Pramāṇa, Vol. 8, No. 1, 1977, pp. 1-13. © Printed in India.

Amplitude scintillations of ATS-6 radio beacon signals within the equatorial electrojet region (Ootacamund, dip 4° N)

R G RASTOGI, M R DESHPANDE, HARI OM VATS,
K DAVIES,* R N GRUBB* and J E JONES*
Physical Research Laboratory, Ahmedabad 380009
*NOAA Environmental Research Laboratories, Space Environment Laboratory
Boulder, Colorado 80302, USA

MS received 28 May 1976; in revised form 21 October 1976

Abstract. The recordings of the amplitudes of radio beacon signals on 40, 140 and 360 MHz from ATS-6 (at 34° E longitude) recorded at Ootacamund, India (11·43° N, 76·70° E, dip 4° N, elevation angle 41°) have revealed largest occurrence of scintillations for about 60% of cases around 2200 hr during the nighttime, and two secondary peaks (25% of cases) around 0900 hr and 1400 hr during the daytime.

During the daytime, the scintillation decreases approximately as the inverse of the frequency for higher frequencies while for lower frequencies the law is valid till scintillation index at 40 MHz does not exceed 0·9. The temporal variation of daytime scintillation shows impulsive character, the duration of activity lasts for 1–2 hours at a time.

During the nighttime, the scintillation decreases inversely with frequency for weak and moderate scintillation activity. The scintillation index at 360 MHz becomes independent of that at 140 MHz when the index at 140 MHz exceeds 0·85. For the set of frequencies 40–140 MHz, on some occasions scintillation index at 40 MHz is seen to be less than that at 140 MHz. The nighttime scintillations are in general stronger and remain so for extended length of time.

The daytime scintillations are suggested to be due to blanketing or some other non-*q* type of sporadic *E* layer. The nighttime scintillations are most probably due to spread *F* condition and the abnormal frequency variation of the scintillations may be due to multiple scattering layer during periods of intense spread *F*.

Keywords. Ionospheric scintillation; radio beacon signals.

1. Introduction

Soon after the discovery of the cosmic radio noise, it was found that the amplitude of the signals from a discrete radio source fluctuated with about one fade per minute (Hey *et al* 1946). The spaced site observations of these signals clearly demonstrated the ionospheric origin of the irregularities causing these fluctuations of radio signals (Little and Lovell 1950); this phenomenon is now known as ionospheric scintillations. The earlier studies showed that it is basically a nighttime phenomenon and that it is associated with spread *F* observed in the ionograms (Wild and Roberts 1956, Koster 1958, Booker 1958, Bhargava 1964).

The advent of the telemetry or the beacon radio signals aboard the artificial satellites provided the opportunities for global studies of the ionospheric scintillations. Both the signals from low orbiting satellites like Explorer 22 and Explorer 27 as well as from geostationary satellites like Intelsat IIF2, Intelsat IIF3 and ATS–3 have been widely used for ionospheric scintillation studies (Titheridge and Stuart 1968, Bandyopadhyay and Aarons 1970, Frihagen 1971, Koster 1972, Mullen 1973, Chandra and Rastogi 1974, Nielson and Aarons 1974, Hajkowicz 1975).

Most of the ionospheric scintillation studies using beacons from the geostationary satellites were carried out at high and middle latitudes and only a few studies for equatorial latitudes are available for Legon, dip 9° S (Koster 1972) and for Huancayo, dip 2° N (Mullen 1973). Scintillations have been found to be strong over the auroral and the polar regions and are relatively mild at mid-latitudes. Koster (1972) reported that for over 50% of the nighttime, the scintillation index at the low-latitude station, Legon, exceeds 90% indicating that the scintillations are again strong at equatorial latitudes.

The equatorial scintillation is basically a nighttime phenomenon with its occurrence being maximum before midnight for any longitude and is mainly due to spread *F* (Koster 1972), Mullen 1973, Chandra and Rastogi 1974). At high latitudes, some scintillations are observed during the daytime hours (Bolten *et al* 1953, Dueno 1956, Chivers and Greenhow 1959, Liszka 1963, Munro 1966, Frihagen 1971, Nielson and Aarons 1974). McClure (1964) estimated the height of the irregularities responsible for the daytime scintillations to be embedded in the *E* region. Association of the scintillations and Es patches has been noted at middle and low latitudes (Aarons and Whitney 1968, Rastogi and Iyer 1976).

One of the most important aspects of ionospheric radio scintillation is the frequency dependence of the amplitude fluctuations. Hewish (1952) used the frequencies in the range of 36 to 200 MHz and showed that the amplitude of scintillations increases as the square of the observing wavelength whilst scintillation rate is independent of frequency. Chivers (1960) studied radio star scintillations on different frequencies within 26 to 408 MHz and found that the scintillation amplitude varies as the square of the observing wavelength up to the point where the lower frequency index saturates at 100%. The rate of scintillation is independent of observing wavelength under weak scattering condition and for strong scattering the rate increases with wavelength. Aarons *et al* (1967) studied the amplitude scintillation at some discrete frequencies in the range of 30 to 400 MHz and found the scintillation index to vary inversely to the square of frequency for weak scintillations and for higher frequencies during periods of low magnetic activity. For lower frequencies and for higher levels of ionospheric activity the dependence approached to inverse frequency law.

