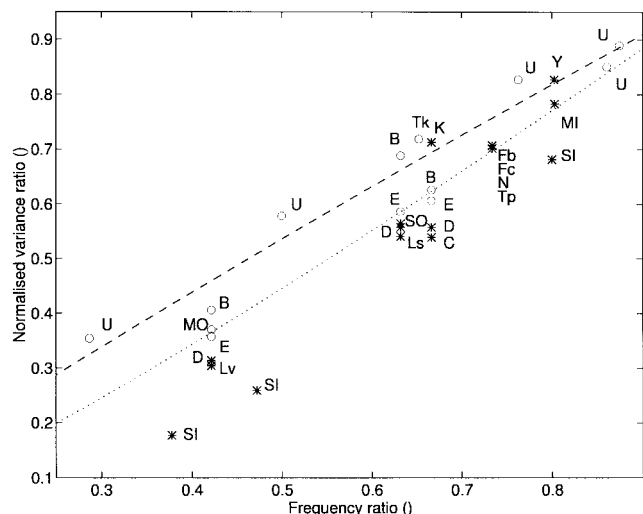


Fig. 4. Normalized variance ratio versus frequency ratio for all frequency pairs of all measurement sites. The letters are initials of the names of the sites (MI = Martlesham-Intelsat; MO = Martlesham-Olympus; SI = Spino d'Adda-Italsat; SO = Spino d'Adda-Olympus; Fb = Fairbanks; Fc = Fort Collins; Lv = Louvain; Ls = Lessive; Tp = Tampa; Tk = Tokyo). "o": observations over one or a few events; "*": observations over periods ≥ 1 month. Theoretical relations by ITU-R (.....) and Karasawa (----).

and Spino d'Adda results and the "event" results ("o" in Fig. 4) a larger one.

VI. DISCUSSION

Fig. 4 shows a large spread between the results of the different sites. Assuming different values for h or η did not change this situation significantly. Neither is there a clear distinction between "event" and "longer period" observations. In an attempt to create a bit of order in this chaos, we have searched for a correlation with other parameters. A dependence of the exponent on frequency seems a logical suggestion, however, we found no correlation between these parameters as sites with similar frequency pairs gave very different results.

It might be stated that at some sites, the sampling frequency of the scintillation measurement was quite low (1 Hz), which could cause an essential part of the scintillation spectrum to be cut off from the measurements, which, in turn, would cause an error in the calculation of the ratio. However, this still would not explain the difference between the result from Kirkkonummi and those from Fairbanks, Fort Collins, Norman, and Tampa, where the sampling frequencies were all 20 Hz, which is generally considered high enough.

From Fig. 4, it seems that the sites with low elevation angles (Upolu, Tokyo, Yamaguchi) reach the highest normalized variance ratios and those with high elevation angles (Crawford Hill, Spino d'Adda with Italsat) the lowest. This suggests that the frequency exponent α may be dependent on the elevation angle. This should be more clearly seen in Fig. 5, where the frequency exponent α , as it would result from all the measurements by applying (9), has been plotted versus the elevation angles ε of the sites. In this picture, some of the results seem to point in that direction, but the results from Fort Collins, Norman, and Tampa clearly contradict this hypothesis.

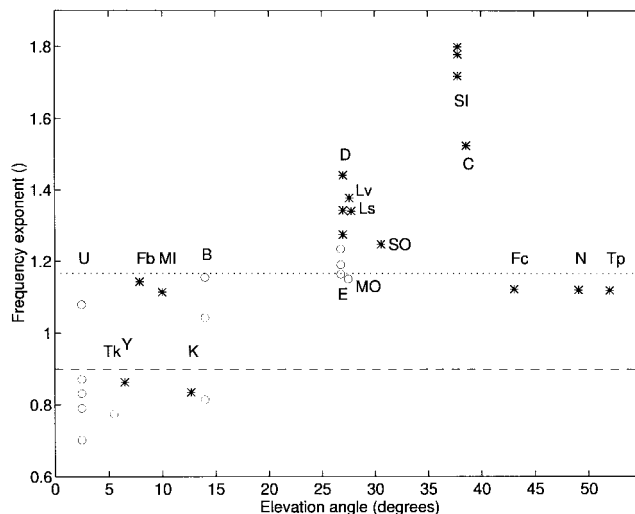


Fig. 5. Frequency exponent α versus elevation angle ε for all frequency pairs of all measurement sites. Theoretical relations by ITU-R (.....) and Karasawa (----).

A possible relation between α and the turbulent height could be suggested, but in order to check this, meteorological data from all the sites during the measurement periods would be needed. However, such a relation seems unlikely considering that the turbulent height, assuming that it is related to the 0° isotherm height, is correlated with the ground-level temperature. This height should, therefore, in Upolu and Tokyo in September, be comparable to Spino d'Adda in the summer, while Figs. 4 and 5 show that the frequency dependencies of scintillation observed at these sites are furthest apart of all.

