Case Study of Intense Scintillation Events on the OTS Path

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***Abstract*—Selected events of enhanced field amplitude fluctuations recorded on the Orbital Test Satellite (OTS) path have been analyzed. The statistical properties of the beacon signals together with their correlation with the concurrent radiometric signal suggest that both scintillation and a variable attenuation mechanism act to produce the field fluctuations. Analysis of the coherence between the beacon and the radiometric signals gives an indication of the fluctuation frequency range over which each effect prevails. The comparison between scintillation data collected by a large (17 m) and a small (3 m) antenna indicates that the turbulence of the refractive index was particularly high during the course of the considered events.**

I. Introduction

Statistical inhomogeneities of refractivity cause short-term (0.1 to 100 s) fluctuations of the electromagnetic field amplitude on microwave links through the earth's atmosphere [1]–[6]. Turbulent fluctuations of temperature and humidity originate the clear air effects, but fluctuations of absorbing atmospheric constituents (e.g. O_2) are also responsible when the frequency of the link falls in an absorption band [7], [8]. The presence of clouds in the electromagnetic path is often accompanied by scintillation effects, which eventually can be considerably more intense than those in clear air [9], [10]. In turn, rain usually results in an appreciable mean attenuation with superimposed short-term fluctuations whose amplitude is variable from event to event as well as within the same event [11].

Field fluctuation data find application in radio link engineering as well as in remote sensing of the atmosphere. The design of microwave and millimeter wave links has to cope with the eventual severity of scintillation, especially when small size antennas, low elevation angles, and low margin systems are involved [12], [13]. Impairments in the performance of adaptive power control and interference suppressing techniques are also expected under strong signal scintillation. On the other hand, interesting remote sensing techniques have been proposed and tested that make use of microwave and millimeter wave scintillation data to retrieve meteorological parameters such as wind velocity or strength of atmospheric turbulence [14]–[18].

In this paper we confine our attention to selected strong amplitude scintillation events which occurred on the Orbital Test Satellite (OTS) experimental space-earth downlink. The analysis of the received signals suggests that two mechanisms are present, one prevailing at the lower fluctuation frequencies and the other in the higher frequency range. Statistical properties of the fluctuations of the sky temperature measured by the radiometric channel support the interpretation of the data. The availability of two antennas of different sizes allows some information on the intensity and spatial distribution of the refractive turbulence to be gained.

Manuscript received July 26, 1988; revised February 7, 1989. This work was supported in part by MPI and by CNR.

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IEEE Log Number 8929470.

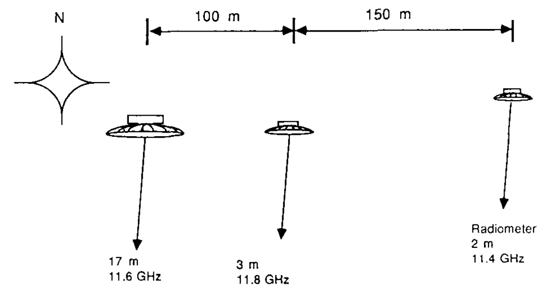

Fig. 1. Schematic representation of OTS beacon and radiometer antennas at the Fucino ground station.

II. The Experiment

The Orbital Test Satellite was launched in 1978 and remained operative until 1982 for a propagation experiment supported by the European Space Agency (ESA). The Italian ground station was operated by Telespazio S.p.A. and was located in the Fucino Plain in the central part of Italy about 100 km east of Rome, at an elevation of about 700 m above the sea level. Two antennas were used, one 3 m and the other 17 m in diameter (Fig. 1), 100 m apart, pointing directly at the satellite, whose local coordinates were 185° in azimuth and 41°30′ in elevation. The small antenna received a circularly polarized wave at 11.8 GHz, while the field received by the large one was horizontally polarized at 11.6 GHz. An ESA radiometer was also operating at the frequency of 11. 4 GHz with a 2-m antenna located at a distance of 150 m from the small antenna. Data were recorded continuously with a sampling time of 1 s.

