

Ionospheric Scintillation Modelling

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The phenomenon of ionospheric scintillations has long been observed by radio astronomers and physicists. The observations have provided valuable information towards the (qualitative) morphology of the phenomenon. The (quantitative) information about scintillation effects for today's satellite system design is rather meagre. Thus, it is not possible to know (and predict) as to how much of the time a given level of scintillation activity will remain in different parts of the world. It is shown that a more organized approach towards the collection and dissemination of data, in time and geographic location, is needed for a realistic worldwide model of ionospheric scintillations.

1. Introduction

Radio signals from a discrete point source may undergo an irregular scattering in the inhomogeneous ionosphere causing an irregular diffraction pattern on ground. When this pattern changes with time or has a coherent drift, such as that due to a wind, scintillations occur. The fluctuations in the intensity of the signal measured in a narrow high frequency bandwidth are caused by temporal fluctuations of the transmission characteristics of the medium between the observer and the source. Scintillations perturb trans-ionospheric telecommunication, radar system performance and radio astronomical observations, resulting in a serious degradation of data quality. For instance, the following two cases may be cited (see Ref. 1). (a) The relation between the digital signal transmission error rate and the signal-to-noise ratio (SNR) depends upon the characteristics of the medium through which the signal propagates. For many conditions, the probability of an error occurring decreases with increasing SNR, but this may not be true for all signal bandwidths. In that case, an increase of signal power does not improve the transmission error rate and the system may have to be operated at a much reduced transmission speed in order to prevent excessive errors being received. (b) The rate of fading is a parameter that is defined for a single-tone transmission as the average rate at which the received envelope crosses its median value. Of more interest for high speed digital transmission are the statistics of the duration of fades below a given level. If this time be long in comparison with the information pulse length (the spacing between successive pulses in digital transmission), and the fade depth below the system sensitivity, information bits could be lost. The advent of satellite communication

systems as the prime mode of global communications, has highlighted the need to account for ionospheric scintillations in predicting system performance. The characteristic pattern of its occurrence and severity pertaining to (i) geographical extent, (ii) diurnal and seasonal behaviour, (iii) frequency dependence in HF-SHF spectrum, (iv) various solar epochs, (v) magnetic activity and (vi) zenith angle dependence need be studied over statistically long periods of time. Morphological knowledge with appropriate quantification on spectral characteristics, fading rates and per cent of time at various fading levels are the data input needed for system prediction capability.

What is primarily needed now is a realistic worldwide model of ionospheric scintillations. Stanford Research Institute (SRI) has developed an empirical nocturnal global model, the only one of its kind, based on some observational scintillation data and on theory that is limited in its application^{2,3} (and is still being developed further). The data inputs, particularly, in the equatorial region are statistically inadequate. In this paper, it is intended to briefly recapitulate some of the salient morphological features of ionospheric scintillations in different regions of the globe; in particular, the equatorial region.

2. Survey of Scintillation Data

Table 1 provides a subjective rating of the relative understanding that exists about scintillation effects on various phenomenological and signal parameters for different geographic regions¹. For many of the parameters nil or almost nil quantitative information exists. Even for many of these quantities where it is indicated that considerable knowledge is available, this knowledge is based mainly towards the VHF band

Table 1—Knowledge Concerning Ionospheric Scintillation Effects: Subjective Summary (after Utlaut¹)

Parameter	Important for	Geographic Region		
		Equatorial	Mid-latitude	High Latitude
Signal amplitude fading				
Rate	D, P	K	L	L
Depth and time distribution	D, P	L	L	L
Space correlation	D, P	L	U	U
Frequency dependence				
In band	D	K	L	L
Between bands	D	L	U	U
Signal phase	D, P	U	U	U
Geographic				
Broad extent	E	K	L	K
Local region size	E	L	L	L
Occurrence				
Time	E, P	K	L	L
Duration	E, P	K	L	L
Geophysical causes	E	U	U	U

Note:

D, System design and affect alleviation; P, System performance prediction; E, Event prediction; U, Unknown; L, Limited information; K, Knowledge considerable.

of frequencies and much less is known about their values in L and S bands.

