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**Citation for published version (APA):**

Touw, S. I. E., & Herben, M. H. A. J. (1996). Short-term frequency scaling of clear-sky and wet amplitude scintillation. *IEE Proceedings - Microwaves, Antennas and Propagation*, 143, 521-526.

**Document status and date:**

Published: 01/01/1996

**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.
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# Short-term frequency scaling of clear-sky and wet amplitude scintillation

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*Indexing terms: Amplitude scintillation, Frequency scaling, Radiowave propagation, Uplink power control*

**Abstract:** For the design of ULPC systems that can compensate for different types of fading, the short-term frequency scaling factor of all types of fading is needed. Attention is focused on the short-term frequency scaling factor of clear-sky amplitude scintillation and amplitude scintillation occurring with rain attenuation simultaneously, often referred to as wet amplitude scintillation. It is shown that these factors are strongly variable: they depend on various meteorological parameters and on the aperture illumination efficiency of the receiving antenna. In addition, it is shown that amplitude scintillation can only be compensated partly by means of ULPC, owing to the limited correlation of amplitude scintillation measured on two radiowaves with different carrier frequencies propagating along the same path simultaneously. Furthermore, a new procedure is presented to separate rain attenuation and amplitude scintillation.

## 1 Introduction

Electromagnetic waves with frequencies above 10GHz and which propagate through a turbulent atmosphere exhibit rapid random fluctuations of amplitude and phase, known as scintillation. The analysis of these turbulence-induced signal scintillations is important for both the remote sensing of the propagation medium and the design of radio communication systems.

Tropospheric amplitude scintillation can be observed during rain as well as under clear weather conditions. Clear-sky amplitude scintillation manifests itself as rapid random fluctuations around the mean signal level. If rain is present on the propagation path, the receiver will see fast amplitude fluctuations superimposed on the slow variations caused by rain attenuation. This type of amplitude scintillation is often referred to as wet scintillation.

In heavy rainfall climates, the attenuation caused by rain is often too severe to be accounted for by a fixed

margin in the link budget. The availability of such rain attenuation-limited satellite communication systems can be upgraded by the application of uplink power control (ULPC). An ULPC system adjusts the power transmitted from an Earth station to the satellite adaptively, according to the actual propagation conditions. The amount of extra power needed to compensate for the attenuation experienced on the uplink is obtained from measurement of the attenuation at the down-link frequency, which is generally lower than the up-link frequency, and applying a frequency scaling algorithm. It is expected that ULPC systems can compensate partly for amplitude scintillation as well.

For the design of ULPC systems the short-term frequency scaling factor of both rain attenuation and amplitude scintillation is required. These factors differ from the long-term frequency scaling factors, which are intended to scale the statistics of a propagation effect. In this paper the attention is focused on the analysis of the short-term frequency scaling factor of clear-sky and wet amplitude scintillation, using the measurements of the 12.5/20/30GHz beacon signals of the Olympus satellite (referred to as B0, B1 and B2, respectively), performed at the ground station of the Eindhoven University of Technology (EUT), which is equipped with a triple-frequency 5.5m Cassegrain antenna system. Furthermore, the theory of clear-sky amplitude scintillation, as published by Haddon and Vilar [1] is verified, and its validity with respect to wet scintillation is discussed.

## 2 Theory of clear-sky amplitude scintillation

### 2.1 Short-term frequency scaling factor

The short-term frequency scaling factor of amplitude scintillation is defined as the ratio of the standard deviations of amplitude scintillation experienced by two radiowaves with different carrier frequencies, propagating along the same path simultaneously, measured during a time interval within which the turbulence can be modelled as a stationary random process. Tatarskii [2] derived an equation for the variance of amplitude scintillation, assuming that the radio signal is received by a hypothetical point receiver. From Tatarskii's equation it can be concluded that, in this case, the short-term frequency scaling factor only depends on the ratio of the frequencies in question and the power  $n$  with which the turbulence spectrum falls off.