Time series of the signals in the two beacon channels were selected from particular events for which the scintillation was considerably more intense than the average, i.e., not less than 1 dB peak-to-peak, but only a weak (lower than 0.6 dB) attenuation of the mean signal level was observed. No rain was

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detected by the rain gauges at the receiving site during the chosen events or at adjacent times, so that clouds are believed to be mainly responsible for the observed effects. Eight events having durations of two hours (three hours in one case) and occurring on eight different days in three years were arbitrarily selected. In addition, each event was segmented in five subintervals 24 min long, which were individually analyzed. Particular care was exercised in the segmentation of the events in order to reduce the effects of the eventual nonstationarities. Detrend of the time series was accomplished by a moving average routine. A standard covariance and spectral estimation routine [19] was used.

III. Results and Discussion

Fig. 2 shows the autocovariance functions of the two beacon signals and of the radiometric channel for a typical event. The autocovariance functions that have been produced for the other events possess the same kinky patterns as those reported in the figure. It has been observed [20] that the dominant characteristics of functions having such a shape may be modeled by superimposing two autocovariance functions corresponding to two independent sources of fluctuations, each prevailing in a different range of frequencies. To single out the mechanisms that are eventually responsible for the effect, the coherence functions of each beacon signal with the radiometric signal have been computed. Fig. 3 reports a typical result: the coherence function has appreciably high values at low frequencies and drops to low values at frequencies higher than 7 mHz. From the analogous behavior of the coherence functions for the other events it appears that the low frequency fluctuations of the beacon signal are coherent with the fluctuations of the absorption along the propagation path. On the other hand, low coherence appears between the high frequency beacon fluctuations and the radiometric signal. Moreover, when no absorption is present, coherence is low at all fluctuation frequencies (results are not shown here). We conclude that the variability of the absorption on the propagation path is responsible for the low frequency fluctuations of the field amplitude, while scintillation effects prevail beyond a threshold frequency which, in the present case study, for the encountered meteorological situations (mainly wind speed aloft) and for the antenna distances mentioned in the preceding section, varies between 5 and 8 mHz, according to the event considered.

The variances of the beacon fluctuations imputable to each mechanism, i.e., absorption or scintillation, have been estimated from the autocovariance functions, as sketched in Fig. 2. The corresponding standard deviations σ_L and σ_H have been so labeled according to the range of frequencies, low or high, in which each mechanism prevails. It should be noted that for the radiometric signal $\sigma_{HR} = 1.2$ K irrespective of the event. Therefore the source of the radiometric fluctuations prevailing at the higher frequencies presumably is not an atmospheric effect, but, rather, a system effect. As mentioned, the events were subdivided into 24-min periods, for which the statistical analysis was individually carried out with the intent of getting information on the temporal evolution of the scintillation process within each 2 h event. Fig. 4 reports the low frequency standard deviations σ_L of the two beacon signals as functions of the low frequency standard deviation of the radiometric signal σ_{LR}. It is observed that some frequency system instabilities affecting the 3-m antenna channel increase the dispersion of the data. Nevertheless, a correlation between the σ is apparent both for different events and within each event. Exceptions are the points close to the origin where weak fluctuations are faintly correlated with weak absorption. The observed correlation at low frequency between the intensity of the beacon amplitude fluctuations and the intensity of the radiometric fluctuations is consistent with the above assumption that the variations of absorption on the propagation path act as a common source of fluctuations both in the radiometric and in the beacon channels.

As far as the intensity of the "high" frequency fluctuations is concerned, Fig. 5 reports the standard deviations σ_H of the two beacon channels as functions of the radiometric σ_{LR}. It can be noted that each event is characterized by a minimum intensity of scintillation which is quite variable from one event to another. The variability of the minimum σ_H is attributed to the variable strength of the refractive turbulence, which depends on the atmospheric dynamics existing during each event, irrespective of the absorption on the path. For all the events the scintillation tends to increase with increasing σ_{LR}, the increase being considerably larger for the 3-m antenna channel. Indeed, enhanced fluctuations of the sky temperature are indicative of stronger inhomogeneities of the relevant atmospheric parameters (e.g., cloud density, thickness, temperature, etc.) and are expected to be associated with an increase of the strength of turbulence in the course of each event. On the other hand, the effect of the dimensions of the receiving apertures on the amplitude scintillation is consistent with the existing theory and observations. When the σ of the beacon signals are considered against the sky temperature rather than its fluctuations, a behavior analogous to that of Fig. 5 is observed, consistent with the observations by Vanhoenacker and Vander Vorst [10].

