

Ionospheric Amplitude & Phase Scintillations at Multiple Frequencies

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Simultaneous scintillation observations for both amplitude and phase from the ATS-6 beacon experiments for signals at 40 and 140 MHz, recorded at Lindau (51°6'N; 10°1'E) have been analyzed. It has been found that a combination of 1 sec sampling period and a value of about 200 for the filter-coefficient for a digital high pass filter gives reasonable value of scintillation index S_4 . The average value of spectral index n varies from 1.4 to 1.5 both in case of weak as well as strong scintillation cases. For a power-law irregularity spectrum of the form K^{-p} , the value of p derived from actual spectra varies from 3.5 to 4.9 for 40 MHz and from 3.2 to 4.2 for 140 MHz against the value of 3.6 predicted by n based on weak scintillation theory. The autocorrelation functions behave quite well in accordance with the expectations of the theory. For strong scintillation cases the data show broadening of spectrum and a relative difference in the behaviour of autocorrelation functions. The high frequency roll-off rate is sometimes smaller at 140 MHz than at 40 MHz which is contrary to the results published in literature. In the case of phase scintillations the slope of the spectrum varies from 2.1 to 2.6 and does not show any systematic trend as we pass from weak scintillations to strong ones.

1. Introduction

Scintillations due to electron density fluctuations have been observed on line-of-sight paths through the ionosphere at frequencies ranging from about 10 MHz to several GHz in the form of amplitude, phase and angle-of-arrival fluctuations. By studying these fluctuations, one can learn much about the characteristics of the irregularity embedded medium.¹⁻⁶ Simultaneous scintillation data for both amplitude and phase from the ATS-6 beacon experiments for signals at 40 and 140 MHz, recorded at Lindau (51°6'N, 10°1'E) during the period Sep. 1975 to Aug. 1976 have been analyzed to study the characteristics of the scintillation phenomena.

2. Theory of Scintillations

2.1 Weak Scintillations

In the analytical study of the scintillation phenomena, one has to solve the inhomogeneous wave equation for the electric field. First order perturbation techniques provide solutions in the limit of single scatter (weak scintillation). Two of the methods used are known as the Born⁷ and Rytov⁸ approximations. For weak scintillations both yield similar results.

The scintillation index S_4 is a very important quantity in characterizing scintillation. It is the

normalized second moment of the intensity I of the wave and is given by

$$S_4^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} \quad \dots(1)$$

For single scattering Wernik and Liu⁹ showed

$$S_4^2 = 2\pi^2 K^2 L (f_p/f_i)^4 \int_0^\infty F_F(K) \phi_N(K) dK \quad \dots(2)$$

where

$$F_F(K) = 1 - \frac{2K}{K^2 L} \sin [K^2 L / 2K] \cos [K^2 / (KZ - L/2)] \quad \dots(3)$$

and

- L Thickness of the irregularity slab
- Z Distance from the ground to the top of the irregularity slab
- K Spatial wave number vector
- $\phi_N(K)$ Power spectrum of the electron density irregularities
- f_i Transmitted signal frequency
- f_p Plasma frequency of the background
- K Wave number, equal to $2\pi f_i/c$
- c Velocity of light

The quantity $F_F(K)$ is known as Fresnel filtering function. Due to the fact that it multiplies the irregularity spectrum, it turns out that the effects of those irregularities of the Fresnel size ($\sqrt{\lambda(2Z-L)}$) make the largest contribution to the scintillation. In the temporal spectrum the Fresnel zone size can be related to F_F which is the point at which the spectrum begins to roll off, and hence we get

$$f_f = \frac{V}{\sqrt{\lambda(2Z-L)}} \quad \dots(4)$$

Thus from an experimental spectrum, by deducing the Fresnel frequency f_f and knowing the height, the velocity V of the irregularity may be inferred.⁶

For a power law irregularity spectrum and under single scatter approximation, Jokippi and Hollweg¹⁰ showed that

$$n(f_a/f_b) = \log(S4_a/S4_b)/\log(f_b/f_a) \quad \dots(5)$$

where

$$n = (p + 2)/4 \quad \dots(6)$$

f_a, f_b Transmitted frequencies

p Power law exponent

The high-frequency asymptote can also be shown⁴ to be equal to f^{1-p} .

2.2 Strong Scintillations

In sharp contrast to single scatter problem, the multiple scatter problem is so complex that in simplifying it to a level at which it can be handled, the results can only be compared semi-quantitatively with observations.