Haddon and Vilar [1] derived an equation for the variance  $\sigma_\chi^2$  [dB<sup>2</sup>] of the log-amplitude fluctuations  $\chi$  [dB] owing to turbulence, taking into account the smoothing effect of an antenna aperture. Their

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*IEE Proceedings* online no. 19960694

Paper first received 5th February 1996 and in revised form 24th June 1996

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equation leads to the following expression for the short-term frequency scaling factor:

$$\frac{\sigma_x(k_2)}{\sigma_x(k_1)} = \left[ \frac{k_2}{k_1} \right]^{(6-n)/4} \left[ \frac{g(x_2)}{g(x_1)} \right] \quad (1)$$

where  $k$  is the wavenumber, and  $g(x)$  is an antenna averaging function which depends on  $k$ ,  $n$ , the height of the turbulent layer  $h$ , the elevation angle to the satellite  $\theta$ , the effective Earth radius  $R_e$ , the antenna diameter  $D$  and the aperture illumination efficiency of the antenna  $\eta$  [1]. Unfortunately, the last three parameters are difficult to measure. Therefore the CCIR [3] recommends to assume  $h = 1000\text{m}$  and  $n = 11/3$ . Further, Haddon and Vilar [1] proposed to choose the aperture illumination efficiency such that the effective aperture diameter of the antenna is 75% of the physical diameter, so  $\sqrt{\eta} = 0.75$ . It should be noted that  $\eta$  is not the antenna efficiency, as suggested by CCIR, but the aperture illumination efficiency, which can be substantially larger than the antenna efficiency.

The frequency scaling factor resulting from eqn. 1, after substitution of the values of  $h$  and  $n$  as recommended by the CCIR, is meant for scaling statistical functions of amplitude scintillation and is called the long-term frequency scaling factor. It cannot be used for the prediction of the short-term frequency scaling factor of amplitude scintillation, because the meteorological parameters  $h$  and  $n$  are time-dependent owing to the nonstationary character of turbulence.

## 2.2 Power spectral density (PSD) function

Tatarskii [2] showed that, in the case of reception at a point receiver, the PSD function of amplitude scintillation exhibits two distinct regions: a low-frequency region within which the function is flat and a high-frequency region within which the function falls off as  $f^{1-n}$ . Thus the shape of the spectrum is given by two asymptotes, namely one for the low frequency region,  $W_x^0(\omega, 0)$  [dB<sup>2</sup>s/rad], and another for the high-frequency region,  $W_x^\infty(\omega, 0)$ . These two asymptotes intercept at a cut-off frequency  $\omega_c$  which is proportional to the cross path wind velocity  $v$ . In this section both the frequency  $f$  and the angular frequency  $\omega$  ( $= 2\pi f$ ) are used to conform our equations to those published by Haddon and Vilar [1].

Haddon and Vilar [1] derived equations for the PSD function of amplitude scintillation in case of reception with an antenna with a nonzero aperture diameter. They showed that, owing to aperture smoothing, the flat part of the spectrum ( $\omega < \omega_c'$ ) is lowered with respect to the point receiver case and that the spectrum falls off exponentially in the high-frequency region ( $\omega > \omega_s$ ). Knowing that the PSD function is a continuous function and assuming that the spectrum falls off as  $f^{1-n}$  in the frequency interval  $[\omega_c', \omega_s]$ , an additional equation for the asymptote in the intermediate frequency region can be derived [4]. Hence, in case of reception with a large reflector antenna, the PSD function of amplitude scintillation exhibits three distinct regions. The asymptotes in the lower-frequency region  $W_x^0(\omega, D)$ , the intermediate-frequency region  $W_x^i(\omega, D)$  and the high-frequency region  $W_x^\infty(\omega, D)$  are given by [1, 4]:

$$W_x^0(\omega, D) = W_x^0(\omega, 0)[b(x)]^2 \quad \text{for } \omega < \omega_c' \quad (2a)$$

$$W_x^i(\omega, D) = W_x^\infty(\omega, 0) \frac{\Gamma[\frac{n}{2}]}{\Gamma[\frac{n-1}{2}]} \exp(-1) \quad \text{for } \omega_c' < \omega < \omega_s \quad (2b)$$

