Ionospheric Scintillation Predictions for the Geostationary Satellites GOES & ATS-F

JOSEPH H. POPE
National Oceanic & Atmospheric Administration, Boulder, Colorado 80302, USA

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Maps of scintillation indexes over the region of the earth viewed by a geostationary satellite at 100°W longitude were produced using the SRI global model for scintillation [Fremouw, E. J. & Rino, C. L., Radio Sci., 8 (1973), 213]. These maps were calculated for several times of the day, for the solstitial and equinoctial variations, and for sunspot numbers corresponding to high, medium and low solar active periods. The contours represent a convolution of the elevation angle, position, and diurnal variations. The equatorial region shows the most severe scintillation effects in the region of ±20° from the geomagnetic equator. Strong effects are also shown for the auroral zone, while midlatitudes are nearly free from scintillation activity. The worst case conditions occur in the equatorial region for sunspot number 200 during the equinoctial periods, and for the regions of the earth having local time near midnight. Under these conditions, the scintillation indexes will be saturated (i.e., approximately 1). These maps should be useful in determining the deployment of buoys and other surface stations for use with the GOES (Geostationary Operational Environmental Satellite) data collection and relay system. The method is also applied to the radio beacon frequencies .10 and 360 MHz of ATS-F to be launched in 1974 for communication experiments to be conducted in India. The predictions indicate that scintillation activity will be large at times even during periods of low solar activity particularly near midnight, and during equinoxes.

1. Introduction

A perturbing effect to trans-ionospheric radio signals, known as scintillations, is produced by the irregularities in ionospheric electron density. This phenomenon has been studied for some time, using radio stellar and satellite sources. Reviews have been presented by Briggs¹, Getmantsev and Eroukhimov², and Aarons et al.³. It is found that the scintillations are large in the equatorial and in the polar regions. They show strong diurnal variations peaking near midnight, seasonal variations with peaks near the equinoxes, and a positive correlation with solar activity. In addition, the scintillations have a dependence on the transmitted frequency, decreasing with higher frequencies.

The irregularities producing the scintillations are field aligned 'blobs' of electron density with transverse sizes ranging from perhaps 100 to several kilometres⁴. The length along the field line of the irregularities ranges from 2 to 10 times that of the transverse size. Similar irregularities also produce the phenomenon known as spread F, observed by using ionospheric sounders, and in particular, the type of spread F known as 'range spreading' seems to be most nearly related to the scintillation phenomenon at low latitudes⁵. The propagation theory can be adapted to explain both scintillations and spread F on the basis of the existence of irregularities.

Although various attempts have been made to develop theories for the mechanism of the generation of the irregularities themselves, there has been little success in producing formulations in agreement with experimental results⁶. Several suggested approaches include production by precipitating protons⁷, production by means of hydromagnetic waves⁸, and various types of plasma instabilities caused by ionospheric vertical drift⁹. A number of other mechanisms have also been suggested, some of which are described in the review papers cited above.

The Geostationary Operational Environmental Satellite (GOES) will be launched during the last half of 1973. The satellite, which is now under development by NASA as the Synchronous Meteorological Satellite (SMS), will contain a number of sensors and subsystems which are concerned with meteorology, hydrology, oceanography, and space environment. Among the various subsystems is a data collection and relay system, operating near 400 MHz, that will relay data from numerous land- and sea-based stations. In view of the limited power budgets and operating conditions, it is important to examine the various propagation parameters associated with this system including effects of scintillation.

Application Technology Satellite-F (ATS-F), to be launched in 1974, will have on board a radio beacon transmitter to be used for ionospheric electron
content measurements by means of the Faraday and group delay methods. The satellite will be located near 95°W longitude initially and will move to about 35°E longitude about one year after the launch.

The purpose of the present study is to estimate scintillation effects for the two geostationary satellites GOES and ATS-F under various conditions of solar activity, including temporal variations. For GOES, a parking longitude of 100°W is assumed and a frequency of 400 MHz is used for data collection and relay subsystem. For ATS-F, two parking longitudes are assumed, viz. 95°W and 35°E; calculations were made for the radio beacon experiment at the two frequencies 40 and 360 MHz. The results were contoured onto earth projections that approximate the earth as viewed from the geostationary satellite position.