The ATS-6 satellite was launched in a geostationary orbit on 30 May 1974 at 94° W longitude. It carries radio beacon designed to monitor the integrated electron content between the space craft and ground. The multi-frequency radio beacon enables measurement of the integrated electron content along the ray path, the spatial structure and time dependent behaviour of the ionosphere and the overlying plasmaspheres on the way in which these characteristics affect the operation of HF and VHF communication systems. Technical aspects of the beacon, the receiving system developed at NOAA Environmental Research Laboratories, Boulder, Colorado, USA and some early results were described by Davies *et al* (1975). The satellite was restationed at 34° E longitude on 1 August 1975. The Physical Research Laboratory had installed the complete NOAA–ERL ATS–6 receiving system at Radio Astronomy Centre, Ootacamund (11·43° N, 76·70° E, magnetic dip 4° N). The look angles of the ATS–6 from Ootacamund were 40·5° N above horizon and 258° east of north. This set up provided for the first time the most comprehensive study of the equatorial ionosphere through the satellite-borne radio beacons.

The installation at Ootacamund consisted of short back-fire antennae at 40, 140 and 360 MHz with preamplifiers, the outputs of which are brought to the receiving room through underground cables to avoid phase fluctuations through the cables due to temperature variations. The receivers have phase lock loop system with a maximum bandwidth of 30 Hz and as a result clear signals are received at all the frequencies; in addition the detected output of the receivers is linear with input voltage. All the data elements are digitized every tenth of a second and recorded on the magnetic tape, simultaneously some of the selected data are recorded on an eight channel paper chart recorder. The present paper describes the amplitude fluctuations of these beacon signals as analysed from the paper charts.

2. Observations

The recordings of the radio beacons at Ootacamund were started in September 1975. The beacon transmissions were not regular till the middle of October 1975 due to the shortage of power on board the satellite as the satellite was being eclipsed by the earth for a considerable part of the day during these months. In the present investigation, the data from 15th October to 10th November 1975 have been used. Following Whitney *et al* (1969), the scintillation index $SI = (P_{\max} - P_{\min})/(P_{\max} + P_{\min})$ was calculated for every 15 min periods centred at 00, 15, 30 and 45 min past every hour; where $P_{\max}$ is the third excursion of the power level down the peak and $P_{\min}$ is the third excursion up the minimum. The advantage of this method is that the index can be scaled directly from the charts without complex analyses.

A few typical records of the amplitude scintillations at 40, 140 and 360 MHz are shown in figure 1 for the daytime as well as nighttime hours. The deflection in the charts is calibrated in terms of the signal input at the antenna. Referring to the daytime records of 3 and 7 November 1975, the fluctuations are definitely the strongest on 40 MHz and decreased with increasing frequency. Secondly the scintillation seems to occur in short bursts and on 3 November 1975 the scintillation on 360 MHz is present for a period of less than half an hour only. Referring to the nighttime records it is to be noted that the chart speed is twice that of the daytime records. On 25–26 October 1975 the scintillation is seen to be strongest at 40 MHz and weakest at 360 MHz. Rather unexpectedly the scintillation on 19 October 1975 is seen to increase with increasing frequency. The scintillation index for the 15 min period centred at 2200 hr on 19 October 1975 was 0·68 for 40 MHz, 0·90 for 140 MHz and 0·95 for 360 MHz.