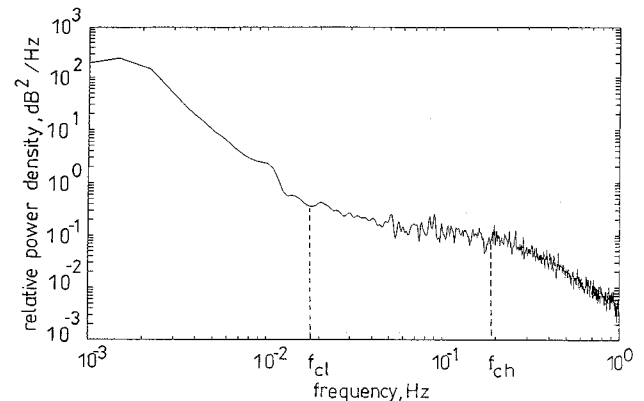
$$W_x^\infty(\omega, D) = W_x^\infty(\omega, 0) \frac{\Gamma[\frac{n}{2}]}{\Gamma[\frac{n-1}{2}]} \frac{\omega_s}{\omega} \exp\left(\frac{-\omega^2}{\omega_s^2}\right) \quad \text{for } \omega > \omega_s \quad (2c)$$

where  $\Gamma$  is the gamma function and  $b(x)$  is an antenna averaging function which depends on  $k$ ,  $n$ ,  $h$ ,  $\theta$ ,  $R_e$ ,  $D$  and  $\eta$  [1]. It can be shown that the asymptotes in the low- and intermediate-frequency region intercept at a frequency  $\omega_c'$  [4]:

$$\omega_c' = \left[ \frac{\exp(-1)\Gamma[\frac{n}{2}]}{[f(x)]^2\Gamma[\frac{n-1}{2}]} \right]^{1/(n-1)} \omega_c \quad (3)$$

## 3 Separation of rain attenuation and amplitude scintillation

Fig. 1 shows the temporal PSD function of an event with concurrent rain attenuation and amplitude scintillation measured on the 30GHz beacon signal of the Olympus satellite at the EUT ground station on 8th August 1992. This PSD function, which is estimated using standard data analysis procedures [5], reveals three distinct regions. In the first region, extending from zero to a frequency  $f_{cb}$  the function shows a steep decrease. The second region, ranging from  $f_{cl}$  to  $f_{ch}$  is approximately flat, and in the third region, that is above  $f_{ch}$ , the PSD function falls off again. Thus, above  $f_{cl}$  the function resembles that of clear-sky amplitude scintillation. Below  $f_{cb}$ , however, the PSD function shows an enhancement, owing to the slowly varying rain attenuation.



**Fig. 1** Power spectral density function of event with concurrent rain attenuation and amplitude scintillation measured on 30 GHz beacon signal of Olympus satellite at EUT ground station 8th August 1992, 01.00 – 04.48h GMT

The cut-off frequency  $f_{cl}$  is determined by the dynamic characteristics of rain attenuation and the intensity of amplitude scintillation. Therefore the cut-off frequency varies from one event to another. Furthermore, the cut-off frequency increases with increasing carrier frequency because the frequency dependence of rain attenuation is much stronger than the frequency dependence of amplitude scintillation.

To analyse the wet amplitude scintillation independently from the rain attenuation, these two phenomena should be separated, achievable by means of low-pass filtering. The low-pass filter should have an adjustable cut-off frequency and should be easy to implement.

Karasawa and Matsudo [6] used a moving average filtering technique to separate rain attenuation and amplitude scintillation from events measured on the 11 and 14GHz beacon signals of the Intelsat-V satellite.

**Table 1: Short-term frequency scaling factors of clear-sky amplitude scintillations measured on 12.5/20/30GHz beacon signals at EUT ground station**

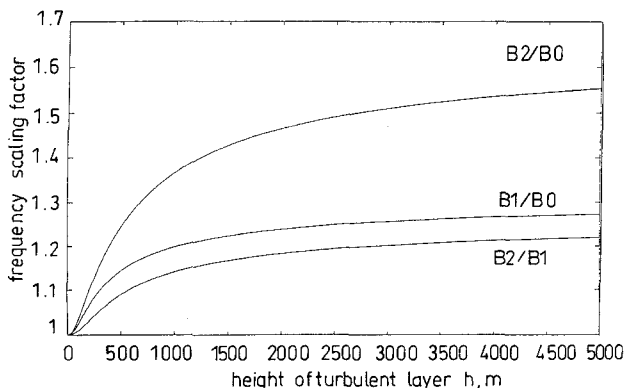
Event	B2/B0	B1/B0	B2/B1	$n$	$h(m)$	$C_n^2(m^{3-n})$	$v(m/s)$
10/06/92	1.74	1.31	1.33	3.40	3750	1.02e-12	3.70
13/06/92	1.52	1.31	1.26	4.00	1750	4.65e-13	2.65
14/06/92	1.58	1.21	1.31	3.75	1000	3.11e-12	1.95
25/06/92	1.74	1.26	1.39	3.30	1000	1.67e-11	1.90
27/06/92	1.62	1.23	1.32	3.65	1250	7.24e-12	2.50

