1. Radio Scintillation History

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In 1933 Karl Jansky [1] determined that a persistent radio noise emission was coming from the direction of the center of our Milky Way galaxy. Evolving radio technology was used in World War 2 to detect attacking airplanes [2] and to intercept radio communications. In the post-war period a plethora of extraterrestrial radio emissions were detected, and Radio Astronomy was born. The first observation of radio scintillation was the *twinkling* of radio-star emissions [3]. A review paper by Jules Aarons [4], a major early scintillation contributor, describes the first radio scintillation observations and the identification of structure in the earth's ionosphere as their source.

On October 4, 1957, Russia launched the first artificial earth satellite, Sputnik-1. It broadcast a 40 MHz modulated signal for three weeks before it reentered the atmosphere and burned up on January 4, 1958. [5]. The impact of Sputnik in the United States was profound. The National Science Foundation had been established in 1950. However, the development of additional agencies to stimulate technology and science was being resisted by President Dwight Eisenhower, who was concerned about large permanent government agencies. Within a year of Sputnik's launch the Advanced Research Projects Agency (ARPA) (February 7, 1958) and the National Aeronautics and Space Association (NASA) (October 1, 1958) were established.

Scientists at the Johns Hopkins Applied Physics Laboratory measured the Doppler shift of the Sputnik beacon to determine the satellite orbit. They realized that measuring the Doppler shift of a satellite with a known position could be used for position measurement [6]. Autonomous position determination was a critical need at the time for targeting submarine-launched ballistic missiles. Within a decade low-earth-orbiting (LEO) satellites were being used for navigation and communication. Dedicated and satellite transmissions of opportunity replaced radio stars as the primary sources for ionospheric scintillation observations.

Regarding theory, Maxwell's equations fully characterize the interaction of radio waves with transparent media. However, incorporating irregular structure requires the introduction of stochastic processes. The sequential developments of cybernetics by Norbert Wiener [7] and information theory by Claude Shannon [8] laid the foundations for the theory of propagation in random media, which includes the theory of scintillation. The history of scintillation morphology is well documented in many excellent survey papers. The theory of scintillation still initiates lively debates. The remainder of this survey will trace the history of scintillation morphology followed by the history of scintillation theory and a brief summary of the current status and challenges.

2. Scintillation Morphology

A theoretical paper by Briggs and Parkin [9], which is cited in the review by Jules Aarons [4], introduced four numbered statistical measures of intensity were scintillation. The index S4, which is a normalized measure of intensity variance, has carried the name to this day. The seminal paper by Booker [10] provided a framework for combining plasma-physics, electromagnetics, and stochastic processes to interpret scintillation diagnostics. Booker's theory predicted scintillation coherence measures. Calculations were simplified with the introduction of an *equivalent* phase-screen model. The initiating field has constant intensity with a phase variation generated by integrating the electron density along the propagation path, formally TEC. Intensity scintillation develops as the field propagates away from the phase screen. Plasma physics provides analytic relations between the ionospheric refractive index and the electron density. Statistical measures of the refractive index, particularly the power spectral density (PSD), are functionally related to statistical measures of the electron density structure.

The earliest systematic radio-star scintillation observations have been attributed to Father Koster, a Catholic missionary and physicist, whose first assignment was Ghana, West Africa [12]. His obituary credits him with having first recorded Sputnik outside the Soviet Union. Africa was a propitious location because of the structure associated with ionospheric high-frequency (HF) sounder measurements at geomagnetic equator latitudes. The phenomenon came to be known as spread F or equatorial spread F (ESF) [13]. The high-latitude auroral zones were also known to be regions of ionospheric activity. Morphological studies of radio star and early satellite scintillations were consolidated into probability-of-occurrence models. The morphology review by Aarons [11] describes an early occurrence model developed by Fremouw and Bates [14], which is still used.

The wideband satellite, designated P76-5, was dedicated to scintillation measurements. The mission was sponsored by the Defense Nuclear Agency to measure the UHF frequency coherence of the disturbed ionosphere, hence the name wideband satellite [15]. Narrow-band signals were transmitted at S-band (2891 MHz), L-band (1239 MHz), with seven UHF spectral frequencies from (378.6 to 445.5 MHz), and VHF (137.6 MHz). Receiving sites were operated at Poker Flat, Alaska, and Ancon, Peru, and for a time at Roi Namur in the Kwajalein Atoll. Both the satellite and the Scout D launch vehicle were spare components of TRANSIT, the Navy Navigation Satellite program. They were available because of the high reliability of the Scout-D launch vehicle.

Multi-disciplinary studies of ionospheric structure, including satellites instrumented to measure ionospheric structure directly, rocket probes, and chemical releases were pursued from the late 1960s. Morphological studies by Aarons et. al, Costa et. al, Santimay and Sunanda Basu, et. al, Wernik et. al., and Bhattacharyya et. al, [16], [17], [18], [19], [20], [21], [22], [23] refined the solar-cycle, seasonal, diurnal, and geographical dependencies of scintillation and its association with solar-induced magnetic activity. ESF attracted considerable interest in part because there was a well-developed theory as reviewed in papers by Ossakow [24] and Fejer [25].