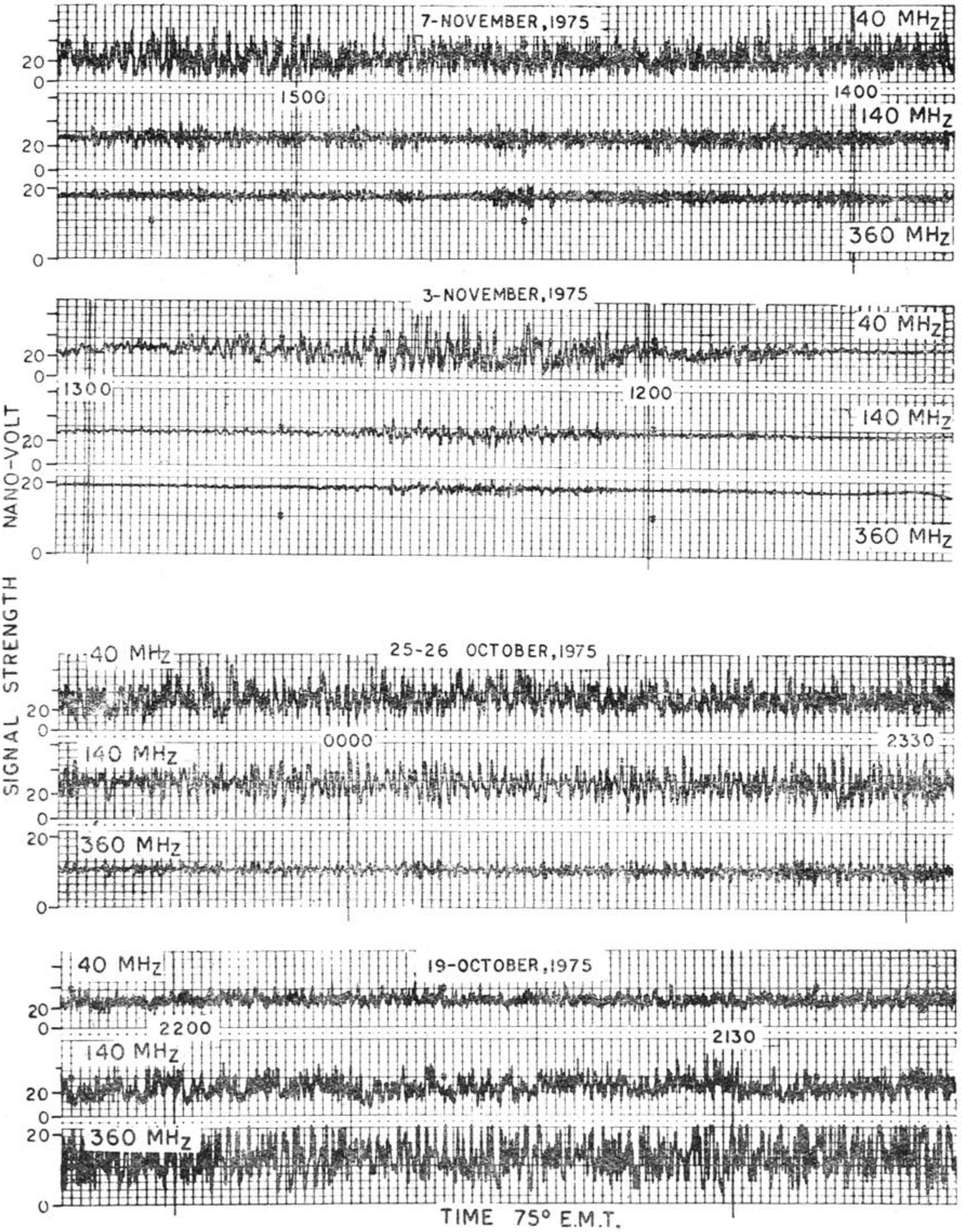

Figure 1. Records of amplitude scintillation of 40, 140 and 360 MHz beacon radio waves from ATS-6 satellite received at Ootacamund for the daytime hours (3 and 7 November 1975) and for the nighttime hours (19 and 25-26 October 1975). The signal strength is expressed as input voltage of the receiving aerials.

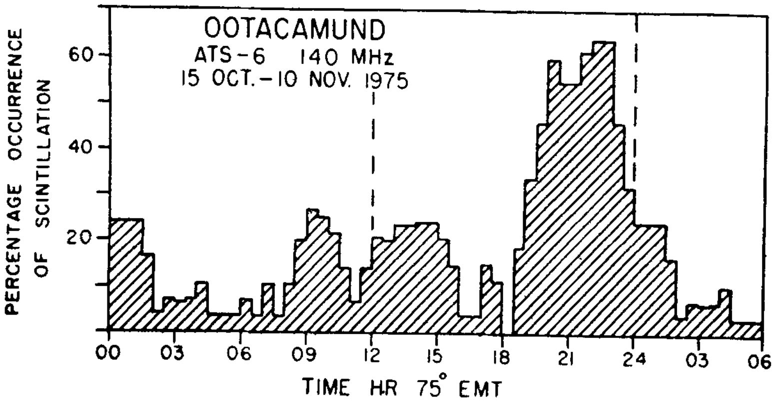

Figure 2. The averaged daily variations of the occurrence of scintillation of 140 MHz radio beacon from ATS-6 satellite received at Ootacamund. Note the primary peak around 2200 hr in the night and two secondary peaks around 0900 hr and 1400 hr during the daytime.

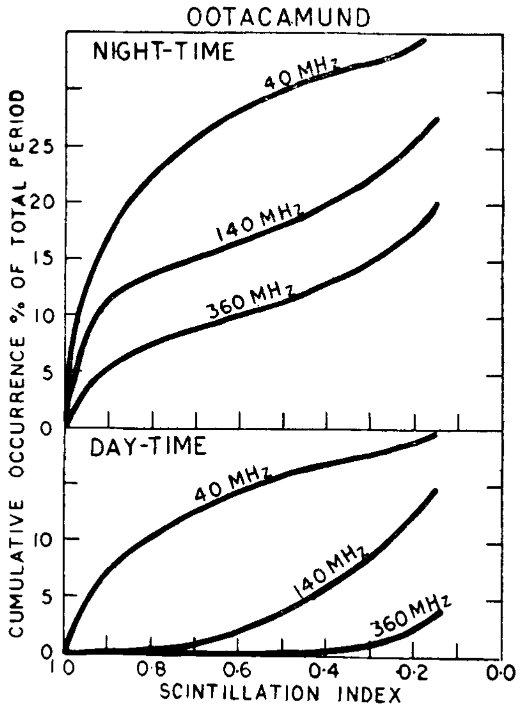

Figure 3. Curves showing the period during which the scintillation of 40, 140 and 360 MHz radio beacons from ATS-6 received at Ootacamund exceeds a particular index indicated as the percentage of total period of the daytime or the nighttime hours separately.