Liu *et al.*¹¹ and Yeh *et al.*¹² have done theoretical computations which have shown that under multiple scatter theory it is no longer possible to obtain a constant exponent n that describes the frequency dependence of the scintillation index $S4$. Also, under certain conditions, the index $S4$ can be greater than unity. This is known as the focussing effect.¹²

Concerning the power spectra of strong scintillations, Rumsey¹³ and Marians¹⁴ have done some theoretical computations using the phase screen model. Their results indicate that under strong scintillation, the power spectrum will broaden while the slope of roll-off will remain same as under single scatter conditions. Liu *et al.*¹¹ and Yeh *et al.*¹² showed that under multiple scatter effects the correlation distance (distance for the correlation to decrease to 0.5) would increase with increasing transmitted frequency, though it would decrease under single scatter case.

2.3 Phase Scintillations

In case of phase fluctuations one has to consider only mean square phase fluctuations in place of $S4$ for amplitude scintillations as the phase index is very much affected even by low frequency fluctuations and the process cannot be considered stationary in this case. The single scatter theory predicts the frequency dependence of $\langle \phi^2 \rangle$ as f^{-2} .

Fremouw *et al.*¹⁵ have proposed a two-component scintillation model, a slow component with large phase fluctuations and a fast component with both phase and amplitude fluctuations and this may explain some of the observed features not otherwise explained by other existing models.

3. Data and Method of Analysis

Linearly polarized signals transmitted from the ATS-6 satellite (0°N; 35°E) at carrier frequencies of 40, 140 and 360 MHz were recorded at Lindau (51°6'N; 10°1'E) during the period Sep. 1975 to Aug. 1976. In the present work data on A40, A140 and DD40 have been analyzed to study the amplitude and phase scintillations. The details of various types of measurements, calibration procedures and data pre-editing problems have been given by Davies *et al.*¹⁶

3.1 Amplitude Scintillations

3.1.1 Scintillation index $S4$ — The signals were sampled at the rate of 10 Hz. The data were plotted to locate the periods of scintillations. A number of segments of data which appeared stationary to the eye and were of sufficient time-duration were chosen for the analysis. To obtain a measure of intensity of the fading and its characteristics, we computed the scintillation index $S4$ from Eq. (1) where I was replaced by the square of the amplitude of the received signals. Due to the fact that we anticipated computing power spectra which are sensitive to large low frequency trends, we passed all the data through a weighted running mean high-pass digital filter. To decide that the cut-off frequency would be appropriate for filtering the data, we calculated $S4$ for different sampling periods ranging from 0.1 to 2 sec for each filter coefficient ranging from M equal to 10 to 100 (filter coefficient = $2M + 1$) as the cut-off frequency depends on both of these parameters. It may be seen from Fig. 1 that a combination of 1 sec sampling period and a value of about 200 for filter coefficient would give a reasonable value of $S4$ and would also result in saving of computer time. Therefore, each second, ten of the original 0.1 sec samples were averaged together to make the final sampling rate as 1 Hz. The detrended data were at almost

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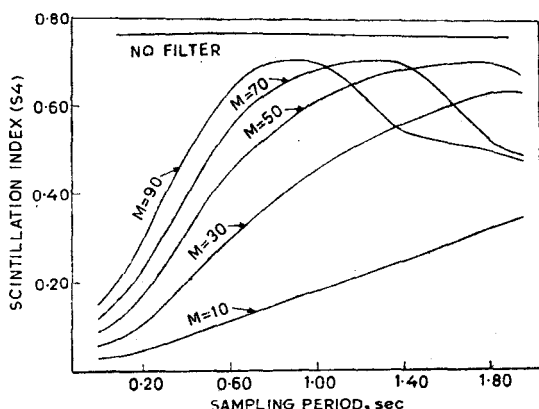


Fig. 1 — Effect of the sampling period and the number of filter coefficients ($2M + 1$) on scintillation index (S_4)

zero mean and 180° out of phase with the input. Also due to transient response of the filter, a number of data points equal to number of filter coefficients had to be discarded.

With the data detrended, we again calculated S_4 . However, before doing so, the 180° phase shift was removed and the mean restored, because the inversion of data changes its features, and also since S_4 is essentially the normalized variance of the intensity fluctuations, the mean is a very important quantity. As a final check for stationarity, we set up the criteria that for a sufficiently long period of data (~ 20 min) the standard deviation of S_4 for the various blocks should be less than 15%.