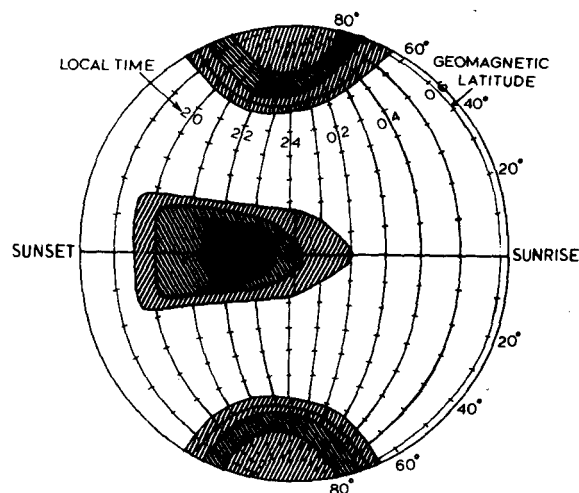
3. Global Scintillation Morphology

A nighttime structure of the occurrence of global scintillations during magnetically quiet nights is depicted in Fig. 1 (Ref. 4). Middle-latitude scintillation activity is of lesser intensity, both in occurrence and in depth of fading (severity). The density of hatching in the figure is a measure of depth of fading and implies greater scintillation intensity in the equatorial region than at high latitudes. It may be noted that this is only a representative nighttime picture of the occurrence of deep fading and the phenomenological factors such as seasonal pattern, solar cycle variations, magnetic storm effects and others need be considered for a more realistic and complete picture^{5,6}. The formation of equatorial scintillation belt within $\pm 20^\circ$ geomagnetic latitude is clearly evident from Fig. 1. The latitudinal extent of the belt and the scintillation characteristics, in general, vary with longitude.

A measure of the strength of scintillation activity is the empirical scintillation index SI ,

$$SI = (P_{\max} - P_{\min}) / (P_{\max} + P_{\min})$$

$P_{\max}$ being the power level of the third peak down from the maximum excursion of the scintillations and $P_{\min}$ the power level of the third minimum up from the

Fig. 1—A nighttime picture of the occurrence of deep fading⁴Table 2— SI - S_4 Calibration (after Whitney⁷)

SI %	S_4 %	$P_{\max} - P_{\min}$ dB
2	—	0.18
5	—	0.43
10	7	0.87
15	—	1.32
20	11	1.76
25	—	2.22
30	17	2.69
35	—	3.17
40	20	3.68
45	—	4.21
50	25	4.77
55	—	5.37
60	30	6.00
65	—	6.74
70	36	7.54
75	—	8.45
80	45	9.54
85	48	10.91
90	56	12.80
95	64	15.90
99	—	23.00
99.9	—	33.00

lower excursions in the given sample period (usually taken to be fifteen minutes). Another scintillation index, S_4 , is defined as the root mean square of fluctuations divided by the mean signal. Table 2 presents the inter-relationship between the indices SI and S_4 (Ref. 7). It suffices for the intermediate range of values to quote that $SI \approx 2 S_4$; this can be proved statistically⁸. For practical implications, empirical conversion of SI into $P_{\max} - P_{\min}$ (in dB) is also included in Table 2.

The scintillation index S_4 (henceforth quoted as S) may be represented by the following functional form to

take care of the phenomenological parameters (see Ref. 9) i.e.

$$S = F_1(\lambda, N_o, L, a, \alpha, i, \psi, z) \quad \dots (1)$$

where λ is the observing wavelength, N_o the rms electron density fluctuation, L the thickness of the irregularity-embedded medium, a the scale size of the irregularity structure, α the axial ratio of the irregularity structure, i the depth of incidence at the irregularity height, ψ the propagation angle, i.e. the angle between radio ray direction and the earth's magnetic field at the irregularity height and z the effective distance of the irregularity medium from ground.

In addition, S depends on various morphological parameters individually as

$$S = F_2(\Phi, T, D, R) \quad \dots (2)$$

where Φ is the geomagnetic latitude, T time of the day, D day of the year and R the sunspot number.

Table 3 presents a summary of the physical characteristics of scintillation causative irregularities in the HF-UHF band for the different zones. Table 4 presents a summary of the global scintillation morphology for the different zones.