An interesting point is the comparison between the intensities of scintillation in the two beacon channels connected to receiving apertures with different dimensions. Fig. 6 reports the standard deviation of scintillation in the 17-m antenna channel vs. the one in the 3-m antenna channel. The trend of the experimental points appears to be consistent both within each event and from one event to another, with a slight nonlinearity in the region of low scintillation intensities. The influence of the receiver aperture size on the intensity of the field amplitude scintillation has been studied both theoretically and experimentally [1], [21]–[23], [9], [11]. The ratio between the variances for receiving apertures with diverse sizes has been related to an effective turbulent path, directly connected with the thickness h either of a ground-based turbulent slab or of an elevated turbulent layer modeling the scintillation process [24], [17]. The variance of the scintillation, in turn, can be expressed in terms of the path integrated refractive index structure constant C_n^2, once the effective turbulent path is known. Curves with constant values of C_n^2 and h have been calculated from the ground-based turbulent slab model and are reported on the same Fig. 6. The estimated values of C_n^2, on

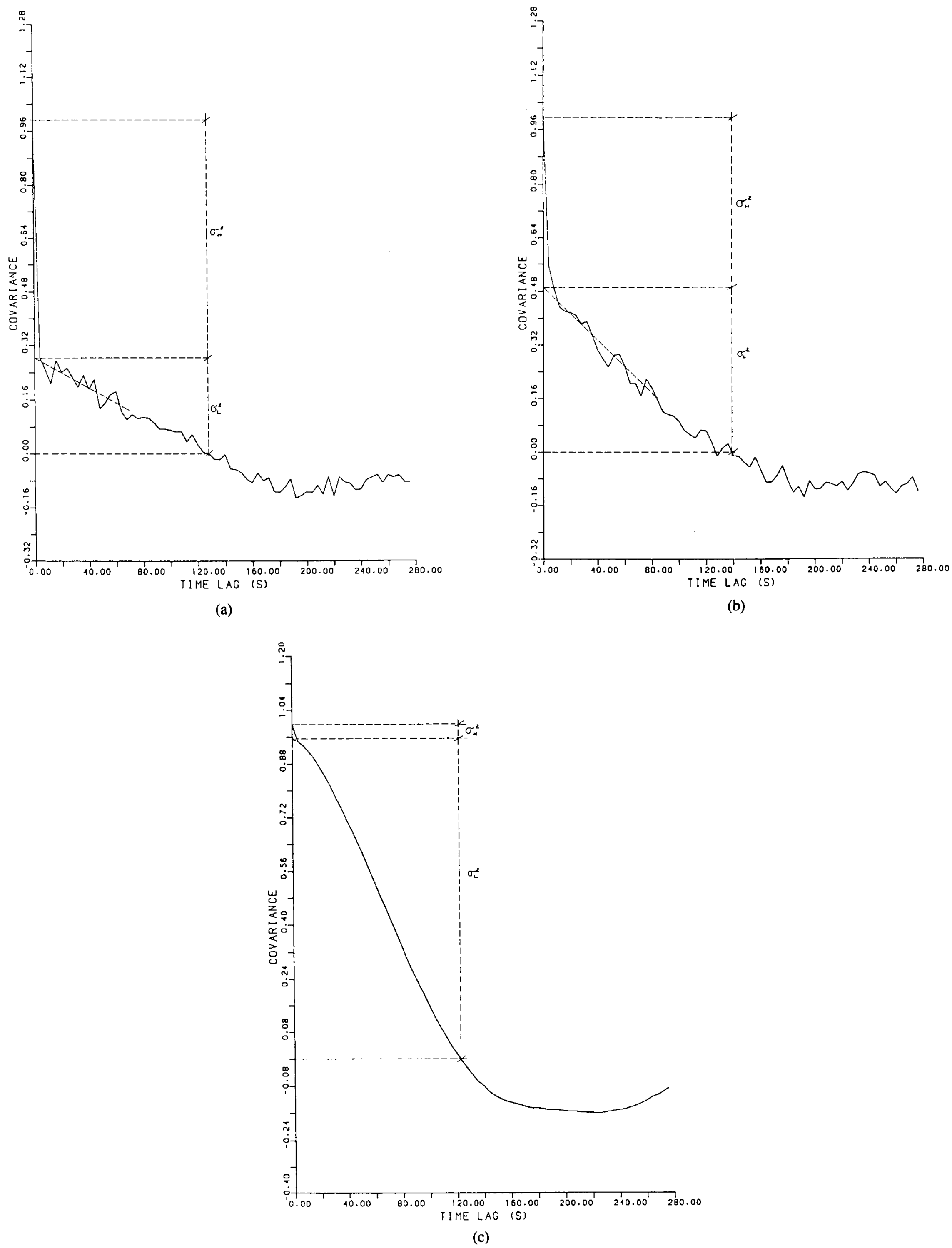

Fig. 2. Autocovariance functions of fluctuations for event on August 8, 1979, 12:00–14:00 GMT. (a) Field amplitude received by 3-m antenna. (b) 17-m antenna. (c) Atmospheric brightness temperature.

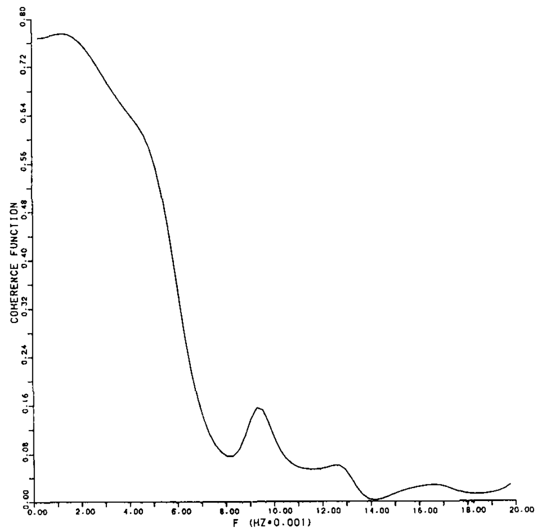

Fig. 3. Coherence function between field amplitude fluctuations received by the 3-m antenna and the atmospheric brightness temperature fluctuations for event on August 8, 1979, 12:00–14:00 GMT.

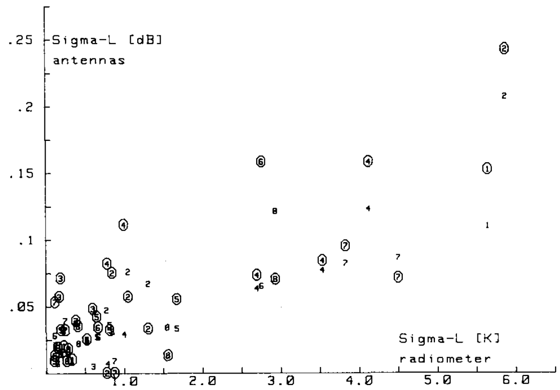

Fig. 4. Low frequency rms field amplitude fluctuations σ_L versus low frequency rms fluctuations of atmospheric brightness temperature σ_{LR} for individual 24 min segments of eight long duration events, numbered 1 to 8. Circled numbers refer to 3-m antenna data, others to 17-m antenna data.

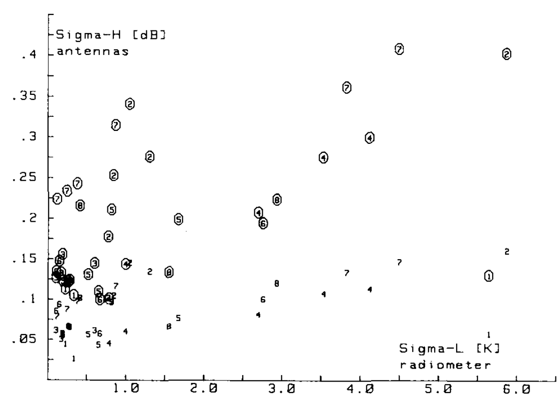

Fig. 5. High frequency rms field amplitude fluctuations σ_H versus low frequency rms fluctuations of atmospheric brightness temperature σ_{LR} for the same segments of the eight events as in Fig. 4.