In figure 2 are shown the average daily variations of the occurrence frequency of scintillation on 140 MHz beacon received at Ootacamund. The diagram shows a very distinct peak exceeding 60% of time between 2000 hr and 2300 hr. This is in conformity with the results at various other equatorial stations (Bandyopadhyay and Aarons 1970, Koster and Wright 1963) and is associated with the occurrence of the equatorial spread F(Bhargava 1964). It is interesting to note that there are two minor peaks exceeding 25% of time around 0900 hr and 1400 hr.

In order to give some idea of intensity of scintillation of these radio waves at Ootacamund, in figure 3 are plotted the occurrences of scintillation on a radio frequency exceeding the particular index as a percentage of the total period of observation. These curves are shown for 40, 140 and 360 MHz separately for the daytime and the nighttime hours. The scintillations are in general weaker on higher frequencies during a particular period and weaker during daytime than the nighttime for a particular frequency.

The scintillation on 360 MHz exceeding 0·2 index occurs on about 2% of daytime hours and more than 20% of the nighttime hours. On the lowest frequency, 40 MHz scintillation index exceeds 0·2 about 18% of daytime hours and about 28% of nighttime hours. On 140 MHz the scintillation index for the nighttime exceeding 0·9 occurs on about 10% of the time while the scintillation index on 137 MHz exceeding 0·9 at Legon has been reported to be more than 50% of the nighttime hours. These data should not be interpreted as a large longitudinal difference in the scintillation activity along the magnetic equator. The Indian data refer to minimum solar activity period while those for Ghana refer to maximum solar activity period.

To evaluate the frequency law of the scintillation, the ratios of scintillation indices for a set of two frequencies were calculated for each fifteen minute intervals and the histograms for these ratios for different frequency sets are shown in figure 4 for the daytime as well as the nighttime hours. The mean and median values of these ratios are also indicated in the figure.

For the daytime hours, the ratio of scintillation index for 140 MHz to 360 MHz ranges between 1·0 and 4·0 with the median value of 2·9 which is close to the theoretical value of 2·6 according to inverse frequency law. Similarly, the ratio of scintillation index for 40 MHz to 140 MHz ranges between 0·5 and 5·0 with the median value of 2·7 whereas according to the theoretical $1/f$ law the value would be 3.5. The ratio of scintillation index for the set of 40 MHz to 360 MHz is widely scattered between 2·0 and 10·5 suggesting that the fades are comparatively less correlated between extreme frequencies. It may be seen that during the daytime the scintillation clearly decreases inversely with increasing frequency.

Referring to the histograms for the nighttime hours, the ratio of scintillation index 140 MHz to 360 MHz ranges between 1·0 and 4·0 with the median value of 1·8 in contrast to the theoretical value of 2·6. The ratio of scintillation index for 40 MHz to 140 MHz ranges between 0·5 and 7·0 with the median value of 1·4 in contrast to the theoretical value of 3·5. It is interesting to note that in about 30% of occasions the ratio is less than one suggesting that the scintillation is higher in the lower frequency. The ratio of scintillation index for 40 MHz to 360 MHz is only 1·9 which is very different from the theoretical value of 9·0. This clearly indicates that contrary to the daytime conditions, the inverse frequency law of scintillation is