However, analysis of events measured on the beacon signals of the Olympus satellite showed that the performance of this low-pass filtering procedure is not satisfactory [4]. The relatively high sidelobes and the wide transmission bandwidth of the mainlobe of the moving average filter lead to insufficient suppression of the higher-frequency components.

What is needed is a filter with ideal frequency domain characteristics, that is a unity gain and a linear-phase characteristic in the passband and a zero gain within the stopband. Such an ideal filter is not causal and therefore not physically realisable. Mathematically, however, ideal filtering can be performed in the frequency domain by calculating the discrete Fourier components of the original data using an  $N$ -point FFT algorithm, setting the unwanted components to zero and transform the resulting components back to the time domain. For the event presented in Fig. 1, the components corresponding to the frequency interval  $[0; f_{cl}]$  are set to zero, such that high-pass filtering is performed and the output of the ideal filter contains solely the wet amplitude scintillation. Then, the filter output is subtracted from the original signal such that the rain attenuation signal is obtained. The performance of this filtering procedure appears to be excellent [4].

#### 4 Analysis of short-term frequency scaling

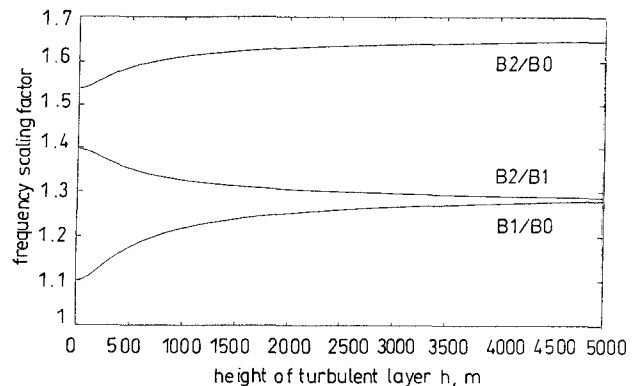
Table 1 gives the short-term frequency scaling factors measured at the EUT ground station for five different clear-sky events. It can be seen that the factors vary greatly from event to event. This is due to the variability of the meteorological parameters  $n$  and  $h$ .



**Fig. 2** Frequency scaling factor as function of height of turbulent layer  $n = 11/3$ ,  $\sqrt{\eta_{B0}} = \sqrt{\eta_{B1}} = \sqrt{\eta_{B2}} = 0.75$

Fig. 2 shows the frequency scaling factors as a function of the height of the turbulent layer  $h$ , for  $n = 11/3$ , based on eqn. 1. The aperture illumination efficiency is chosen  $\sqrt{\eta} = 0.75$ , as proposed by Haddon and Vilar [1]. It can be observed from Fig. 2 that the frequency

scaling factor increases with increasing ratio of carrier frequencies for all values of the height of the turbulent layer. Changing the value of  $n$  results in a vertical shift of the curves: the frequency scaling factors increase with increasing  $n$ . The relative position of the curves, however, remains unchanged. The behaviour of the measured frequency scaling factors given in Table 1, however, differ from the results shown in Fig. 2: the frequency scaling factor of the 30 and 20GHz beacon signals is larger than the frequency scaling factor of the 20 and 12.5GHz beacon signals. This discrepancy between the measured frequency scaling factors and the theoretical ones is caused by the assumption that the aperture illumination efficiency is equal for all carrier frequencies namely  $\sqrt{\eta} = 0.75$ . This is illustrated in Fig. 3 where the frequency scaling factors are given as a function of the height of the turbulent layer using the aperture illumination efficiencies estimated from the measured radiation patterns of the 5.5m Cassegrain antenna in the quasi-azimuth plane, namely  $\eta_{B0} = 0.92$ ,  $\eta_{B1} = 0.78$  and  $\eta_{B2} = 0.44$ . Fig. 3 clearly shows that in this case the relative positions of the theoretical frequency scaling factor curves correspond with the measured ones. Therefore it can be concluded that it is very important to know the exact aperture illumination efficiencies for the calculation of the short-term frequency scaling factors.