To have a feel for the data, two sample records are shown in Figs. 2 and 3.

3.1.2 Power spectra — In recent years, the use of the power spectrum of the temporal amplitude fluctuations to study the ionospheric irregularities has gained recognition. To compute the power spectra, we chose to utilize the fact that the spectrum is the Fourier transform of the autocorrelation function. This proved to be a good choice since the behaviour of the autocorrelation function is itself of interest and can also be used to calculate the Bessel spectrum.

Due to the fact that our data segments do not extend to infinity, the resulting spectra will only be an estimate of the true spectra.¹⁷ Further, the autocorrelation function can only be computed for a finite number of lags. By truncating this function, we are in effect multiplying it by a "window function" and hence our estimated spectra will be convolved with the Fourier transform of the window function. We used the Hanning window which has very small sidelobes though a wider main lobe. A wider window in time will produce a narrower window in frequency and thus allow frequency components which are closer together to be resolved.

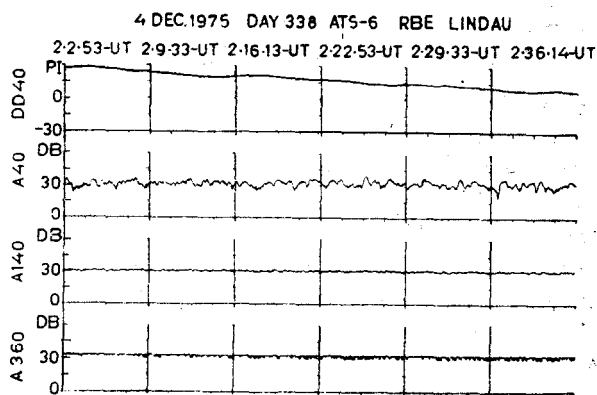


Fig. 2 — Sample records of weak amplitude oscillations

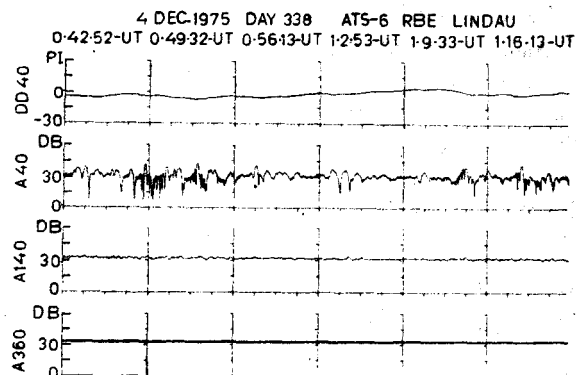


Fig. 3 — Sample records of strong amplitude oscillations

At the same time, however, it must be realized that computing an increased number of lags for the same length of data will decrease the number of degrees of freedom and hence the stability and reliability of the spectrum. For our data, a resolution of 0.005 Hz was considered necessary, and hence 200 lags were computed for all cases. The power spectrum is evaluated only at discrete frequencies since it is done digitally. Therefore, it is desirable to space the frequencies rather closely to avoid what is known as the picket fence effect.¹⁸ This can be done without altering the present data by merely adding zeros to the end of the autocorrelation function.

3.1.3 Bessel spectra — We will now consider the computation of the Bessel spectrum. Due to low frequency components in the autocorrelation function, it was found necessary to use a pre-whitened version of the Bessel transform.¹⁹ To compute the Bessel spectrum the differentiated autocorrelation function was multiplied by the Gaussian lag window, and the resulting integrand was integrated using Simpson's rule.⁶ Before plotting, the pre-whitening was removed by dividing each frequency component by its frequency.

3.2 Phase Scintillations

3.2.1 Mean square phase fluctuations — The signals were detrended by a digital filter. The detrended time series of DD-40 were then used to compute mean square phase fluctuations $\langle \phi^2 \rangle$.

3.2.2 Phase power spectra — The phase power spectra for 40 MHz were calculated using a procedure similar to amplitude records after calculating autocorrelation function from the mean square phase-time series instead of intensity-time series. Attempts shall be made whenever possible to interpret the data using theoretical results from model studies.