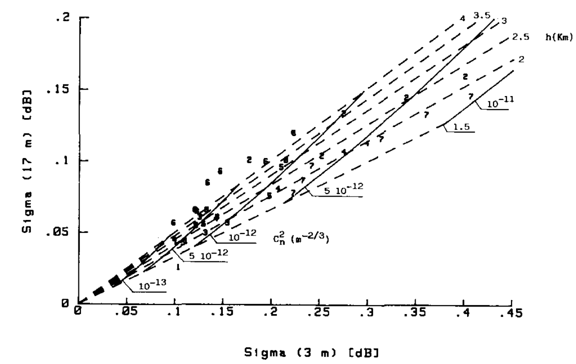

Fig. 6. High frequency rms field amplitude fluctuations received by the 17-m antenna versus the 3-m antenna ones for the same segments of the eight events as in Fig. 4. Theoretical curves for constant turbulent slab thickness h (broken lines) and for constant C_n^2 (continuous lines) are also shown.

the average, are higher than those usually reported in the literature [24], [17]; however, it should be remembered that they do not refer to the mean situation, but to particular events of enhanced scintillation.

A spectral analysis was also carried out on the time series of the two beacon signals and on the radiometer output for the considered events. As mentioned, the time series were detrended via a moving average routine before Fourier transformation, so that frequencies below about 3 mHz were cut off. As an example representative of the obtained results, Fig. 7 reports the spectra for the same 2 h event to which Figs. 2 and 3 refer. The spectrum of the radiometric signal fluctuations decreases steadily with a slope that, on the average, is close to $-8/3$, before entering into a flat region where the system noise prevails. Since the radiometric signal fluctuations can be reduced to temporal fluctuations of the atmospheric water associated with the turbulent irregularities transported by the wind across the beam of the radiometer, the