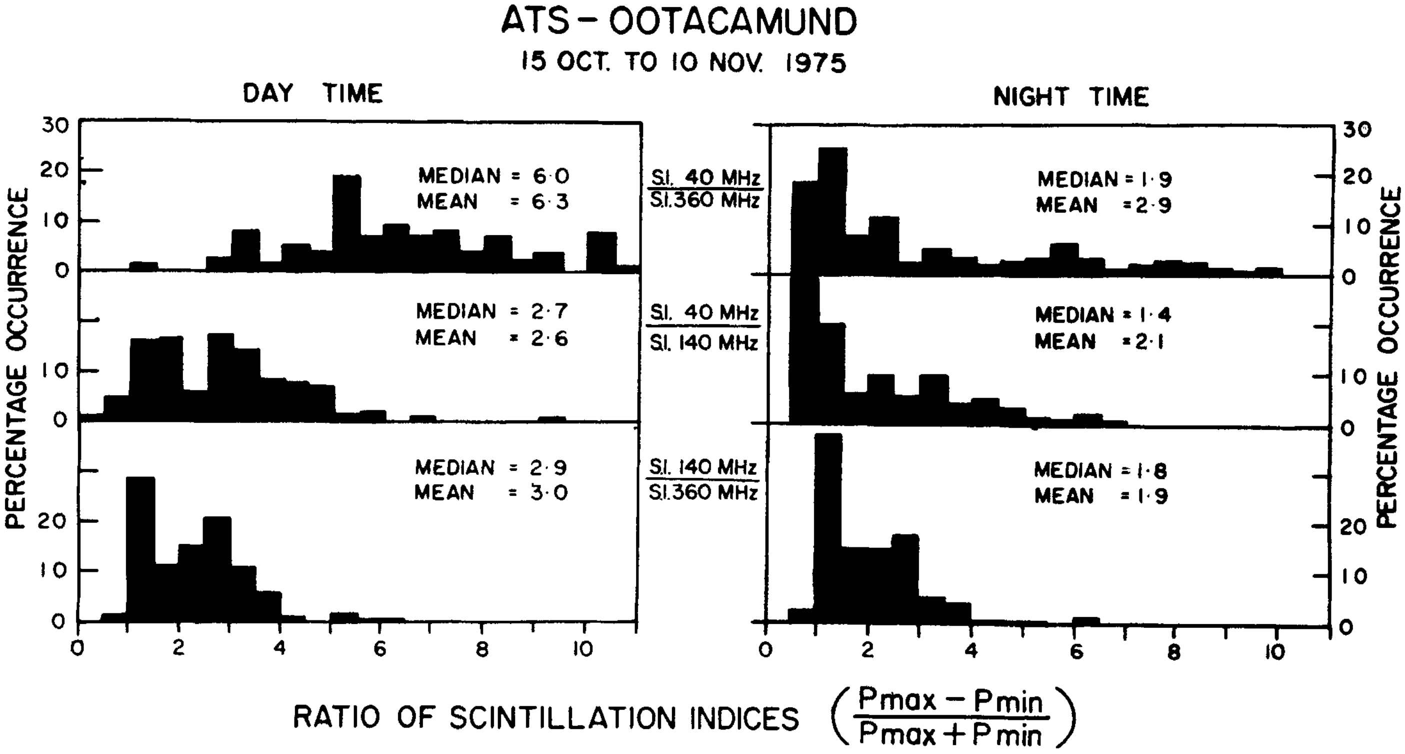

Figure 4. Histograms of the ratio of scintillation indices on two frequencies (140 MHz/360 MHz, 40 MHz/140 MHz and 40 MHz/360 MHz) of radio beacons from ATS-6 satellite received at Ootacamund.

not valid for the nighttime hours.

Briggs and Parkin (1963) defined index for the scintillation depth as

$$S^2 = \frac{R^4 - (R^2)^2}{(R^2)^2}$$

where R is the amplitude of the wave. They have shown that

$$S \propto \lambda \, (\mathrm{Sec}\ i)^{\frac{1}{2}} \{1 + \pi^2 r_0{}^4/4\lambda^2 z^2\}^{-\frac{1}{2}}$$

where S is the wavelength, i is the zenith angle at the ionospheric interaction point, z is the slant distance of the irregularity and r_0 is the irregularity autocorrelation distance in the medium. If $\lambda/r_0{}^2$ is very small, the observer is in the near zone, the scintillation would be proportional to λ^2, this condition is known as Fresnel limit. Conversely when $\lambda/r_0{}^2$ is large, the observer is in the far zone, the limit known as Franhoufer limit, the scintillation would be proportional to λ. Assuming that $S \propto f^{-n}$, the mean value of the index 'n' for any set of two frequencies can be calculated by the relation:

$$n = -\frac{\log (S_1/S_2)}{\log (f_1/f_2)}$$

where S_1 and S_2 are the scintillation indices for the frequencies f_1 and f_2 respectively.

In order to get a better understanding of the frequency variation of the scintillations, the mass plots were made for the simultaneous values of the scintillation indices on two frequencies and are shown in figure 5 for the daytime as well as for the nighttime hours.

Referring to the daytime plots, the points for the 140 MHz/360 MHz set show fairly linear relation, assuming S_{140}/S_{360} to be approximately equal to 3·0, the index n comes out to be 1·15. For the lower frequency set 40 MHz/140 MHz it is seen that there is a linear increase of scintillation index for both the frequencies till the scintillation index at 40 MHz reaches about 0·9. In case of severe scintillations on 40 MHz there is no clear relation between the scintillations and the two frequencies. Excluding these cases of intense scintillations, the ratio of scintillation index 40 MHz to 140 MHz is about 3·0 which yields the index value to be 0·88.

Referring to the nighttime conditions the scintillation index at 360 MHz increases linearly with scintillation index at 140 MHz only for weak scintillations till scintillation index at 140 MHz is less than 0·8. The mean ratio of scintillation index at 140 MHz to 360 is 3·7 which yields the index n to be 0·84. Similarly for weak scintillations, the scintillation index at 40 MHz/140 MHz is about 2·9 yielding the index n to be equal to 1·03. It is interesting to note that some of the points in the mass plot indicate scintillation index to be smaller for lower frequencies contrary to the theoretical expectations. This condition has not been seen for the daytime hours. Aarons *et al* (1967) have noted that in case of very intense scintillations the frequency dependence index becomes zero and on occasions becomes negative.

To obtain some idea on the temporal variation of the scintillations on these frequencies, the scintillation indices for 40, 140 as well as 360 MHz on some individual day and night are shown in figures 6 and 7 respectively.