**Fig. 3** Frequency scaling factor as function of height of turbulent layer  $n = 11/3$ , measured aperture illumination efficiencies

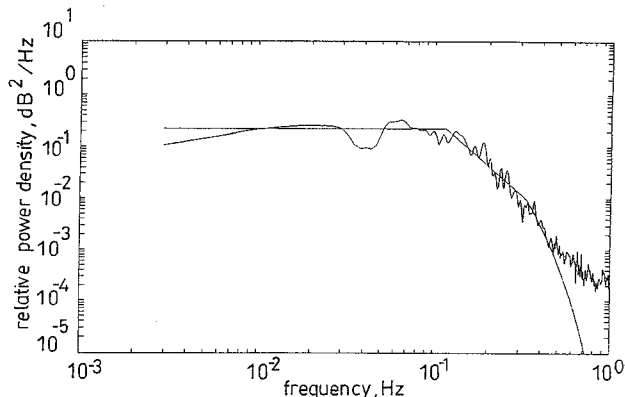
Assuming that the estimated values of the aperture illumination efficiencies are correct, the measured frequency scaling factors can be used to calculate  $n$  and  $h$ . Using eqn. 1 leads to a set of three equations, of which only two equations are independent, with two unknown variables. The calculated values of  $n$  and  $h$  are given in Table 1 as well. It can be seen that the resulting values are physically acceptable [7].

A similar analysis is performed on the wet scintillation signals measured at the EUT ground station. The short-term frequency scaling factors and the corresponding calculated values of  $n$  and  $h$  are given in

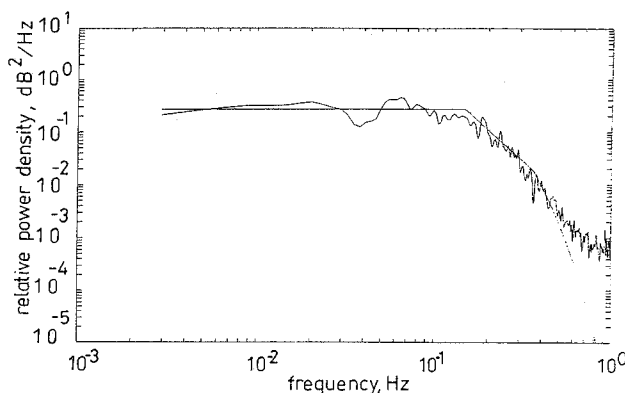
**Table 2: Short-term frequency scaling factors of wet amplitude scintillations measured on 12.5/20/30GHz beacon signals at EUT ground station**

Event	B2/B0	B1/B0	B2/B1	$n$	$h$ (m)	$C_n^2$ (m <sup>-3-n</sup> )	$v$ (m/s)
17/08/91	1.47	1.19	1.24	4.15	1750		
22/09/91	1.41	1.15	1.22	4.30	1000		
25/09/91	1.66	1.23	1.35	3.50	1000	2.61e-12	4.20
25/09/91	1.54	1.19	1.29	3.90	1000	1.25e-12	4.10
12/07/92	1.85	1.34	1.38	3.10	3000	3.96e-12	5.30

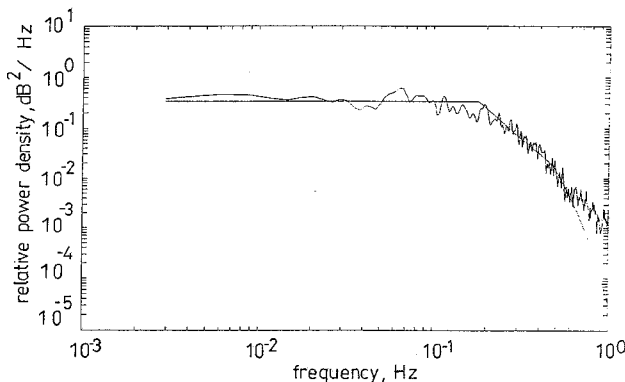
Table 2. Again, these values are physically acceptable. Furthermore, the resulting values of  $n$  and  $h$  for the wet amplitude scintillation events do not differ significantly from the values of the clear-sky amplitude scintillation events.