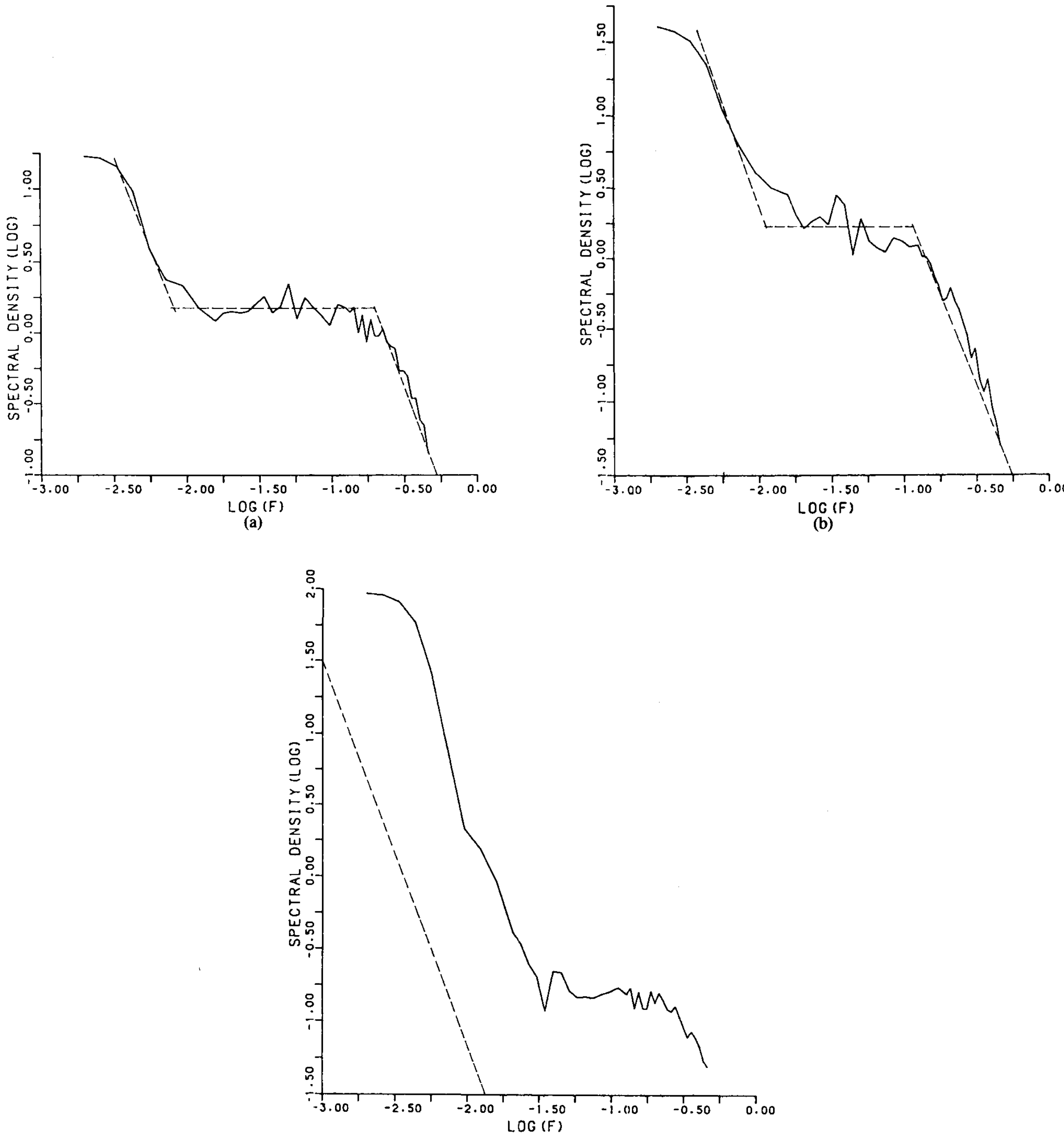

Fig. 7. Spectra of fluctuations for event on August 8, 1979, 12:00–14:00 GMT. (a) Field amplitude received by 3-m antenna. (b) Field amplitude received by 17-m antenna. (c) Atmospheric brightness temperature. Lines with $-8/3$ slopes are also shown.

Kolmogorov model of turbulence appears to account for the observed behavior of the atmospheric brightness temperature fluctuations [25], [26]. On their hand, the spectra of the beacon signals show three regions, analogous to those derived theoretically [7] or observed experimentally [8] when an absorption mechanism is present on the propagation path together with the refractive index turbulence. In our case the moderate increase of the atmospheric brightness temperature detected by the radiometer denotes that absorption indeed exists, probably primarily due to cloud liquid water. A Kolmogorov model for the water density fluctuations, again, seems to be consistent with the observed spectral shape of the beacon field amplitude fluctuations.

IV. Conclusion

Field scintillation on space-earth paths appears to be generally enhanced when clouds are present. The cloud liquid water, whose irregular spatial distribution contributes to an increase in the fluctuations of refractivity and in turn the scintillation, is also responsible for coexisting attenuation.

Field amplitude fluctuations produced by scattering from refractive index irregularities combine with the concurrent fluctuations caused by the variability of the atmospheric water, as indeed is implied by the peculiar shapes of spectra. Analyzing the coherence between the beacon and the radiometer signals may help to single out the two different fluctuation mechanisms.

Acknowledgment

Telespazio S.p.A., Roma, kindly provided OTS data.

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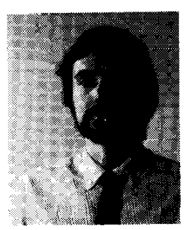

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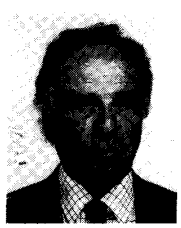

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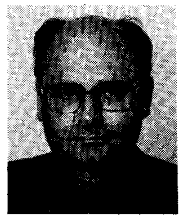

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