50 Years of Radio-Scintillation Observations

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1. Abstract

The author attempts a brief summary of the history of ionospheric fading from sources beyond the upper atmosphere. The concentration is on the early studies of scintillation. The first sources used as transmitters were radio stars with varying diameters. With the advent of satellite transmissions at altitudes varying from 300 km to several earth radii, fading was studied as a function of various regions of the globe. In years of high solar flux, trans-ionospheric propagation through polar and equatorial regions has experienced deep fading at frequencies ranging from 54 MHz to 4 GHz. Fading of radio signals from satellites still plays a role in evaluating operational and proposed system effectiveness. The relevance of these studies to Global Positioning System reception and users of proposed systems at L band is discussed.

2. Introduction

In the years following World War II, with the advent of large antennas, the improvement of receivers, and the reorientation of the academic community, radio astronomy flourished. The study of discrete sources of radio waves in the galaxy followed. In 1946, Hey, Parsons, and Phillips [1] reported that the Cygnus source fluctuated in their observations at 68 MHz. Were these genuine fluctuations of the sources, or effects of the atmosphere? Experimental studies in Australia and New Zealand [2], and in the UK at the Jodrell Bank Experimental Station of the University of Manchester and the Cavendish Laboratory of Cambridge University, found that the fluctuations were not coherent when observed simultaneously at the widely spaced radio-astronomy observatories; nor were the fluctuations coherent when received at antennas spaced 20 km apart [3].

Two possible sources for the irregular diffraction patterns were discussed by Ryle and Hewish [4]. Diffraction by interstellar matter would imply that the pattern had a structure the dimensions of which were at least 900 km; this was dismissed based on the spaced-receiver experiments, but scattering from ionospheric irregularities was not. Major theoretical studies of scattering were developed by Ratcliffe [5] and by Booker [6]. An index of fluctuation was defined as the ratio of the mean deviation of the intensity to the mean intensity: this remains as one current definition of scintillation intensity. The correlation of the discrete-source fluctuation with spread F was clearly shown, but with a correlation coefficient of 0.42 to 0.45.

Studies showed two peaks in scintillation occurrence, i.e., near noon and near midnight. This confirmed the proposal by Wild and Roberts [7] that daytime scintillations were due to sporadic E, and nighttime, to F-layer irregularities [8]. Many studies were directed at a correlation of the occurrence of spread F and scintillation. However, in the spread-F data extant at the time of the older studies [9, 10], there was no indication of intensity of the F-layer irregularities. In addition, when scintillation occurrence was used, it was at a distinct frequency and a distinct level of intensity. The attempt to correlate scintillation with the occurrence of spread F, as reported in the International Geophysical Year (1958-1959) and earlier routine observations, has turned out to be a relatively fruitless study.

An attempt to determine the frequency dependence of amplitude scintillations resulted in the statement that "the amplitude of scintillations varies with the square of the observing wavelength" [11]. This turned out to be somewhat more complex than first thought, since the angular diameter of the radio-star sources was involved. In addition, one had to make sure that only weak scattering was extant on the two or more wavelengths to be evaluated. At the present, there is agreement that instead of the square of the frequency, the ratio of frequencies should be raised to the power -1.5: the higher-frequency transmissions are dramatically less subject to fading.

3. The advent of satellite beacons

The launch of the low-altitude Sputnik series, particularly Sputnik 1 and Sputnik 3, allowed a plethora of observations to be made with simple equipment. The relatively high power of radiation at 20 and 40 MHz permitted the use of a simple antenna (instead of the large radio-astronomy collectors), a preamplifier, and a communications receiver. The lower frequencies of 20 and 40 MHz allowed plotting scintillation occurrence and intensity all over the globe. Surveys and long-term measurements were made, beginning in 1958, but in some areas they suffered from very strongly scattered signals saturating the receiver range. Results on the morphology of E- and F-layer irregularities gradually emerged.