Inter-comparison of results from various morphological studies of scintillations must invoke the differences in observing geometries and frequencies, and the variety of scintillation measures (indices) employed. This could be illustrated as follows: (a) The radio sources available for scintillation studies are the radio stars and geostationary and orbiting satellites. Radio stars, the natural radio sources, are distributed all over the sky and follow fixed tracks in the sky. Their meridional transits over an observatory change with local time. With large collecting area and steerability of the tracking antenna it is possible to survey large areas

Table 3—Physical Characteristics of Scintillation Causing Irregularities in HF-UHF Band: Summary

Parameter	Geographic region		
	Equatorial	Mid-latitude	High latitude
Height (km)	250-450	200-350, L	100-600
Scale size (m)	200-500	L	L
Typical size at VHF (m)	300	1500	1000
Drift speed (msec ⁻¹)	40-200	L	L
Typical speed (msec ⁻¹)	125		
Drift direction	West-to-east	L	East-to-west, L
Wavelength dependence	$\sim \lambda^1$, L	L	$\sim \lambda^{1.5}$, L

L means Limited information

Table 4—Global Scintillation Morphology: Summary

Parameter	Geographic region		
	Equatorial	Mid-latitude	High latitude
Latitudinal extent (geomagnetic)	$\pm 20^\circ$	$\pm (20^\circ-60^\circ)$	$> 60^\circ$
Diurnal pattern			
Nighttime maximum (local time)			
Prominent	Premidnight (~2230 hrs)	Midnight	Premidnight, L (~2200 hrs)
Secondary	0300 hrs, L	N	N
Daytime maximum	L	N	L
Seasonal pattern		C	L
Seasonal maximum	Equinox		Equinox
Seasonal minimum	Solstice		Solstice
Sunspot variation	C, P	L, P	Positive, L
Magnetic activity-variation	C, P	P	Positive, possibly time delay, L

Note:

P, Probably no variation; C, Complex and variable information; L, Limited information; N, Not noticed.

of the irregularity-embedded ionosphere. On the other hand, with geostationary satellites it is possible to watch a fixed region. Orbiting satellites are visible over an observatory for a very short duration and for a few passes per day only. With orbiting satellites it is possible to obtain important information about the height and latitudinal and longitudinal extent of the irregularity region. It is important to compare scintillation levels of a source (radio star or geostationary satellite) which is effectively at infinity and the one at a finite distance above the scattering layer (orbiting satellite). It may be shown, from theoretical considerations, that in the 'near zone' the scintillation level will be less for an orbiting satellite signal than for a radio star or geostationary satellite one. On the other hand, in the 'far zone' situation there is no variation of scintillation level with height and the scintillation level of an orbiting signal will be nearly the same as that of a radio star or geostationary satellite one. (b) Since the irregularities are highly field-aligned ($\alpha \sim 10$), on the basis of the mechanism believed to produce diffraction pattern the scintillation level would be greater when the radio ray travels parallel to the magnetic field in the medium. Each observing station defines magnetic zenith and magnetic azimuth angles at a given ionospheric height, and hence the 'least' angle of the radio ray path with the earth's magnetic field. Since at equatorial latitudes the magnetic field is horizontal, the following conclusion may be drawn. The dependence of S on the axial ratio

α and the propagation angle may be ignored provided that $\psi \gg 30^\circ$, a condition which is satisfied by most of equatorial zone observations. The scaling procedures for zenith angle and frequency dependence studies depend on the characteristics of the local irregularities and can be deduced in some cases by direct observations. To take care of the zenith angle effect, a good approach is to normalize scintillation index at a given zenith angle to a fixed zenith angle, say zenith, by dividing the computed scintillation index by $(Z/h)^{1/2} \times \sec^{1/2} i$ [in Eq. (1)]. The factor Z/h takes care of the situation in which the transmitter is either at infinity or at a finite distance. The inter-frequency dependence has no consistent picture^{10,11} (see Table 5). To a first approximation conversion of scintillation indices in HF-UHF band may be conducted through the multiplying factor $(f_{HF}/f_{UHF})^{-1.5}$, such that $S_4 \leq 0.3$ is satisfied on either frequency. The problem of different levels of scintillations (the indices) used by researchers

may be tackled by providing plots of percentage occurrence of scintillations for various levels for inspection of scintillation activity.

4. Summary of Equatorial Scintillation Morphology

The dependence of local time of occurrence of nocturnal scintillation maximum on geophysical parameters is rather complex and uncertain. In general, it has been observed that for $SI > 0.5$ the maximum occurs an hour or two before local midnight (Ghana^{12,13}, 137 MHz; Peru¹⁴, 136 MHz; Peru and Marshall Islands³). In addition there is a secondary weak pre-sunrise maximum (Thumba¹⁵, 40 MHz; Ooty⁸, 327 MHz; and Thumba¹⁶, 140 and 360 MHz). The diurnal scintillation patterns at different stations in the equatorial region are presented in Fig. 2.