4. Experimental Results

4.1 Amplitude Scintillation Index S_4

The computed scintillation index S_4 for the frequencies 40 and 140 MHz are shown in Table 1. There are seven cases of weak scintillations (A) with $S_4 < 0.5$. The spectral index n is relatively constant with a mean value of about 1.4

Table 1 — Scintillation and Spectral Indices

Time (UT) LT=UT+1 hr	S_4		n	p	
	40 MHz	140 MHz		40 MHz	140 MHz
A. Weak Scintillations					
3 Dec. 1975					
2130-2150	0.32	0.05	1.42	4.2	3.2
2150-2210	0.43	0.07	1.46	3.6	3.5
2210-2230	0.43	0.08	1.29	3.5	3.4
2230-2250	0.49	0.10	1.27	4.2	3.6
2250-2310	0.38	0.07	1.39	3.8	3.7
2310-2330	0.44	0.08	1.34	3.8	3.6
5 Dec. 1975					
0144-0204	0.42	0.06	1.58	4.5	3.6
B. Medium Scintillations					
4 Dec. 1975					
0136-0156	0.54	0.10	1.39	4.0	3.9
0223-0243	0.63	0.08	1.62	4.3	3.7
0243-0303	0.63	0.10	1.47	4.2	4.1
5 Dec. 1975					
0003-0023	0.55	0.08	1.52	4.0	3.8
0023-0043	0.53	0.09	1.43	4.6	4.2
C. Strong Scintillations					
3 Dec. 1975					
2330-2350	0.85	0.13	1.50	4.1	3.7
4 Dec. 1975					
0003-0023	1.12	0.16	1.56	4.2	3.2
0023-0043	0.90	0.15	1.43	4.6	4.0
0036-0056	1.14	0.15	1.62	4.9	3.9

which, assuming a power law irregularity spectrum, would correspond to a value of about 3.6 for p . This value is lower than that reported by Rufenach⁵ and Umeki *et al.*⁶ They found n equal to 1.6 and hence $p = 4.4$.

In Table 1, there are five cases of medium scintillations (B) with S_4 at 40 MHz lying between 0.5 and 0.75. Here again, n is more or less constant with a mean value of 1.4 and hence giving p equal to 3.6. Again, in Table 1, there are four cases of strong scintillations (C) with S_4 (40 MHz) more than 0.75. Again n is more or less constant with a mean value of 1.5 and thus giving a value of 4 for p .

In two of the cases the value of the 40 MHz S_4 index is more than 1 and according to theory this should correspond to a strong multiple scatter effects. However, these results are quite different from those reported by Umeki *et al.*⁶ who found that spectral index n decreases to about 0.9 for very strong scintillation cases. Present results show that even in the case of strong scintillations n is about 1.6 and thus n has increased instead of decreasing. Thus it may be seen from the present results that the spectral index n does not show any distinction between weak and strong scintillations.

4.2 Power Spectra of Amplitude Scintillations

To simplify the interpretation of the spectra, the autocorrelations were calculated for 200 lags in all the cases. Since the portion of the spectrum which is of interest is usually between 0.01 and 0.1 Hz, it was felt that 200 lags would provide sufficient resolution (0.005 in case of Fourier spectrum).

The computed Fourier spectra for 40 and 140 MHz for a typical weak scintillation case are shown in Fig. 4. Both the spectra are at about the same

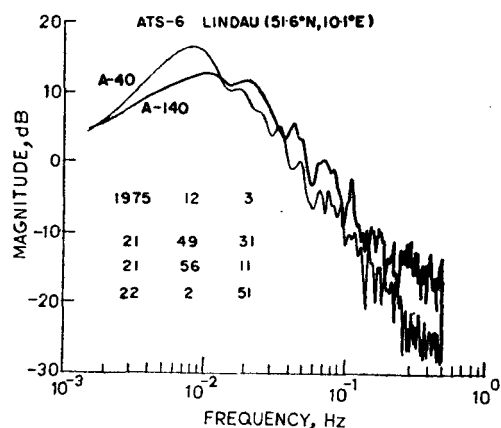


Fig. 4 — Superimposed amplitude spectra of 40 and 140 MHz for a weak scintillation case