**Fig.4** Theoretical and experimental power spectral density function of amplitude scintillation measured on 12.5GHz beacon signal of Olympus satellite at EUT ground station  
13th June 1992, 12.00 – 12.23h GMT



**Fig.5** Theoretical and experimental power spectral density function of amplitude scintillation measured on 20GHz beacon signal of Olympus satellite at EUT ground station



**Fig.6** Theoretical and experimental power spectral density function of amplitude scintillation measured on 30GHz beacon signal of Olympus satellite at EUT ground station

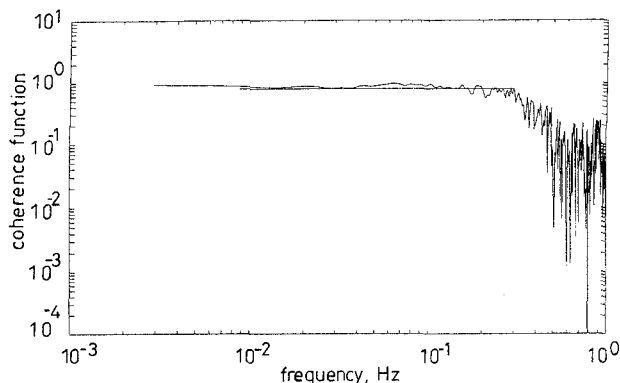
## 5 Spectral analysis

The PSD functions of amplitude scintillation events are estimated using standard data analysis procedures [5]. To verify the theory of the PSD function, the values of  $C_n^2$ ,  $h$ ,  $n$  and  $v$  are needed. Since the values of  $n$  and  $h$  are already determined from the frequency scaling factors, the refractive index structure parameter  $C_n^2$  can be calculated from the measured variance at a single frequency [2]. Then, a value of the cross path wind velocity  $v$  can be selected such that the theoretical PSD function of amplitude scintillation on one beacon signal fits the corresponding measured PSD function. Subsequently, the resulting parameters can be used to check whether the measured PSD functions of amplitude scintillation on the other two beacon signals satisfy their theoretical PSD functions as well. Figs. 4–6 show the PSD functions of amplitude scintillations measured on the three beacon signals at the EUT ground station on 13th June 1992, and the corresponding theoretical PSD functions found from eqn. 2. It can be concluded that the theoretical PSD functions fit the measured ones very well, except at the highest frequency components, where the measured functions show an enhancement with respect to the theoretical ones owing to thermal noise which has a flat PSD function. At these high-frequency components the multiplicative scintillation noise becomes smaller than the additive thermal noise. All clear-sky amplitude scintillation events listed in Table 1 and all wet amplitude scintillation events listed in Table 2 give similar results. The corresponding values of  $C_n^2$  and  $v$  are given in Tables 1 and 2. It can be observed that these values are physically acceptable as well [7]. For the first two events listed in Table 2, the values of  $C_n^2$  and  $v$  could not be determined accurately because the cut-off frequency  $\omega_s$  fell outside the range of the bandwidth within which the PSD function could be calculated. Furthermore, it can be concluded that wet amplitude scintillation can be described with the same theory as clear-sky amplitude scintillation, which indicates that wet amplitude scintillation is also mainly caused by turbulence.

## 6 Compensation of amplitude scintillation by means of ULPC

The performance of an ULPC system with respect to compensation of amplitude scintillation depends on the degree of correlation between amplitude scintillation measured on the two carrier frequencies in question: if they are highly correlated, it is possible to predict the behaviour of the amplitude scintillation at one frequency from measurement at the other so that the transmit power can be adjusted accordingly. Information about the degree of correlation between the amplitude scintillations measured on any pair of beacon

signals can be obtained from the coherence function, which provides the correlation between the spectral components of amplitude scintillation measured at two different carrier frequencies. The coherence function is defined as the ratio of the square of the cross spectral density function of amplitude scintillation experienced by two radiowaves with different carrier frequencies and the product of the corresponding PSD functions. It can be estimated using standard data analysis procedures [5].