In general, it is found that during quiet and disturbed conditions, the season of minimum nocturnal scintillation occurrence is the June-solstice. The season of maximum nocturnal scintillation is around the December-solstice at Peru¹², at Thumba, at Ooty and at Kwajalein Islands¹⁷, and near the equinoxes, September-equinox more pronounced at Ghana. The seasonal variation at Guam Islands¹⁸ (250 MHz) shows a broad maximum, increasing in March and decreasing in October, with little activity during November to February. The seasonal scintillation patterns at different stations in the equatorial region are presented in Fig. 3.

The nocturnal scintillation occurrence is higher in a year of 'higher' sunspot number than in a year of 'lower' sunspot number (Peru¹⁹, Ghana²⁰, 137 MHz).

Table 5—Spectral Index in Equatorial and High Latitude Regions: Summary

Reference (not quoted in the list of References)	Frequencies MHz	Spectral index ($\sim \eta$)	
		Equatorial	High Latitude
Basu <i>et al.</i> (1964)	63 and 112 112 and 224	—	≈ 1.5
Aarons (1967)	22 and 34	1.6	—
Aarons <i>et al.</i> (1967)	30, 63 and 113 113 and 228	—	1.0 1.5-2.0
Allen (1969)	63 and 113	—	1.75
Golden (1970)	137 and 1695	—	1.0
Pope and Fritz (1970)	137 and 1695	—	1.0
Pope and Fritz (1971)	137 and 1695	—	1.0
Craft and Westerland (1971)	4 and 6(GHz)	2.0	—
Sailors (1971)	137 and 412	—	1.5
Golden (1972)	137 and 1695	—	1.0
Whitney <i>et al.</i> (1972)	137 and 412	—	1.2-1.8
Taur (1973a, b)	1.55 and 4(GHz)	1.0	—
Blank and Golden (1973)	150 and 400	—	1.5
Crane (1974)	150 and 400	—	1.5
Crane (1975)	150 and 400	—	1.5
Taur (1974)	1.55 and 4(GHz)	1.0	—
Krishna Murthy <i>et al.</i> (1976)	40, 140 and 360 140, 360 and 860	0.46 1.2	— —
Rastogi <i>et al.</i> (1977)	40 and 140 40 and 140 (daytime) 140 and 360 140 and 360 (daytime)	1.0 0.88 — 0.84 1.15	— — — — —

Note: Other studies in the equatorial region not quoted here are those of Christiansen (1971), Crampton and Sessions (1971) and Stevens (1973), Ott (1977) and Umeki *et al.* (1977).

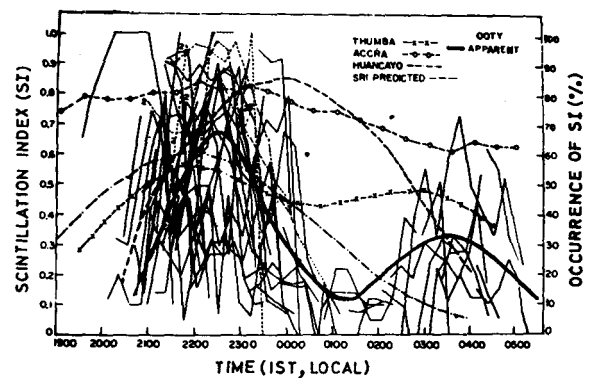


Fig. 2—Scintillation diurnal pattern observed at Ooty (— and ----) as compared with diurnal pattern at Thumba, India (-x-x-x-), Accra, Ghana (-o-o-o-o-), and Huancayo, Peru (-.-.-.-). [The dotted curves in Ooty diurnal pattern represent scintillation activity displaced backward in time (in hours indicated) so that the maximum scintillation activity is around 2230 hrs. Accra scintillation pattern is in local time and Huancayo pattern is expressed in terms of percentage of indices $SI > 0.6$. The thick solid curve brings out the apparent diurnal pattern. The diurnal pattern as generated through the SRI model for the Ooty scintillation conditions is given by (-.-.-)]