Radio-star studies had prepared the ionospheric-propagation and ionospheric-physics communities for satellite-transmission studies. Sputnik 3, with its 20 MHz transmissions, was, at times, transmitting from within the F layer of the ionosphere. During those periods of time, when the satellites were below the horizon, HF propagation, with its multi-hops, was noted. Eventually, the satellite disintegrated in the dense atmosphere.

The satellites BEB and BEC, with their 40 and 41 MHz signals at a nominal 1000 km altitude, were used over long periods of time to look at scintillation and total electron content; their inclinations differed, so that equatorial, middle-, and high-latitude irregularities could be studied. The synchronous-satellite series, ATS (Advanced Technology Satellites), were placed at various longitudes. Their original expected life of one year expanded to many years of transmissions. The advent of the ATS series, transmitting at many different longitudes at 136 MHz, allowed for Faraday-rotation studies and, therefore, studies of total ionospheric and protonospheric electron content. Among the large number of satellites that were used for propagation studies, two satellites were used extensively: ATS-6 [12], and the low-altitude noon-midnight satellite WIDEBAND [13, 14], and its follow-up, HILAT. Each had a series of frequency transmissions developed from a single oscillator. A large number of ground stations participated in determining total electron content and scintillations from the transmissions of ATS-6. The WIDEBAND satellite was used for determining phase and amplitude scintillation at equatorial and high latitudes. The 150 and 400 MHz (plus the earlier transmissions at 54 MHz) of the NNSS [Navy Navigational Satellite System] series of Transit satellites added to the plotting of high-latitude scintillation activity [15, 16]. This series is now used in tomography studies.

Early contributions to the morphology of irregularities emerged from beacon measurements. Kent [17] reported that the fading of the 40 MHz signals radiated from Sputnik I disappeared south of the UK observing station. In time, the effect of magnetic activity emerged; the use of the radio stars had made this difficult. For some radio-star sources, middle-latitude-based observations took place at the same time that the propagation paths to the sources were at sub-auroral or auroral latitudes. Low-angle observations suffered from tropospheric scintillation. At first, corpuscular streams were invoked as the origin of the irregularity development, but at this period, little data were available as to those sources.

Several studies examined the role of magnetic activity and the occurrence pattern of irregularities at sub-auroral and auroral latitudes. Using 40 and 54 MHz satellite scintillations, it was found that the high-latitude-irregularity region expanded with increasing K index and with solar flux [18]. Aarons and Allen [18] also noted an abrupt transition between the low level of the average scintillation intensity of the southern edge, and the increasing level to the north. The idea of the boundary emerged, with the suggestion that the boundary moved as a function of time of day. Ryan [19] used radio-star scintillations from the relatively high geomagnetic latitude of 55° in Canada to observe scintillation at upper transit of four sources, during the high-solar-flux period of December, 1957, to November, 1958. Scintillations well to the south showed lower amplitude and rate indices than those to the north. Ryan also noted that the transition between the quiet lower latitudes and the highly disturbed auroral scintillation was found within a few degrees of latitude. The beacon and radio-star studies led to the same conclusion, i.e., that irregularities were extant on a particular pass up to what was termed the scintillation boundary. This was defined arbitrarily at a average level of intensity, at a particular frequency or occurrence, at a given level of intensity. Magnetic storms produced irregularity regions that pushed equatorwards. One could set a boundary of the extension of auroral-region irregularities under both quiet and disturbed magnetic conditions [20]. Hajkowicz [21] has defined the scintillation boundary for the southern hemisphere.

Using radio-star sources, Ko [22] was able to push the study to the higher frequency of 915 MHz. The auroral region showed much lower levels of scintillation at this frequency, even observing through optically observed aurora.

The propagation angle to satellite beacons was an important area of study for all latitudes. There were discussions of the effect of looking along the lines of force of the Earth's magnetic field, and perpendicular to them [23]. The aim of studies of this problem is to determine amplification of scintillation as a function of the configuration of the irregularity. The evaluation of this parameter depends on the assumed or measured dimensions of the small-scale (less than a kilometer) irregularities. Are these sheets, needles, or small bubbles? Irregularity dimensions are a function of where in geomagnetic space they are found. Different configurations are favored for the auroral oval, for the equatorial region, and for the polar cap.