2. Theory

Scintillations result from a phase interference of signals that have been transmitted through randomly distributed ionospheric irregularities. These irregularities occur in the form of elongated enhancements in electron density with elongation along the magnetic field lines. The current theoretical formulation of the manner in which the irregularities produce the scintillation effects was enunciated by Briggs and Parkin. This theoretical development relates the electron density enhancement in the irregularities to the resulting amplitude variation of the transmitted signal. Rays passing through irregularities have a phase shift imposed in addition to that produced by the normal unperturbed ionosphere due to the change in the total electron content. As received on the surface, these rays produce the interference pattern.

The theory is treated in two steps. First, the rms phase shift ($\phi_\text{rms}$) due to the rms change in electron density ($\Delta N$) is calculated. The overall effect appears as a corrugated wavefront emerging from the ionosphere. Secondly, the geometry of the situation is taken into consideration in order to calculate the amplitude variations observed as a result of this corrugated wavefront. In order to relate the phase shifts produced to the scintillation amplitude measurements as observed by the surface station, it has been customary to assume that the change in the phase shift produced by the irregularities is smaller than one radian. For this reason the theory is known as the "weak scatter" theory and is strictly valid only for those conditions under which this situation holds. At present, there is no generally applicable formulation for strong scatter conditions.

A given ionospheric screen of irregularities then produces a diffraction pattern on the surface from a given source. This pattern moves on the surface by an amount depending on the ionospheric motions of the irregularities and of the motion of the source. In the case of a fixed source, ionospheric motions impart a horizontal motion of the order of 100 m/sec to the ionospheric irregularities. For sources in motion, such as polar orbiting satellites, the diffraction pattern moves in a direction opposite to that of the satellite, with the velocity depending on the height of the irregularities relative to the height of the satellite and on its velocity. For radio star and geostationary satellite sources, the motion of the pattern is almost entirely caused by the motion of the ionosphere, while for polar orbiting satellites the motion is almost entirely that due to the motion of the satellite itself. In either case, the signal received on the surface appears to fluctuate in amplitude in a manner that has the appearance of a superimposed noise. Owing to the slow speed of the ionospheric irregularities relative to the satellite velocity, the fluctuation rate for the geostationary satellite is smaller than that for the polar orbiting satellite.

3. SRI Irregularity Model

Recently, Fremouw and Rinof of the Stanford Research Institute (SRI) have used scintillation data along with the theory of Briggs and Parkin to develop a global model of the irregularities. They used scintillation index data obtained by a number of stations located over a range of latitudes from the equatorial through the polar regions, taken primarily in the vhf range. The data used were selected to satisfy the validity constraints of the weak scatter theory. It was also necessary to make certain assumptions regarding the height, scale size of the irregularities, and the thickness of the scattering layer. The scale size is the distance from which the spatial autocorrelation function drops to 1/e, or roughly the average size of the irregularities in the small dimension. The height was taken to be 350 km, with a thickness of 100 km. The scale size was taken in three ranges depending on latitude. The resulting representation for the $\Delta N$ model is then a mathematical expression with a number of independent variables that include the mean sunspot number, day of the year, time of the day, and geomagnetic latitude.

This model was used as the basis of a computer programme that computes scintillation index as a function of the above four independent variables. Geographic considerations such as the location of the transmitter and the receiver are also included. Because of the weak scatter limitations, the validity of the model is limited to the region where the differential phase shift is less than 0.7 radian. For phase shifts greater than 0.7 radian, scintillation in-
dexes are computed by the programme, but a notation is made to indicate that the value can be considered to be only approximate. Another limitation is inherent in the fact that the data used to derive the various coefficients were largely restricted to the vhf range. Current theory and observational evidence indicate that extrapolation to much higher frequencies may not be valid.