All the hypothetical explanations mentioned up to here can thus be rejected. However, one possible explanation for the large differences between the results from different sites, is the occurrence of different scintillation mechanisms at the same time, which have different frequency dependencies. The short- and long-term results for the highest frequency pair in Spino d'Adda are very different (see before). This suggests that two mechanisms may be active, which have different statistical properties.

A physical explanation of this kind was pointed out by Jones *et al.* [13]. The frequency exponent from Martlesham/Intelsat as shown in the figures of this paper was obtained from a "nonrain-event" data subset. The frequency exponent resulting from the "rain event" subset, characterized by fades ≥ 3 dB, would be significantly higher. This indicates that scintillation measured during clouds and precipitation is caused by a different mechanism than "dry" scintillation and has a different frequency dependence. They call this mechanism "turbulent attenuation," being due to the turbulent mixing of air masses with different liquid water contents. In that case, the discrepancies between the sites may be explained by different contents of cloudy/rainy data in the databases due to climatic differences between the sites, and differences in preprocessing procedures, in particular "event"- and "clear sky"-selection procedures. Even though it was found that for Kirkkonummi, the inclusion or exclusion of rain events did not significantly change the result of the analysis; for other sites in different

climates this influence may be larger. In climates with a large average probability of rain, turbulent attenuation could even play a major role in the observed scintillation.

As another possible explanation, the extreme results from Spino d'Adda may have been caused by angle-of-arrival fluctuations. In case of a very narrow antenna beam, variations in the angle of arrival of the mean signal during a scintillation event may cause fast fluctuating fading (but no enhancement) of the signal. Vilar *et al.* [18] presented a technique to measure these angle-of-arrival fluctuations. Although still very little is known quantitatively about this effect, its frequency dependence can be estimated in the following way. The main lobe of the antenna pattern can be modeled as a parabolic function

$$\Phi = -\Phi_o \theta^2 \quad (\text{dB}) \quad (10)$$

where θ is the angle from the antenna axis and Φ_o is related to the 3-dB beamwidth $\theta_{3\text{ dB}}$ as

$$\Phi_o = 3 \text{ dB} / \theta_{3\text{ dB}}^2. \quad (11)$$

Now, if a radio wave is refracted due to turbulence such that it is received at an angle θ_1 from the main axis of the antenna, it will be received with a signal fade $A = -\Phi = \Phi_o \theta_1^2$ relative to a wave received at the main axis. Assuming now that the magnitude of the angle-of-arrival fluctuations does not depend on frequency, the ratio of momentary fades A_1 and A_2 for two signals at frequencies f_1 and f_2 , arriving both at angle θ_1 , is

$$\frac{A_1}{A_2} = \frac{\Phi_{o,1} \theta_1^2}{\Phi_{o,2} \theta_1^2} = \frac{\theta_{3\text{ dB},2}^2}{\theta_{3\text{ dB},1}^2}. \quad (12)$$

Thus, under this assumption, the frequency ratio of momentary fades is constant, depending only on the ratio of the 3-dB beamwidths for the two frequencies and not on the angle θ_1 . Then the waveform of the fluctuations will be similar for the two frequencies and the ratio of the variances will be equal to the square of (12)

$$\frac{\sigma_1^2}{\sigma_2^2} = \left(\frac{A_1}{A_2} \right)^2 = \left(\frac{\theta_{3\text{ dB},2}^2}{\theta_{3\text{ dB},1}^2} \right)^4. \quad (13)$$

The 3-dB beamwidth of an antenna at a certain frequency can be found from

$$\theta_{3\text{ dB}} = \frac{18.84}{fD\sqrt{\eta}} \quad \text{degrees} \quad (14)$$

with f in GHz and D in meters. So, in the cases where the effective antenna diameter $D\sqrt{\eta}$ is equal for both frequencies, the variance ratio becomes $(f_1/f_2)^4$ and the frequency exponent becomes 4. Since this is significantly larger than the exponent 7/6 derived from Tatarski's theory, it is considered possible that this effect plays a role in the measurements at Spino d'Adda, where remarkably high-frequency exponents were measured. However, since the variance ratio does not depend on the absolute 3-dB beamwidth, this effect can play a role for any measurement site. Therefore, the whole set of measurement results has been compared to this theory. Because not all sites have equal effective antenna sizes for all frequencies, (13) cannot be represented in Figs. 4 and 5.