The interest in satellite scintillations prompted the important analysis paper of Briggs and Parkin [24]. Corrections for irregularity geometry, frequency dependence, and distance from the observer were all developed. Subsequent corrections to all-sky observations of satellites were then utilized in morphological studies. Considerations of many of the problems of developing a theory to explain the effect of the angular diameter of the source, frequency dependence, and propagation angle were developed by Lawrence et al. [25]. These topics and studies on scattering were further explored by Yeh et al. [26].

The general trends in high-latitude scintillation are shown in Figure 1. While solar flux plays an important role in the latitude of observed scintillation, magnetic index plays a much larger role. In the auroral region, magnetic storms show penetration to lower latitudes, and increased intensity compared to quiet magnetic conditions.

4. The middle latitudes

In summarizing the general trends of intense scintillation, a cartoon of intensity, particularly for solar maximum, has been drawn (Figure 2). While scintillations have been observed at middle latitudes, their impact on high-frequency signals is minimal.

There are a plethora of observations at middle latitudes. Some indications of the results of these studies are given in Bramley and Browning [27]. These regions include the latitude range below the sub-auroral region at times of geomagnetic quiet; this is arbitrarily defined as below 50 degrees Corrected Geomagnetic Latitude, a mapping system based on geomagnetic properties of the auroral region. It is used for latitudes above the equatorial-anomaly region i.e. above 20 degrees dip latitude. The system of

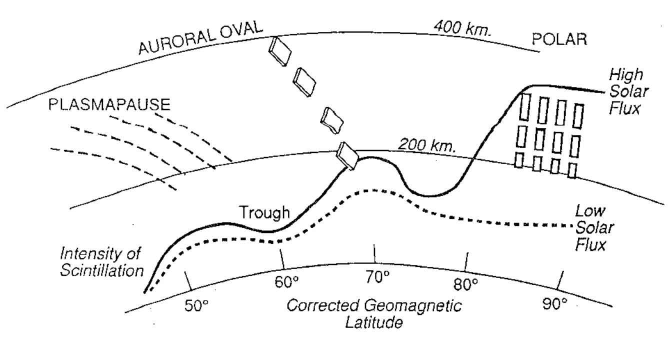

Figure 1. The sub-auroral, auroral, and polar regions are illustrated in this cartoon. The lower latitudes show irregularities during severe magnetic storms. The auroral-region F-layer irregularity intensity increases during scintillations, during years of high solar flux.

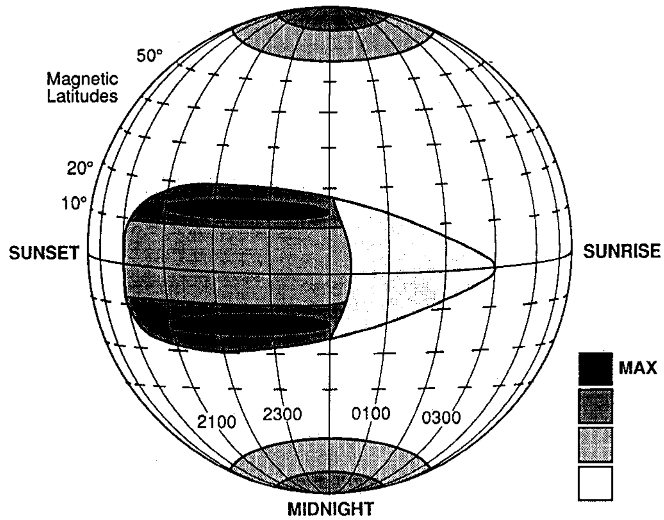

Figure 2. The nighttime scintillation activity during solar maximum. The anomaly regions of the equatorial ionosphere show the most intense scintillation.