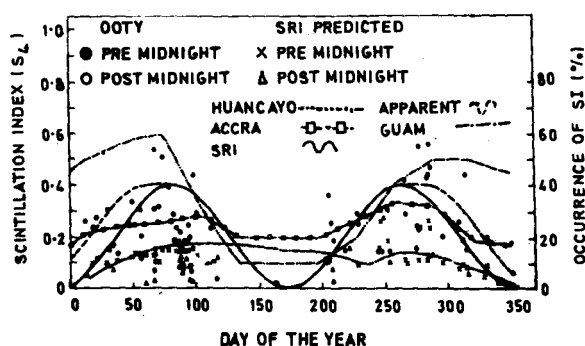


Fig. 3—Ooty seasonal scintillation activity (●—pre-midnight; ○—post-midnight) superimposed on the SRI model predicted seasonal dependence (solid curve) [The SRI model predicted indices corresponding to observed ones are indicated as ×—pre-midnight and Δ—post-midnight. The seasonal scintillation activity pattern at Accra, Ghana (□—□), Huancayo, Peru (—△—), and Guam Islands (—◇—) expressed in terms of percentage occurrence of $SI > 0.3$, 0.6 and probably 0.6 (not quoted by the author), respectively, for stations are plotted here. Apparent seasonal pattern is indicated by the curve ~~~~~]

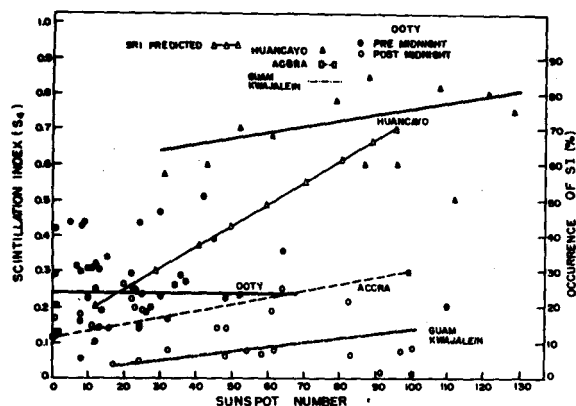


Fig. 4—Solar activity dependence of scintillation activity at Ooty (●—pre-midnight, ○—post-midnight) [Solar activity dependence of scintillation activity at Huancayo, Peru (▲) and Guam Islands (—△—) in terms of percentage occurrence of $SI > 0.6$ are included. The monthly mean S_4 at Accra, Ghana, depicts the solar activity dependence given by the curve □—□. The SRI model predicted solar activity dependence of scintillation activity for the Ooty scintillation conditions (-----)]

At Ooty, for low to medium solar activity observations, there does not appear any consistent trend of the variation of scintillation activity with solar activity. Fig. 4 presents solar activity dependence of scintillation activity in the equatorial region.

In the equatorial region, the evidence is for a positive correlation with solar activity and a negative correlation or no consistent trend with magnetic activity (Table 6).

5. Equatorial Ionospheric Scintillation Modelling

The 'original' SRI empirical scintillation modelling in the form of a computer program²¹ is based on the

Table 6—Solar and Magnetic Dependence of Low-Latitude Scintillations: Summary

Reference (some not quoted in the list of References)	Observations
Koster and Wright (1960)	Negative correlation with magnetic activity at sunspot maximum
Walker and Chan (1970)	Negative correlation with solar activity and positive with magnetic activity
Bandyopadhyay and Aarons (1970)	Positive but statistically insignificant correlation with magnetic activity
Koster ¹³	Positive but statistically insignificant correlation with solar activity and negative with magnetic activity
Mullen and Whitney (1974)	Positive correlation with magnetic activity
Mullen and Hawkins (1975)	No consistent trend with solar activity
Chandra and Rastogi ¹⁵	Negative correlation with magnetic activity
Koster (1977)	Positive correlation with solar activity
Paulson (1979, 1980)	No consistent trend with solar and magnetic activity
Pasricha <i>et al.</i> ⁸	No definite trend with solar and magnetic activity

theory of diffraction by a weakly modulating phase screen²² and on scintillation data of suitable quality according to weak-scatter criterion (For theory see Refs. 23 and 24). The rms value of electron density fluctuation is then expressed in terms of various morphological parameters. The morphological features in-built into the model are based mostly on scintillation data from Ghana prior to 1968 and to medium solar activity (sunspot numbers around 100)^{12,25–27} and may be summarized as follows.

(i) There is an asymmetric Gaussian diurnal variation, peaking at midnight with rather rapid growth of activity in the post-sunset hours and a slower decay in the pre-sunrise hours. The diurnal pattern generated through the SRI model for Ooty observations is presented in Fig. 2 (Ref. 8).

(ii) Two identical equinoxes and two solstices with a simple harmonic seasonal dependence (both occurrence and severity) and with peaks at the equinoxes are observed. The seasonal pattern generated through the SRI model for Ooty observations is presented in Fig. 3 (Ref. 8).

(iii) There is a linear dependence on sunspot number. Solar activity trend generated through the SRI model for Ooty observations is presented in Fig. 4 (Ref. 8).