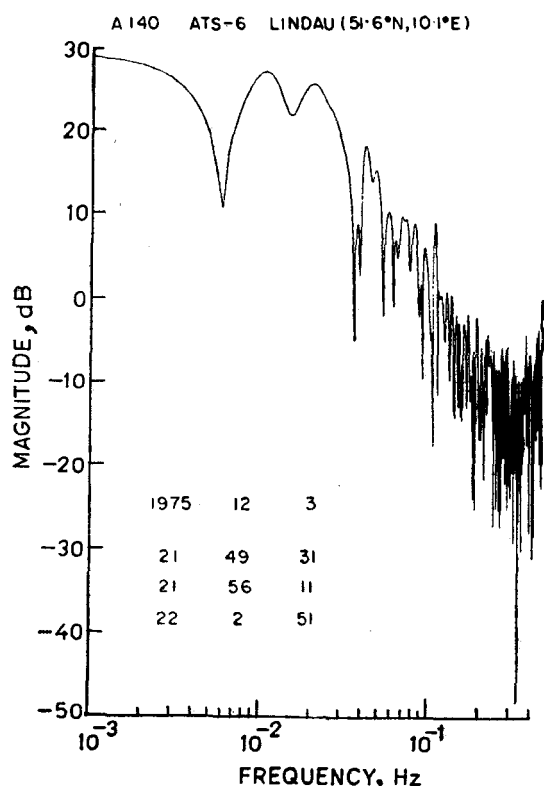


Fig. 5 — Bessel spectrum of 140 MHz signal for the set corresponding to Fig. 4

level due to the fact that the autocorrelation functions were normalized to unity at zero lag. The slope of the high frequency roll-off is proportional to $f^{-2.6}$ in the case of 40 MHz and to $f^{-2.5}$ in the case of 140 MHz. The roll-off rate for this set of data is consistent with that observed by others^{1,3,6} and for a power law irregularity spectrum corresponds to a p -value of 3.5, which is in agreement with the value of p obtained from the frequency dependence of S_4 in Section 4.1. It should, however, be noted that the present results of weak scintillations are quite different in comparison to results reported by other workers in the following aspects.

(i) The high frequency roll-off rate is different at 140 MHz than at 40 MHz in several cases, being smaller at the higher frequency as may be seen from Table 1.

(ii) Though in most of the cases, the value of p at 140 MHz spectrum is consistent with that derived from frequency dependence of S_4 , yet in many of the 40 MHz cases the value of p derived from Fourier spectrum is greater than that derived from frequency dependence of S_4 . The value of p for 40 MHz scintillations varied from 3.5 to 4.9 which is in agreement with that reported by Umeki *et al.*⁶ However, the value of p for 140 MHz varied

from 3.2 to 4.2 which is slightly lower than the value of p at 140 MHz reported by Umeki *et al.*⁶

The Fresnel frequency which corresponds to the point at which the spectrum begins to roll off is theoretically proportional to the square root of the transmitted frequency. In this respect, the present results correspond quite well with the theory as the 140 MHz spectrum begins to roll off, in general, at a frequency of about 2 times that of the 40 MHz spectrum. From Eq. (4) we can see that the Fresnel frequency can be related to the horizontal drift velocity of the irregularity if height and slab thickness are assumed. Using $Z = 400$ km and $L = 100$ km based on previously obtained model parameters,⁶ we get $V = 37$ m/sec which is in good agreement with the value of 45 m/sec reported by Umeki *et al.*⁶

Fig. 5 shows the Bessel spectrum which corresponds to the second case for the 140 MHz signal under weak scintillations. Although some of the high and low frequency portions of the spectrum have to be discarded due to instabilities, it can be seen that the Bessel spectrum shows considerably deeper modulation than the Fourier spectrum. The correspondence in the location of peaks and minima is also quite good. However, the minima do not appear at $f_1 \sqrt{m}$ pattern, and at times, two minima appear where there is only one in the Fourier spectrum. These results are in agreement with those reported by Umeki *et al.*⁶

Let us now consider the spectra for one of the strong scintillation cases (Fig. 6). At 140 MHz we are still in the weak scatter regime and the spectrum shows, in general, a distinct frequency at which the roll-off begins, though appreciable broadening makes