dip latitudes is used for studies near the magnetic equator, and is derived from the dip angle of the magnetic lines of force. The effects of auroral disturbances pushing equatorward, and equatorward effects pushing poleward, has made the isolation of purely middle-latitude scintillation difficult to assess. The effect of sporadic E has been noted from a number of astronomical and beacon satellite observatories. From the point of view of gigahertz scintillation, the middle latitudes are of little interest. They are sporadically of importance during magnetic storms, when the propagation angle to the satellite is parallel to the Earth's magnetic field. At various longitudes, middle-latitude irregularities may exhibit different characteristics. Probably the most unusual are the irregularity structures seen in summer near Japan and Korea, as shown in global studies of spread F [28], and more recent radar studies [29].

5. The equatorial region

Using both radio stars and satellite beacons at VHF, fading was observed in the equatorial region by Koster and Wright [30] and Sinclair and Kelleher [31]. In addition, Skinner et al. [32] found fading in amplitude at 4 GHz, up to 4 dB in carrier level. This took place between 20-24 h local time in March, April, and May in 1971, a year of high solar flux.

From the scintillation point of view, the equatorial region has to be divided into the area near the magnetic equator and the anomaly region. The latter encompasses a swath of over 5 degrees, centered on a magnetic latitude of 15 degrees North and South of the magnetic equator; in 1981, it was found that this is the area where the most intense fading is observed most frequently during years of high solar flux [33]. Figure 2 details the intensity of fading during a year of high solar flux. What takes place at the magnetic equator is that a plume of irregularities is generated in the post-sunset time period. The plume can extend above the magnetic equator to over 1500 km in altitude; it is the initiating factor in gigahertz scintillations at anomaly latitudes. The turbulence above the equator affects the lines of force of the Earth's magnetic field. This, in turn, produces the most intense irregularities at anomaly latitudes, the latitudes that have the highest electron density of the region. At 1.5 GHz, maximum fading near the magnetic equator is of the order of 5-7 dB peak-to-peak. At the same time, fading in the anomaly region has reached saturation levels of 28 dB peak-to-peak level for several hours [34].

A large-scale program at 4 and 6 GHz was carried out during years of low and high solar flux by COMSAT, particularly from Hong Kong [35, 36]. At times, equatorial effects reach a higher latitude than the nominal position of the anomaly, i.e., beyond 15° of dip latitude. The extent of the anomaly region poleward of its nominal latitude appears to vary. Some data from observations made from middle latitudes in Japan may be equatorial scintillations. Considerable fading has been observed at frequencies as high as 20 GHz [37]. Scintillation studies have also been done from the anomaly latitude of Taiwan [38]. The importance of the geometry of the propagation path has become obvious. Propagation paths are, at times, across the lines of force of the Earth's field, but at other times, the path is along the lines of force of the Earth's field; the latter results in an increase in the depth of fades.

6. The polar cap

Early analysis of spread-F data in the polar regions failed to find the morphology of polar fading [39]. Measurements [40] during years of high solar flux first revealed completely saturated fades, to 25 dB at 250 MHz, over many hours. Small-scale irregularities, embedded in patches of several hundreds of kilometers in size, move across the polar cap. During high solar flux years, scintillating signals were observed over many hours, with peak-to-peak values greater than 10 dB on 1.6 GHz signals [41]. In years of low solar flux, 250 MHz scintillations most often showed no more than 3-5 dB fluctuations.

7. Recent studies

At the present, the US military satellites at 250 MHz, with both synchronous and high-inclination orbits, are being used as signal sources for high- and equatorial-latitude studies; the large number of these satellites allows measurements to be made over many longitudes. One group of scientists interested in propagation studies compared records, and emerged with a database ranging from auroral to equatorial latitudes. In a different form, this group still exists as the Satellite Beacon Group.

At Ascension Island, amplitude-scintillation measurements were made over a solar cycle. This site, in the anomaly region, had frequent fading over several hours of over 20 dB at 1500 MHz, during years of high solar flux. The enormous contribution of solar flux to raising the level of scintillations recorded in the anomaly region of the equator was shown in extensive data by Basu et al. [34].