4. Method

To compute the scintillation indexes, a modification of the computer programme described above was used to produce matrices of scintillation index for incremental steps in geographic latitude and longitude. The resulting values were then used to obtain contour maps of scintillation indexes. In computing the matrix, it was necessary to take into consideration that at any particular instant of time, on the meridian of the satellite, a time span of nearly 12 hr from east to west is observed. Also, the time at the penetration point in the ionosphere is generally different from that at the surface station, and this factor was taken into consideration. The resulting contour maps then represent a convolution of several parameters including latitude effects, diurnal variations, and elevation angle dependence. Separate maps were produced for different times of the day, different seasons and sunspot conditions.

The scintillation index (Sₐ) (Briggs and Parkinson) is used. This index is the simple average of the power excursions divided by the average power and is given by

$$Sₐ = \left\langle \left\langle \frac{1}{P} - \frac{1}{P} \right\rangle \right\rangle$$

where $P$ is the instantaneous power and the quantities enclosed by brackets $\langle \rangle$ indicate averages.

5. Results

Fig. 1 shows the scintillation index as a function of latitude computed for the 100° W meridian at time 2400 hrs (100° WMT) and for day 81 (spring equinox). The frequency is taken as 400 MHz. Three curves are shown, parametric for sunspot numbers 30, 100, and 200. The combination of midnight, sunspot number 200, and day 81, corresponding to the spring equinox, can be considered a statistically "worst case" condition. The equatorial region is shown between about -30° and +10° geographic latitude, the displacement from the true latitude being caused primarily by the tilt of the earth's magnetic field. Two elevation angle effects cause additional displacement. One of these is the latitudinal difference between the station and point of ionospheric penetration for ray directions having a north-south component. The scintillation effects corresponding to a different latitude are thus assigned to that of the station. The second effect is that the path length through the ionosphere is greater for lower elevation angles, increasing the scintillation index. Therefore, the equatorial belt is biased by 1° or 2° south of the actual equatorial scintillation belt. The scintillation amplitudes for the midlatitude regions between +10° and +50° in the north and -30° and about -70° in the south are seen to be quite small and probably will only rarely give rise to any scintillation problem. The northern auroral zone is shown starting in the vicinity of 60° N, while the southern auroral zone is mostly beyond the view of the GOES because of the tilt in the earth's field with respect to the geographic coordinate system.

With the exception of a small band in the equatorial region, it is seen that for sunspot numbers corresponding to low solar activity, scintillations are not likely to be a problem at 400 MHz. However, as the sunspot number approaches 100, scintillations become significant in the auroral and equatorial regions. In using these curves, it should be kept in mind that, owing to the limitations in the theory due to weak scatter, scintillation indexes greater than 0.5 are probably not correct for the parameters shown. Hence they can be used in a qualitative sense only.

Plots of $ΔN$ as a function of latitude in the 100° W meridian are shown in Fig. 2 for midnight, sunspot number 100, and for day numbers 81 and 172 to show the effect of seasonal change. Frequency is not specified because $ΔN$ is not dependent on frequency. Note that the auroral zone does not show a seasonal variation. The curve for $D = 81$ in Fig. 2 corresponds to that for $S = 100$ of Fig. 1. Thus, the peak value
The contour map for ATS-F with frequency 40 MHz, sunspot number = 10, and equinox (day=81) is shown in Fig. 7. The local time at the subsatellite point in this figure is midnight at 95° E. Two minor peaks are shown which are the results of the fact that at two points, for a given satellite location, the ray to the satellite parallels the magnetic field in the ionosphere. These two positions are shown near 29° N, 92° W, and 39° S and 99° W. Similar points and corresponding conditions are shown in Fig. 8 for the satellite located at 35° E. In Fig. 9, the conditions are the same as in Fig. 8 except that the frequency = 360 MHz and sunspot number = 50.

of $N$ (about $8.5 \times 10^{10}$ electrons/m$^3$) produces a scintillation index ($S_3$) of about 0.55.

For the SRI model, the spring and fall equinoxes are identical, as are the summer and winter solstitial periods, so that day = 81 is the same as for day 265, and day 172 is the same as day 356. Therefore, plots are shown only for days 81 and 172. Fig. 3 shows contours for frequency = 400 MHz, sunspot number = 100, day = 81, and time = midnight (100 WMT) (contour interval = 0.05).