**Fig. 7** Coherence function of amplitude scintillations measured on 20 and 30GHz beacon signals of Olympus satellite at EUT ground station

Fig. 7 shows the coherence function of amplitude scintillation measured on the 20 and 30GHz beacon signals of the Olympus satellite at the EUT ground station on 13th June 1992. It can be seen that for this event the coherence function is flat for scintillation frequencies up to approximately 0.3Hz. Measures for the degree of correlation between amplitude scintillation measured on two beacon signals operating on different carrier frequencies are the value of the coherence function in the low frequency region and the coherence bandwidth, that is the bandwidth within which the coherence function is flat. For perfect correlation, the coherence function should be equal to 1 for all spectral components.

However, amplitude scintillations measured on two different carrier frequencies are not perfectly correlated, and the degree of correlation depends on the frequencies under consideration and varies from one event to another. The range of the numerical values of the coherence function in the flat region and the range of the coherence bandwidth, obtained from the analyses of the clear-sky amplitude scintillation events presented in Table 1 and the wet amplitude scintillation events presented in Table 2, are given in Tables 3 and 4, respectively, for all beacon frequency pairs of the Olympus satellite. The degree of correlation decreases with increasing value of the ratio of the frequencies of the beacon signals in question: if the carrier frequencies are closer together, the amplitude scintillation will be more correlated.

**Table 3: Coherence of clear-sky amplitude scintillations measured on 12.5/20/30 GHz beacon signals at EUT ground station**

Beacon signals	Coherence	Coherence bandwidth (Hz)
B2/B0	0.52–0.71	0.15–0.25
B1/B0	0.71–0.83	0.20–0.27
B2/B1	0.75–0.91	0.30–0.34

**Table 4: Coherence of wet amplitude scintillations measured on 12.5/20/30 GHz beacon signals at EUT ground station**

Beacon signals	Coherence	Coherence bandwidth (Hz)
B2/B0	0.61–0.65	0.31–0.80
B1/B0	0.74–0.81	0.31–0.80
B2/B1	0.74–0.81	0.38–0.90

Generally, the measured coherence bandwidth of the wet amplitude scintillation events are larger than those of the clear-sky amplitude scintillation events. The coherence bandwidth is determined by the cut-off frequencies  $\omega_s$  and  $\omega_c'$ , of the corresponding power spectral density functions, which are proportional to the cross-path wind velocity. Since rain is often accompanied by a strong wind, the measured coherence bandwidth of wet amplitude scintillation will be larger than that of clear-sky amplitude scintillation.

It can be concluded that amplitude scintillations experienced by two radiowaves with different carrier frequencies and which propagate along the same path simultaneously are well, but not perfectly, correlated. Thus, the behaviour of amplitude scintillation on one frequency cannot be predicted exactly from measurement at the other and therefore amplitude scintillation can be compensated only partly by means of uplink power control (ULPC). Figs. 5–7 show that an ULPC system can compensate for the large slow but not for the small fast-signal fluctuations. It is demonstrated in [4] that for an ULPC system operating at 20/30GHz, the variance of the uplink amplitude scintillation (in dB<sup>2</sup>) can be reduced to about 20% of its original value.

## 7 Conclusions

The short-term frequency scaling factor of amplitude scintillation is highly variable owing to the strong non-stationary character of turbulence. It depends on various meteorological parameters and on the antenna efficiency, which are both difficult to determine. Therefore an average value of the frequency scaling factor has to be used for the compensation of amplitude scintillation by means of ULPC.

The variance and the PSD function of amplitude scintillation on a radio signal received with an antenna having a nonzero aperture diameter are well described by the equations published by Haddon and Vilar [1]. It must be noted, however, that it is very important to know the exact value of the aperture illumination efficiency. The assumption that the effective antenna diameter is 75% of the physical diameter, as proposed by Haddon and Vilar, leads to incorrect results for the events measured at the EUT ground station.

It is shown that wet amplitude scintillation is mainly caused by turbulence and can be described by the same theory as clear-sky amplitude scintillation.

The amplitude scintillations experienced by two radiowaves operating at different carrier frequencies and propagating along the same path simultaneously, are not perfectly correlated and therefore amplitude scintillation can be compensated only partly by means of ULPC.

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