The database has been used to develop a global picture of total electron content and scintillation occurrence. Algorithms and models emerged [42]. The scintillation data were used to develop constraints on satellite transmissions [34]. The total electron content data are being used to correct radar ranges, and to form the basis of the correction algorithm for GPS (Global Positioning System).

There are advantages to taking measurements at many frequencies. The lower frequencies are more sensitive than the higher, but the recordings can suffer from saturation when the fades move below the signal-to-noise level of receivers. The higher frequencies seldom suffer from saturation effects of the equipment.

Today, there is extensive use of the Global Positioning System transmissions at 1.2 and 1.6 GHz to study propagation parameters [43-45]. There is a plethora of satellites (24) available.

At high latitudes, many studies are oriented towards understanding the mechanisms responsible for auroral-latitude scintillation. Mechanisms and correlations between scintillation occurrence and other parameters have included shears in the ionosphere, E-layer irregularities, F-layer irregularities, and high velocities of plasma. One example of observational programs designed to penetrate the physics involved is that by Basu, Su. et al. [46]. Scintillation is basically a measure of the intensity of irregularities over the total propagation path, and the sorting of the necessary and sufficient conditions to develop instabilities and the subsequent irregularities has proven difficult.

From the point of view of the ionospheric physicist, there is much to be learned about the phenomenon of the generation of E- and F-layer irregularities. It is hoped that understanding the forcing functions for the generation of these scatterers of radio transmissions will yield techniques for forecasting and warning of scintillation.

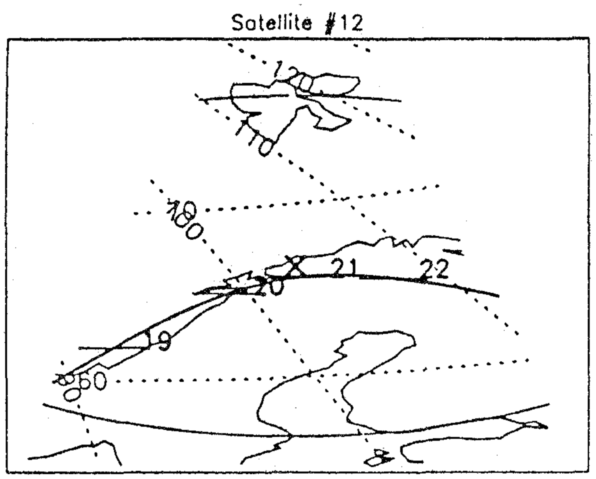

Figure 3a. Phase fluctuations at Trømsø, Norway, using GPS observations UT Date: September 27,1995. The path of the satellite as observed by this station is shown.

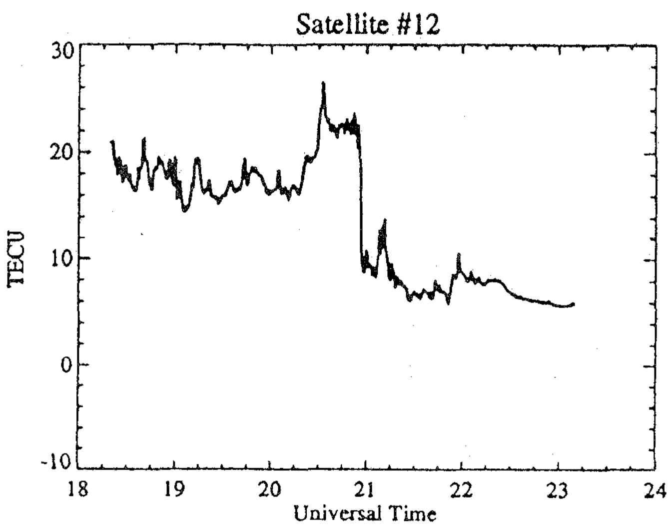

Figure 3b. The fluctuations in total electron content (TEC) at Trømsø along the GPS path shown in Figure 3a.