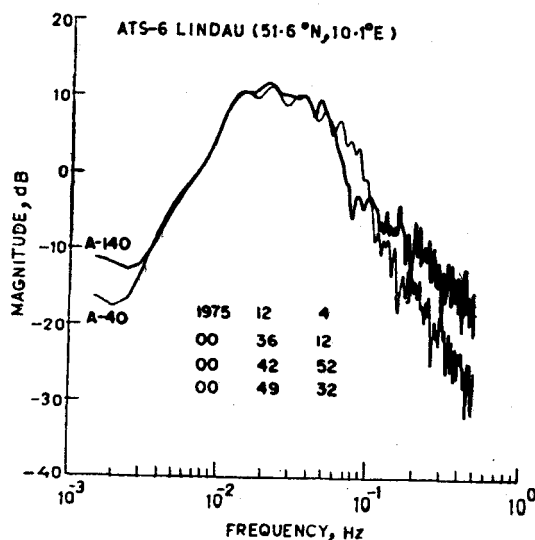


Fig. 6 — Superimposed amplitude spectra of 40 and 140 MHz for a strong scintillation case

its presence felt. At 40 MHz where the scintillation is quite strong, the spectrum shows clear broadening as it rolls off. In this case the frequency at which 140 MHz spectrum begins to roll off is no more than 2 times that corresponding to 40 MHz spectrum, which shows a clear violation of weak scintillation theory. However, there is more or less no difference in the behaviour of p value obtained in the case of strong and weak scintillation cases.

4.3 Correlations for Amplitude Scintillations

The autocorrelation functions for 40 and 140 MHz frequencies comprising one each of the weak and strong scintillation sets are shown in Fig. 7. It may be noticed that the correlation time (time for the correlation to decrease to 0.5) decreases with increasing frequency in case of weak scintillations. However, for strong scintillations this is

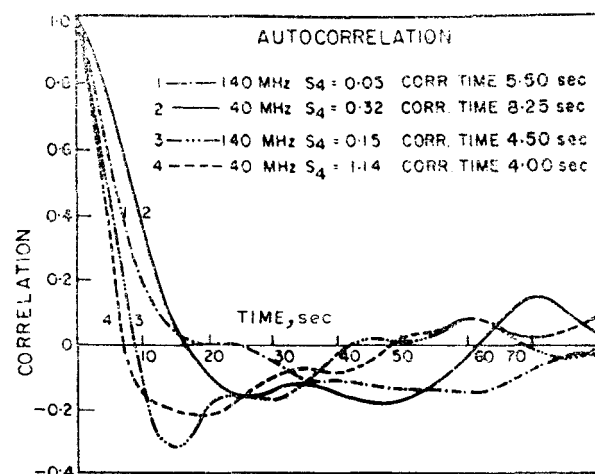


Fig. 7 — Superimposed autocorrelation functions of 40 and 140 MHz for weak and strong scintillation cases

Table 2 — Mean Square Phase Fluctuations

Time (UT) LT=UT+1 hr	rad ²	S4	Slope
3 Dec. 1975			
2150-2210	0.11	0.43	2.6
2310-2330	0.26	0.44	2.2
2210-2230	1.17	0.43	2.4
2230-2250	0.12	0.49	2.2
2250-2310	0.43	0.38	2.3
4 Dec. 1975			
0203-0223	0.59	0.50	2.1
0243-0303	1.32	0.62	2.6
0003-0023	2.47	1.12	2.4
0323-0353	0.86	0.65	2.6
0043-0103	2.30	1.34	2.4

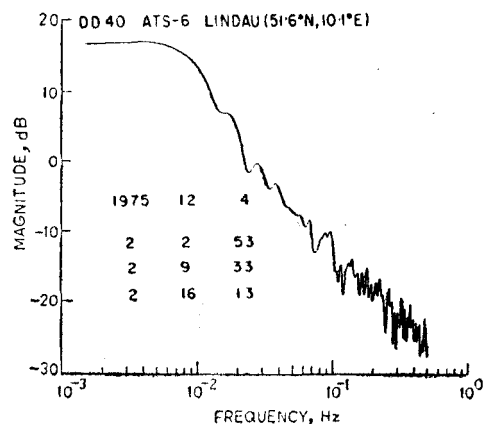


Fig. 8 — A typical phase spectrum for a weak scintillation case

no more the case and the correlation time at 140 MHz is rather smaller than at 40 MHz.