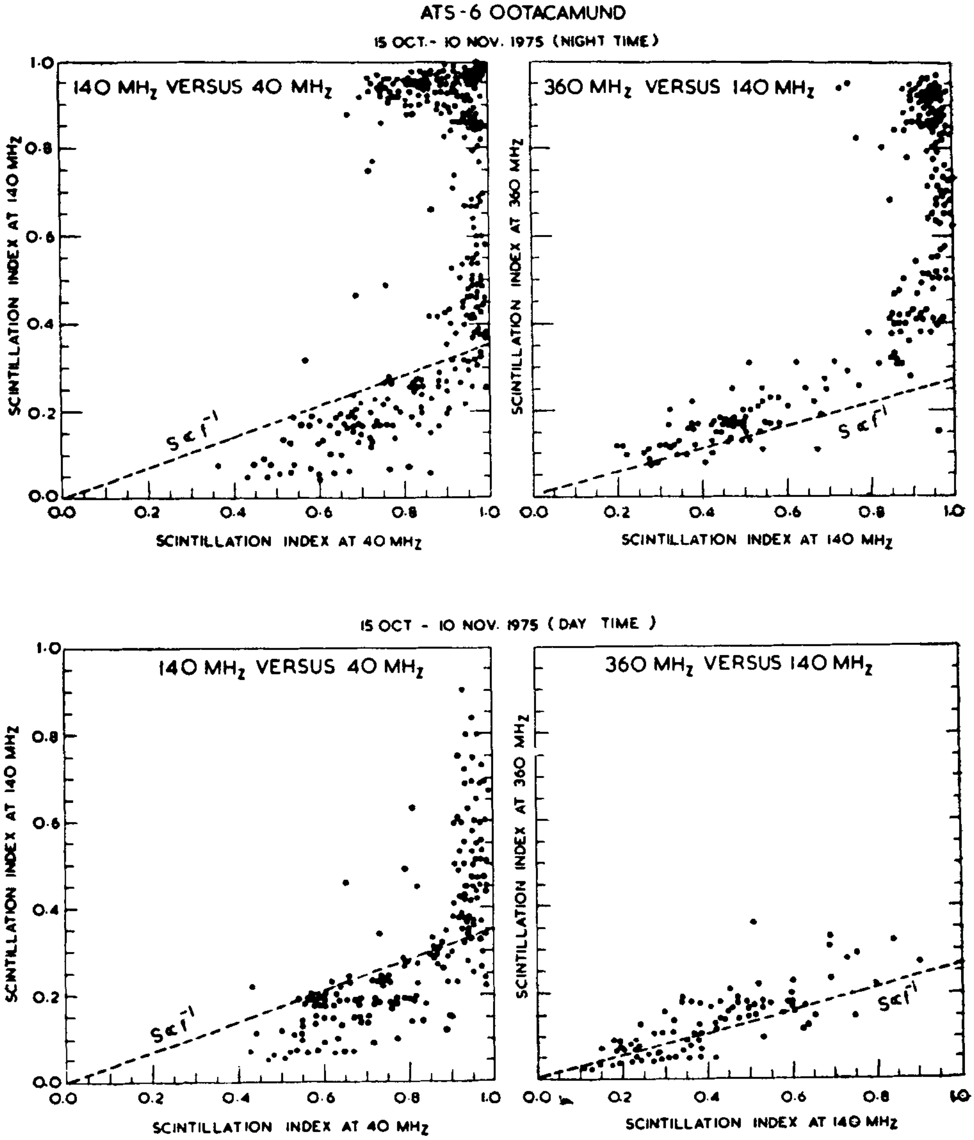

Figure 5. Mass plots of individual value of scintillation index on the set of two frequencies (40 MHz/140 MHz and 360 MHz/140 MHz) for the daytime as well as nighttime hours.

Referring to figure 6 for the daytime scintillations it is seen that the 40 MHz signal has always some fluctuations even when no detectable fluctuations are seen on 140 MHz and 360 MHz. The scintillation on any of the frequencies is seen to occur at bursts of intervals and so the index fluctuates violently with time during most of the intervals. This suggests that the irregularities which cause the scintillation of satellite signals during the daytime hours are very localised (at least in east-west direction) patches of electron density deviations.

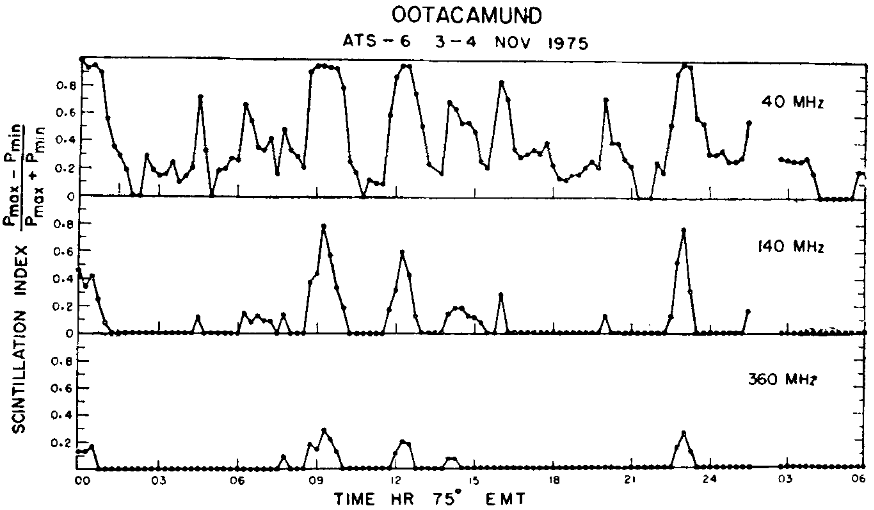

Figure 6. Variations of the scintillation index of 40, 140 and 360 MHz beacon signals from ATS-6 received at Ootacamund on 3-4 November 1975.