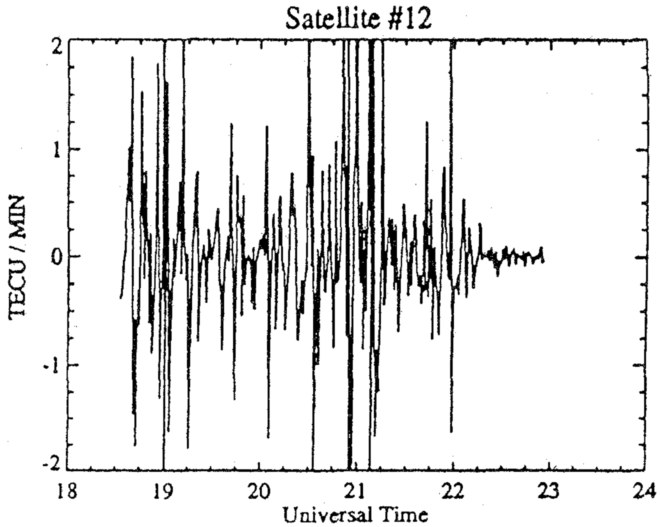

Figure 3c. The rate of change of TEC (phase fluctuations) during this magnetic-storm period at Trømsø, corresponding to Figures 3a and 3b.

8. Relevance to modern systems

What is the relevance of these studies to modern radio systems? Frequently, the discoveries brought bad news to developing systems. A proposed use of 136 MHz for aircraft to satellite-to-ground communications showed that these transmissions would encounter the same problems that HF would during magnetic storms: the development was aborted. The use of 250 MHz military satellite transmissions for both high- and equatorial-latitude communications meant that users had to be aware of the strange fading on their transmissions at certain latitudes and under certain conditions.

The signal statistics that have been measured allow digital transmissions to circumvent some of the effects of scintillations. In many cases, the redundancy needed to minimize scintillation has not been accepted by system operators.

Today, the users of Global Positioning System signals should recognize the conditions and areas where low signal-to-noise equipment might have difficulty in both acquisition and in losing signals for periods of time. Studies are underway cautioning users of GPS. New systems are being proposed and developed in the 1.2-1.6 GHz range (Iridium). Low signal-to-noise receivers will be affected by scintillation. Only recently, a satellite system using 135-140 MHz has been re-proposed; the ionospheric problems should be critically evaluated.

Figure 3 is an illustration of the phase scintillations of a GPS signal in the auroral region during a magnetic storm. The path of the satellite, total electron content (TEC), and rate of change of TEC (phase scintillation) are shown for Trømsø, Norway, during a magnetic storm. Fluctuations can lead to errors and, in very severe cases, to loss of lock at equatorial and auroral latitudes.

9. Acknowledgments

I would like to apologize to the many scientists to whom I have not referred. Many observers contributed to the identification of the regions and the ionospheric parameters that give rise to scintillation. Others have contributed to the understanding of the physics of the development of irregularities. The brevity of this summary did not allow for a full expansion of the history of ionospheric scintillation.

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Dr. **Jules Aarons** is, at present, a Research Professor in the Center for Space Physics at Boston University. His studies at this time and for most of his career have centered on ionospheric effects on radio propagation from satellites. At present, he is working on phase scintillations on GPS transmissions.

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He has written many journal articles, including basic reviews in the *Proceedings of the IEEE*. From 1958 through 1970, he organized and developed an international group involved in satellite-beacon studies. Members of this group included scientists from Norway, Sweden, Denmark, UK, Germany, France, Italy, Japan, Taiwan, Iran, and Israel. In the international field, he has worked with and written joint papers with scientists from many countries. He served as international Chairman of URSI Commission G on Ionospheric Radio Propagation, 1984-1987. He is a member of the American Geophysical Union, and a Life Fellow of the IEEE. He was the recipient of the Harry Diamond Award from the IEEE.

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