4.4 Phase Scintillations

The signals were first detrended by a digital filter with a cut-off frequency of 0.005 Hz. The detrended time series were then used to compute the various statistics of the signals. Table 2 lists the mean square fluctuation of the phase at 40 MHz along with S4 index. The mean square values of the phase fluctuations were found to depend on the cut-off frequency used in the detrending process, as the cut-off frequency was decreased, values increased, while the S4 indices for the intensity did not change very much. This is due to the fact that the phase fluctuations are sensitive to large irregularities while intensity fluctuations are not affected much by irregularities larger than the Fresnel size. Therefore, the phase fluctuations become larger when the lower frequency contributions from large irregularities are taken into account. In some cases, when individual records of 400 sec duration were processed, it was found that two records with apparently similar fluctuations had more or less same value of S4 even if some large irregularity component (low frequency fluctuation) was present, while the $\langle \phi^2 \rangle$ value changed drastically in such records. This corroborates the above statement and hence such records are not considered here. As 140 MHz phase records were not available, no further characteristics of phase fluctuations can be derived from $\langle \phi^2 \rangle$ values.

Another quantity of interest is the correlation time for phase scintillations. The phase fluctuations were found to be much better correlated than the amplitude. The correlation time for the phase fluctuation was found to be 3 to 5 times longer than the corresponding amplitude correlation time. This is consistent with the fact that the major contributions

to phase fluctuations come from irregularities greater than the Fresnel zone size. This result is in agreement with that reported by Myers *et al.*²⁰

Fig. 8 shows a typical phase spectrum for a weak case. The power law behaviour of the spectrum extends to the low frequency end, and is in agreement with the results reported by Crane⁵ and Myers *et al.*²⁰ The slope of the spectrum is given by $\nu = 2.1$ in this particular case. It may be seen from Table 2 that ν varies from 2.1 to 2.6 and does not show any systematic trend as we pass from weak scintillations cases to strong ones. This result is again in contrast to that reported by Myers *et al.*²⁰ who found that for weak scintillations the exponent ν was found to be around 3.8 and only for strong scintillations it reduced to 2.1.

5. Discussion

Umeki *et al.*⁶ have shown that for weak scintillations the existing models fit the experimental data quite well giving an f^{-n} frequency dependence for the scintillation index S_4 . In their case n was found to be about 1.5, thus giving a value of p equal to 4 for power law irregularity spectrum. From spectrum analysis also they found that p varied from 4 to 4.5 for both 40 and 140 MHz. However, the present results show that even in case of weak scintillations the agreement between theory and experimental results is not very good. It has been found that the average value of spectral index n varies from 1.4 to 1.5 both in weak and strong scintillation cases and does not decrease even for very strong scintillations with S_4 greater than 1. The value of p derived from actual spectra varies from 3.5 to 4.9 for 40 MHz which is higher than that derived from n in several cases. For 140 MHz p was found to vary from 3.2 to 4.2 which is quite in agreement with p derived from n values. In the case of strong scintillations n did not decrease as expected from multi-scatter theory. The power spectra remain more or less unchanged except that it showed a broadening around the Fresnel frequency. Thus it may be concluded that existing theories are not fully confirmed by present scintillation data even in case of weak scintillations.

The autocorrelation functions behave quite well in accordance with expectations of the theory, i.e. correlation time for 140 MHz is smaller than that for 40 MHz in case of weak scintillations, but the situation reverses for strong scintillations. This is quite in agreement with the results reported by Umeki *et al.*⁶

The Fresnel frequency derived from the power spectrum is also quite in agreement with the theory.

For weak scintillation, the roll-off for 140 MHz begins at a frequency which is about 2 times that of roll-off at 40 MHz, thus showing $\sqrt{f}$ dependence. This rule is clearly violated for the case of strong scintillations and the results are in agreement with those reported by others.

The mean square values of the phase fluctuations were found to depend on the cut-off frequency of the data detrending process which is in agreement with the results reported by Rino *et al.*²¹ and Myers *et al.*²⁰ The phase spectra showed power law behaviour all the way to the low frequency end. The spectra flattened for strong scintillations. However, the slope of the spectra was very low giving the value of ν between 2.1 and 2.6 and did not show any systematic trend as one passes from weak to strong scintillations. This is in contrast with the results of Myers *et al.*²⁰ who found ν to be as high as 3.8 for weak scintillation cases and reducing to 2.1 only in the case of strong scintillations.

There is no discrete demarcation between weak and strong scintillations. The arbitrary limit of $S_4 < 0.5$ does not seem to be very satisfactory as there is no distinction between weak and strong cases for several features. On the other hand some features such as correlation time show distinct change from weak to strong cases with this limit of $S_4 = 0.5$. Such change in behaviour might be caused either due to wrong demarcation limit, or the existing theories have to be modified in order to explain the observed scintillation behaviour even in the case of weak cases and the demarcation between the weak and strong scintillations has to be clearly defined.

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