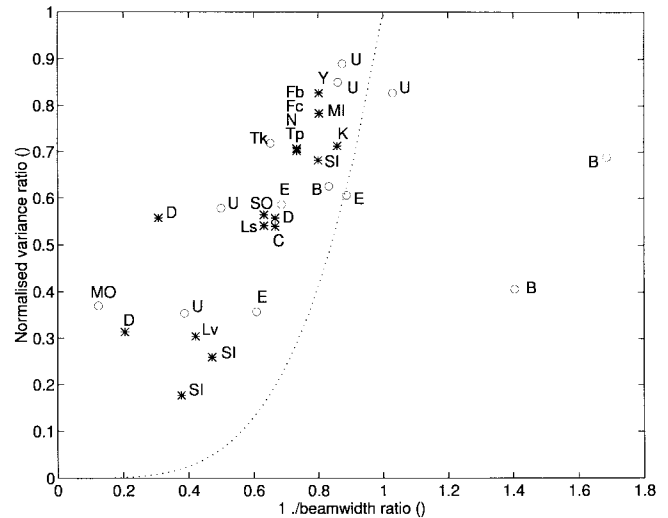


Fig. 6. Normalized variance ratio versus inverse 3-dB beamwidth ratio for all frequency pairs of all measurement sites, and the relation of (13) (.....).

Therefore, the variance ratios have been plotted the versus the inverse of the 3-dB beamwidth ratio in Fig. 6. Equation (13) is represented in this figure by the dotted line.

It is seen in this figure that most of the measured variance ratios are larger than predicted by the angle-of-arrival fluctuation theory. This suggests that this effect might play a role for those cases where the measured variance ratio was smaller than predicted by Tatarski's theory (ITU-R model; dotted line in Fig. 4). However, there is still no explanation why it should especially play such a large role in Spino d'Adda. It could be suspected that the relative impact of this effect is larger for highly directive antennas, however, the antenna beamwidths in Spino d'Adda are not extremely small, but similar to those in Tokyo, Yamaguchi, Martlesham/Intelsat, Eindhoven, and Crawford Hill: around 0.2° , while the others range up to about 1.2° .

VII. CONCLUSIONS

The frequency dependence of scintillation, as obtained from measurement results at various sites, shows remarkable differences. No convincing correlation of this effect could be found with any meteorological or system parameter. A possible explanation is that scintillation due to cloudy turbulence has a different frequency dependence than "dry" scintillation and is present in different portions of the data from the various sites. If this hypothesis is correct, the frequency dependence of scintillation could in future prediction models be expressed as depending on a climatic parameter. In future measurements of tropospheric scintillation, the different properties of scintillation observed during clear sky and during rain should be examined.

As another explanation, angle-of-arrival fluctuations have a different frequency dependence, and possibly play a role in turbulence-induced scintillation for highly directive antennas, but it remains unclear for which sites this effect should be strongest. The relative impact of angle-of-arrival fluctuations on measured scintillation requires much further study.

The observations in this paper illustrate that measurement results covering the whole relevant range of all parameters are needed in order to develop a global model for scintillation prediction. Extrapolations, even if theoretically justified, may not be in agreement with reality at all.

Finally, it has been illustrated that in the case of observed discrepancies between measured results and model predictions of any effect, it is useful to compare this observation with other experiments before modifying the model coefficients to fit to one's own results.