Referring to figure 7 for the nighttime scintillations, it is seen that whenever the fluctuations occur in the nighttime, these persist for number of hours together. On occasions when the scintillation is moderate or weak on high frequency, the scintillation is found to occur earlier on lower frequency and the duration is also longer on lower frequency. When the scintillation is strong even on high frequency the onset of scintillation is almost simultaneous on all the frequencies.

3. Discussion

The nighttime scintillation occurs most frequently around 2200 LT which is the period of maximum occurrence of spread *F* at the equatorial regions (Chandra and Rastogi 1972 *b*). The detailed study of Thumba ionograms has revealed that the pre-midnight spread *F* is predominantly range type and strong scattered echoes can be seen from a multiple of fixed heights of the ionospheric *F* region (Chandra and Rastogi 1972 *a*). Thus unlike the daytime hours the scattering regions during the nighttime hours are situated at a number of heights especially during intense spread *F* conditions. The near consistency of the scintillation index with frequency or the frequent reversal of frequency *versus* scintillation index law during the nighttime hours may be due to the multiple scattering of the radio waves by the comparatively thick spread *F* layer. The type of spread *F* responsible for different types of scintillations is being studied with the help of ground based ionosonde data.

Even as early as 1956, Wild and Roberts (1956) had found that the radio star scintillations during the nighttime were correlated with spread *F* only, while the daytime scintillations were correlated with sporadic *E* only. Aarons *et al* (1964) found that a high value of $f_0 E_s$ may sometimes be associated with scintillations. Das Gupta and Kersley (1976) have suggested that a high sporadic *E* critical frequency is a necessary condition for scintillation, but in addition a diffuse range spreading on the ionograms is important in the production of scintillation. Rastogi and Iyer (1976) have shown that the blanketing type of E_s layer is responsible for

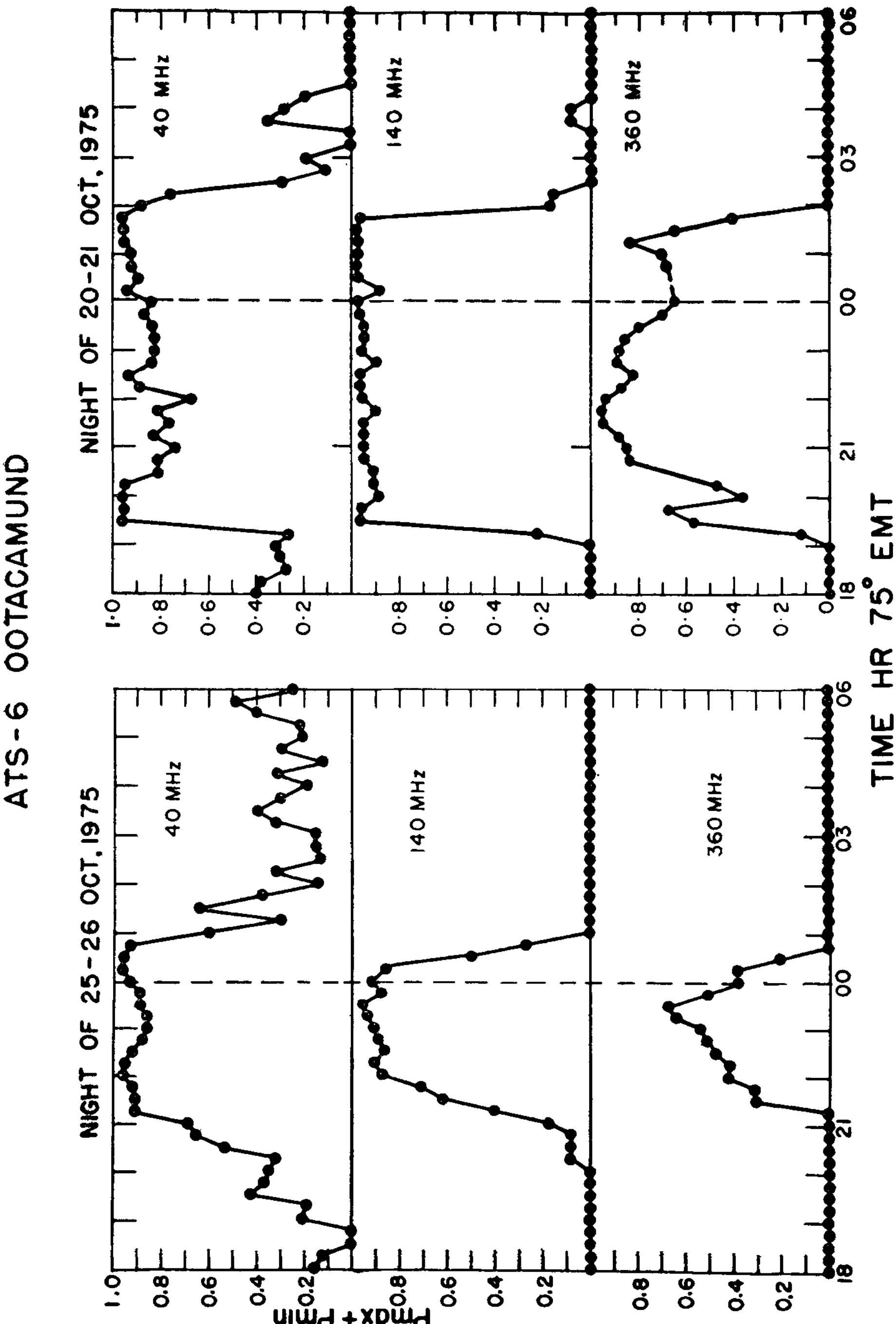

Figure 7. Variations of the scintillation index of 40, 140 and 360 MHz beacon signals from ATS-6 received at Ootacamund during the nighttime hours on 25–26 and 20–21 October 1975.