Fig. 2—Meridian cut of rms electron density variation for 100° W longitude, sunspot number = 100, time = midnight (100 WMT), and for day = 81 and 172.

Fig. 3—Contours for longitude = 100° W (GOES), frequency = 400 MHz, sunspot number = 100, day = 81, and time = midnight (100 WMT) (contour interval = 0.05).

Fig. 4—Contours for longitude 100° W (GOES), frequency = 400 MHz, sunspot number = 100, day = 81, and time = 0600 hrs (100 WMT) (contour interval = 0.05).

Fig. 5—Contours for longitude = 100° W (GOES), frequency = 400 MHz, sunspot number = 100, day = 81, and time = 1800 (100 WMT) (contour interval = 0.05).
During the time that ATS-F is parked at 35° E longitude, it may be of considerable interest to make scintillation studies from various stations in India. It is desirable, therefore, to make calculations of the amount of scintillations to be expected under the circumstances for moderately active solar conditions. Calculations were made for a receiver located at 80° E and 20° N to represent a typical receiver location in India. Fig. 10 shows the diurnal variation that can be expected for the equinoxes and for solstices. In Fig. 10, the sunspot number is assumed to be 50 and the frequency is taken to be 40 MHz. The geostationary satellite is located at 35° E. Although the scintillation index ($S_a$) is shown to exceed the value 1, it will, in fact, not exceed this value because it is intrinsically limited to unity as an upper bound. Indeed the values shown for $S_a$ greater than about 0.5 become increasingly inaccurate as $S_a$ approaches 1, because the scintillation conditions fail to satisfy the conditions for weak scatter. The diurnal curve peaking slightly ahead of midnight is due to the fact...
that the point where the ray to the satellite penetrates the ionosphere is somewhat west of the receiving station. For a frequency of 40 MHz, then, it can be expected that during the night the scintillation activity will saturate at any time of the year for moderate solar active conditions. Because there is no generally applicable formulation for a strong scatter condition it is not possible to calculate the actual magnitude of this scintillation activity during the times when saturation, for the weak scatter theory, occurs.

6. Discussion

In using the results given above, the various limitations of the model should be kept in mind. The model is an average representation, under a given set of parameters, of the empirical data that were taken under those parameters. In its present configuration, the model makes no provision for standard deviations from the average. It is thus to be expected that occasionally values significantly different from those given, for the parameters stated, will occur. The present state of knowledge regarding the irregularities makes certain necessary assumptions that are built into the model. These include the height and the scale size of the irregularities, both of which may vary considerably. In addition, the empirical data on which the model was based may be insufficient in some geographical regions to properly define the coefficients in the model. Since the data were observed in the vhf region primarily at about 137 MHz and below, extrapolation to higher frequencies is probably not valid.

7. Conclusion

These results show that at the frequency to be used on GOES for the data collection and relay subsystem, scintillation effects will be large under moderate solar activity (sunspot number \( \geq 100 \)). The effects will be most pronounced in the equatorial and polar regions, during equinoxial periods, and near midnight.

For ATS-F at 40 MHz, scintillation will be significant in the equatorial regions even during low solar active periods. The satellite should, therefore, present an excellent opportunity for the study of ionospheric scintillations. Stations located in India and various parts of Africa should produce significant results during the time starting in 1975 when the ATS will be located on 35° E longitude. Observations should be made simultaneously on all of the beacon frequencies near 40 MHz and 360 MHz. In addition, observations at frequencies in the GHz range should be attempted when possible, because scintillations are often observed in this range.

The points where the magnetic field line parallels the ray path to the satellite will produce scintillations significantly greater than at other longitudes but similar latitudes. When ATS is at 95° W, such a northern point will be at about 28° N, 90° W, near New Orleans, Louisiana, and when it is at 35° E, at about 35° N, 22° E, near the southern part of Greece. In both cases, the corresponding southern hemisphere points are located away from significant land masses so that observations may be impracticable.

These various observations will help in evaluating and extending the Fremouw global scintillation model, in addition to furthering our knowledge of the ionospheric irregularities.

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References