REFERENCES

- [1] Y. Karasawa, M. Yamada, and J. E. Allnutt, "A new prediction method for tropospheric scintillation on earth-space paths," *IEEE Trans. Antennas Propagat.*, vol. 36, pp. 1608–1614, Nov. 1988.
- [2] ITU-R, "Propagation data and prediction methods required for the design of earth-space telecommunications systems," ITU-R Recommendations, 5F, Rec. PN 618-3, pp. 329–343, 1994.
- [3] J. Haddon and E. Vilar, "Scattering induced microwave scintillations from clear air and rain on earth space paths and the influence of antenna aperture," *IEEE Trans. Antennas Propagat.*, vol. AP-34, pp. 646–657, May 1986.
- [4] V. I. Tatarski, *Wave Propagation in a Turbulent Medium*. New York: McGraw-Hill, 1961 (transl. R. A. Silverman).
- [5] G. Ortgies, "Slant-path frequency scaling of amplitude scintillation during clear-sky conditions and rain," *Archiv für Elektronik und Übertragungstechnik*, vol. 47, no. 4, pp. 203–208, 1993.
- [6] J. S. Bendat and A. G. Piersol, *Random Data: Analysis and Measurement Procedures*, 2nd ed. New York: Wiley, 1986, pp. 82–83.
- [7] J. R. Taylor, *An Introduction to Error Analysis*. London, U.K.: Oxford Univ. Press, 1982, pp. 153–162.
- [8] F. Haidara and C. W. Bostian, "Preliminary results on scintillation intensity frequency scaling from the Virginia Tech Olympus experiment," in *IEEE Int. Symp. Antennas Propagat.*, Chicago, IL, July 1992, pp. 301–304.
- [9] D. C. Cox, H. W. Arnold, and H. H. Hoffman, "Observations of cloud-produced amplitude scintillation on 19 and 28 GHz earth-space paths," *Radio Sci.*, vol. 16, no. 5, pp. 885–907, 1981.
- [10] S. I. E. Touw and M. H. A. J. Herben, "Short-term frequency scaling of clear-sky and wet amplitude scintillation," *Inst. Elect. Eng. Proc. Microwave Antennas Propagat.*, vol. 143, no. 6, pp. 521–526, 1996.
- [11] C. E. Mayer, B. E. Jaeger, R. K. Crane, and X. Wang, "Ka-band scintillations: Measurements and model predictions," *Proc. IEEE*, vol. 85, pp. 936–945, June 1997.
- [12] H. Vasseur, I. Adams, C. Amaya, and D. Vanhoenacker, "Comparison of yearly statistics with CCIR prediction methods," in *Proc. 21st Meet. Olympus Propagat. Experimenters*, Université Catholique de Louvain, Belgium, May 1994, pp. 80–89.
- [13] S. M. R. Jones, I. A. Glover, P. A. Watson, and R. G. Howell, "Evidence for the presence of turbulent attenuation on low-elevation angle earth-space paths—Part 2: Frequency scaling of scintillation intensity on a 10° path," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 85–92, Jan. 1997.
- [14] I. E. Otung, M. S. Mahmoud, and B. G. Evans, "Dual frequency scintillation measurement for remote sensing," *Electron. Lett.*, vol. 31, no. 23, pp. 1972–1973, 1995.
- [15] H. Yokoi, M. Yamada, and T. Satoh, "Atmospheric attenuation and scintillation of microwaves from outer space," *Publ. Astr. Soc. Japan*, vol. 22, pp. 511–524, 1970.
- [16] M. C. Thompson, L. E. Wood, H. B. Janes, and D. Smith, "Phase and amplitude scintillations in the 10 to 40 GHz band," *IEEE Trans. Antennas Propagat.*, vol. AP-23, no. 6, pp. 792–797, Nov. 1975.
- [17] Y. Karasawa, K. Yasukawa, and M. Yamada, "Tropospheric scintillation in the 11/14-GHz bands on earth-space paths with low elevation angles," *IEEE Trans. Antennas Propagat.*, vol. 36, pp. 563–569, Apr. 1988.
- [18] E. Vilar, P. Lo, C. Weaver, and M. Smith, "An offsetting technique to study scintillations in direction of arrival in earth-space paths," in *Proc. URSI Comm. F Symp.*, Louvain-la-Neuve, Belgium, June 1983, pp. 103–110.

Max M. J. L. van de Kamp was born in Driebergen, The Netherlands, in 1963. He received the M.Sc. degree in electrical engineering from Eindhoven University of Technology (EUT), The Netherlands, in 1989.

He has been working as a Research Assistant in different research projects for the European Space Agency (ESA) at EUT from 1990 to 1994, at Helsinki University of Technology, Finland from 1995 to 1997, and again at EUT since 1997. His main activities in these projects have been in satellite wave propagation research in the Olympus Propagation Experiment (OPEX).

Carlo Riva was born in Monza, Milano, Italy, in 1965. He received the Laurea degree in electronic engineering from the Politecnico di Milano, Italy, in 1990.

From 1991 to 1994, he attended the doctorate course in electronic and communication engineering at the Politecnico di Milano in the propagation field with a special focus on scintillation. For three months in 1992 he was at the European Space Research and Technology Center, Noordwijk, The Netherlands, working on scintillation. In 1993 he was with the Université Catholique de Louvain, Louvain-la-Neuve, Belgium, for two months, doing research on the separation of turbulence and rain effects on satellite communication links. He is currently with the Politecnico di Milano as a Postdoctorate Researcher with a research task in millimeter-wave propagation.

Jouni K. Tervonen was born in Turku, Finland, in 1965. He received the Dipl.Eng. (M.S.) degree, in 1992, Lic.Tech. degree, in 1995, and D.Tech. degree, in 1997, all in electrical engineering, from the Helsinki University of Technology, Espoo, Finland.

Since 1992, he has been a Research Engineer with the Radio Laboratory of the Helsinki University of Technology. His main research interest is the modeling of atmospheric effects of radio wave propagation for satellite communications.

Erkki T. Salonen received the Dipl.Eng. (M.S.), Lic.Tech., and D.Tech. degrees in electrical engineering from the Helsinki University of Technology, Espoo, Finland, in 1979, 1986, and 1993, respectively.

Since 1997, he has been at the Telecommunication Laboratory of the University of Oulu, Finland, where he was nominated to a new Professorship of radio engineering. Earlier he was in charge of the radio wave propagation studies at the Radio Laboratory of the Helsinki University of Technology. His main research interest is modeling of atmospheric attenuation phenomena for satellite communication.