the satellite radio scintillation and that the extent of these E_s clouds is very localised. In the present experimental set up, although Ootacamund is near the edge of the equatorial electrojet region, the radio waves from ATS-6 ground station crossed the region where the equatorial E_s is almost always present during the daytime hours, whereas the daytime scintillations are observed only about 20% of the total time. Further the E_s-q is most frequent around noon when we find a minor dip in the average daily variation of the occurrence of scintillations. The secondary peaks in the occurrence of scintillations at Ootacamund are at 0900 hr and 1400 hr which are roughly the most probable times for the occurrence of the blanketing type of E_s layer at Kodaikanal (Bhargava and Subrahmanyan 1964, Chandra and Rastogi 1975). It is thus suggested that the occurrence of daytime scintillation of satellite radio waves at Ootacamund may be associated with the non-q type of E_s. Further a detailed study of these events in relation to different types of E_s as revealed from the vertical sounding ionograms is very desirable and is proposed to be undertaken in future.

Acknowledgements

Grateful thanks are due to G Swarup and his colleagues at the Radio Astronomy Centre, Ootacamund, for providing experimental facilities at their station. Thanks are also due to all the technical and scientific staff at Ootacamund specially to N M Vadher for the excellent operation of the project. Thanks are also due to Indian Space Research Organisation (ISRO) and National Aeronautic and Space Administration (NASA) for the joint collaborative arrangement under whose banner the Oootacamund station was established.

References

Aarons J, Mullen J P and Basu S 1964 *J. Geophys. Res.* **69** 1785
Aarons J, Allen R S and Elkins T J 1967 *J. Geophys. Res.* **72**(11) 2291
Aarons J and Whitney H E 1968 *Planet. Space Sci.* **16** 21
Bandyopadhyay P and Aarons J 1970 *Radio Sci.* **5** 931
Bhargava B N 1964 *J. Inst. Telecommun. Eng.* **10** 404
Bhargava B N and Subrahmanyan R V 1964 *Proc. Indian Acad. Sci.* **60** A 271
Bolten J G, Slee O B and Stanley G J 1953 *Aust. J. Phys.* **6** 434
Booker H G 1958 *Proc. IRE* **46** 298
Briggs B H and Parkin I A 1963 *J. Atmos. Terr. Phys.* **25** 339
Chandra H and Rastogi R G 1972*a* *Ann. Geophys.* **28** 37
Chandra H and Rastogi R G 1972*b* *Ann. Geophys.* **28** 709
Chandra H and Rastogi R G 1974 *Curr. Sci.* **43** 567
Chandra H and Rastogi R G 1975 *J. Geophys. Res.* **80** 149
Chivers H J A 1960 *J. Atmos. Terr. Phys.* **17** 181
Chivers H J A and Greenhow J S 1959 *J. Atmos. Terr. Phys.* **17** 1
Das Gupta A and Kersley L 1976 *J. Atmos. Terr. Phys.* **38** 615
Davies K, Fritz R B, Grubb R N and Jones J E 1975 *Radio Sci.* **10** 785
Dueno B 1956 *J. Geophys. Res.* **61** 535
Frihagen J 1971 *J. Atmos. Terr. Phys.* **33** 21
Hajkowicz L A 1975 *Planet. Space Sci.* **23** 1563
Hewish A 1952 *Proc. R. Soc. London* **A214** 494
Hey J S, Parson S J and Phillips J W 1946 *Nature (London)* **158** 234

Koster J R 1958 *J. Atmos. Terr. Phys.* **12** 100

Koster J R 1972 *Planet. Space Sci.* **20** 1999

Koster J R and Wright R W 1963 in *Radio Astronomical and Satellite Studies of the Atmosphere*, ed. J Aarons, (North-Holland Pub. Co., Amsterdam) p. 114

Liszka L 1963 *Ark. Geofys.* **4** 211

Little C G and Lovell A C B 1950 *Nature* (*London*) **165** 423

McClure J P 1964 *J. Geophys. Res.* **69** 2774

Mullen J P 1973 *J. Atmos. Terr. Phys.* **35** 1187

Munro H 1966 *Radio Sci.* **1** 1186

Nielson E and Aarons J 1974 *J. Atmos. Terr. Phys.* **36** 159

Rastogi R G and Iyer K N 1976 *Curr. Sci.* **45** 685

Titheridge J E and Stuart G E 1968 *J. Atmos. Terr. Phys.* **30** 85

Whitney H E, Aarons J and Malik C 1969 *Planet. Space Sci.* **17** 1069

Wild J P and Roberts J A 1956 *J. Atmos. Terr. Phys.* **8** 55