Apart from the paucity of data points, the modelling has a few serious limitations. The model was based on equatorial data only for sunspot numbers around 100 and the extrapolated estimates for lower sunspot numbers may not be accurate. There is also no apparent separation of data for magnetically quiet days and for storm days. Yet another limitation of practical concern is that the model does not explain deep scintillations at GHz frequencies that have been reported in the equatorial region²⁸.

A fundamental drawback of the 'original' model is the continued usage of the Gaussian description of irregularity structures (developed by Briggs and Parkin²²), which is rather inadequate. In order to have a comprehensive model, the irregularity spectrum ought to be described, in a simple or composite form, by power-law description. A complete model in terms of power-law description is possible only if quantitatively analyzed spectra of ionospheric scintillations (under varied propagation-geometry situations as well as at different probing wavelengths) are available. It must be pointed out that the quantitatively processed data in the equatorial region is rather meagre²⁹. Fremouw and Rino in an up-dated version of the 'original' model³, completely overhaul the Gaussian irregularity methodology by a power-law formulation. So far as the morphological inputs into the up-dated model are concerned, it can be safely said to be 'speculative' (as has been admitted by the authors themselves). The new data-base consists of a limited data set from two stations in Peru and in Marshall Islands. The 'modified' version essentially applies newly developed formulation to a restricted data-base. The 'modified' model has the following 'modified' parameters over those in-built into the 'original' model. The theoretical formulation, of course, is completely switched over from the Gaussian to power-law description. In this process, the GHz scintillations can also be suitably explained. The 'original' SRI model does not depict the large scintillation indices observed in the equatorial region. The 'modified' version suitably increases the scintillation level by increasing the various physical parameters associated with irregularity structures. Various modified physical parameters for the equatorial region are given in Table 7. In addition, the diurnal pattern depicts a peak before local midnight, seasonal pattern shows some longitudinal dependence and the sunspot dependence is not as pronounced as in the 'original' model.

It is worthwhile to note that to a (good) first approximation, the Gaussian and the power-law descriptions lead to matched results. Though the scintillation observations were made for about three decades, it is only since the recent few years that the morphological data are available in the form of

Table 7—Physical Parameters for the Original and the Updated SRI Models

Parameter	Original value	Updated value
Equatorial belt width	12°	20°
Axial ratio of irregularity structure	10	30 near the geomagnetic equator to 10 at a geomagnetic latitude of 20°
Height of the irregularity-embedded medium	350 km	500 km near the equator to 350 km at 20° latitude
Thickness of the irregularity embedded medium	100 km	200 km near the equator to 100 km at 20° latitude
To a first approximation, scale size (power-law visualized from Gaussian description)	300 m	300 m near the equator to 100 m at 20° latitude

quantified index SI or S_4 . However, much more such data are required for modelling purposes. In view of this, it will be practical, at least for 'some time', to use 'good' scintillation data base combined with the incomplete Gaussian formulation for modelling purposes.

Because of the non-availability of comprehensive data at a single station, it would be logical to combine (say) Ooty low-to-medium solar activity data with the high activity data from Ghana and Peru to get a more statistically significant sunspot number variation. But such an attempt is likely to introduce more inaccuracies than in extrapolating the Ooty values for higher sunspot numbers. First, the frequencies are very different and the frequency conversion law is controversial. Secondly, the available data are a mixture of scintillation indices and scintillation percentage occurrence, and thirdly, it is not accurate to combine data from such widely varying longitudes. The SRI model does not take into account the effects due to changes in geomagnetic activity. Of course, the most important fact to be kept in view is that the diurnal and seasonal variations are much more dominant and this makes the study of solar and magnetic activity variation rather obscure. It would be appropriate to point out the rather puzzling solar cycle and magnetic activity dependences of scintillation (see Table 6). It is difficult to reconcile the positive correlation with solar activity and the negative correlation with magnetic activity with the existing knowledge of solar-terrestrial relationships, for it is well known that there is one-to-one correspondence between solar and magnetic activities over longer periods⁸.

6. Conclusion

The modelling described above presents only the 'expectation level' of scintillations for a specified set of

observing conditions. Data should be accumulated (and suitably processed) to include a description of departures from mean scintillation conditions, i.e. to account for night-to-night departures on a given communication link during the same season, at the same local time, and under the same solar and geomagnetic conditions, which can be substantial. The question of course remains, "What about daytime scintillation modelling?" And there is yet no progress in this direction; luckily, daytime scintillation activity is rather weak.

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