On July 23, 1979, a powerful rocket launched from the Kwajalein Atoll intercepted a fully developed ESF structure. The rocket carried plasma diagnostics and a radio beacon, which transmitted a UHF signal through the intercepted structure [26]. A comparative analysis of the beacon scintillation data and the in-situ probe by Rino et. al [27] revealed a two-component power-law PSD through the peak of the F-layer. Later studies, which used in situ satellite measurements by Basu et. al [28] and beacon data by Bhattacharyya and Rastogi [29], confirmed the two-component structure.

The observation of equatorial scintillation on communication satellite transmissions at frequencies above one gigahertz by Craft and Westerlund [30] was unexpected and unexplained by the weak scatter theory. By 1970, computational resources, including early super computers, became accessible. The introduction of strong-scatter theory is traced in the seminal survey paper by Yeh and Liu [31]. Simulations by Franke and Liu [32] showed that the two-component spectral model could reconcile the observed scintillation at S-Band. Parameter estimates that reconciled frequency-dependent measurements were also demonstrated by Bhattacharyya et. al [33]. Simulations of propagation in structured media were published by Knepp, Carrano, and Wernik [34] [35] [36]. The equivalent phase-screen model became more important when it was realized that the free-space propagation of the intensity PSD could be reduced to an analytic form with a small number of scale-free parameters. Carrano developed an efficient algorithm for computing the intensity SDF Carrano [37].

Every element of scintillation morphology and structure has been refined with GNSS satellite observations Jiao et. al [38]. When scintillation is strong enough to degrade or disrupt GNSS operations, phase-screen models have been refined and calibrated against high-quality data sets Xu, et. al [39]. If the ionospheric gradients normal to the occultation paths are small, the path variation can be inverted to extract the ionospheric profile. Scintillation measurements have been interpreted accordingly Wernik, et. al [40].

3. Scintillation Theory

The geometric optics conceptual picture of rays guiding radio wave propagation led to applications by V. A. Krasil'nikov and his colleagues [41]. It worked reasonably well for optics and acoustics applications [42]. Corrections to accommodate diffraction by Obukov [43] were based on the early work of Rytov [44], which led to the method of smooth perturbations by Chernov and others [45] [46], [47], [48], [49], and [50]. The *parabolic wave equation* evolved from form the work of Leontovich, Dolin, Chernov, and Shishov [51], [52], [53], [54]. The challenge was finding a tractable means of characterizing stochastic field measures. The breakthrough came from the development of a hierarchy of differential equations for the complex field moments of all orders developed by V. A. Tatarskii [54]. His work became widely known following an English translation [55].

An international conference was held during August 1992 at the University of Washington, Seattle. A book publication of the papers summarizes numerous applications of the theory [56]. Theoretical developments have continued. Recent research using moment equations has been reported by Bhattacharyya et. al [57], and Carrano et. al [58], [59]. A hybrid integral equation approach was developed by Gherm, et. al [60], [61], and incorporated into a global scintillation model by Beniguel [62]. An unbounded power-law phase screen supported a self-contained theory. The initiating phase screen is a realization of fractional Brownian motion as developed by Mandelbrot [63]. Scintillation structure at any distance from the phase screen admits scalable structure with caustic-like structure described as diffractals by Martin Berry [64]. The scale-free parameters can be extracted with likelihood-based irregularity parameter estimation procedure developed by Carrano et. al [65].

Although the major theoretical effort has addressed coherence measures, For intensity probability distribution functions (PDF) were introduced early in the history of scintillation. PDFs are defined by the statistical moments of the random variable. The earliest models we defined by two moments, which could be related to the intensity variance or gaussian models that assumed jointly Gaussian statistics for the complex components or the logarithm of intensity and phase. These were found to be deficient. Moreover, the only theoretical support came from strong-scatter limits [66]. The most interesting case is when the scintillation index exceeds unity. Following developments in optics, a universal distribution by Jurado-Navas et. al [67] includes all the analytic distributions that have been used. Among them is the $\alpha-\mu$ distribution developed by Oliveria et. al [68], which has been used to characterize GPS fading structure by De O. Morales [69].

4. Current Status

The forward propagation equation and its parabolic approximation is the most general formulation of the theory. Numerical simulations supported by modern computational resources provide accurate realization from megahertz to gigahertz frequencies. Similarly, physics-based simulations by Yokoyama [70] have generated time-dependent realizations of equatorial plasma bubbles with cross-field resolution approaching meter scales. The simulations have been analyzed to determine the time and altitude variation of the power-law spectral parameters. An illustrative snapshot is shown in Figure 1. The analysis procedure is described in Rino et al [71]. Configuration-space realizations comprised of random collections of striations with appropriately scaled size distributions can be constructed to match the measured spectral characteristics. Figure 2 is an example from Rino et al [72]. For ESF, these results connect diagnostic and predictive procedures with structure characteristics measured both with both in situ measurements and simulations.

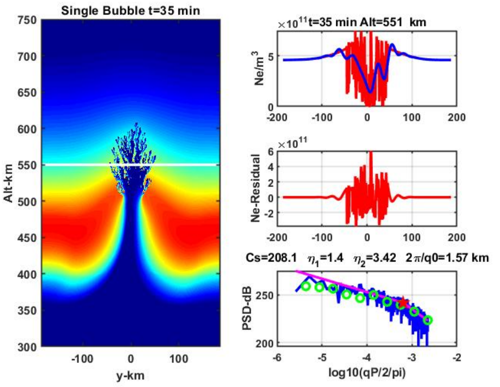

Figure 1 Example of height-dependent spectral structure characterization from EBP plume simulation. The middle frame is the structure residual.

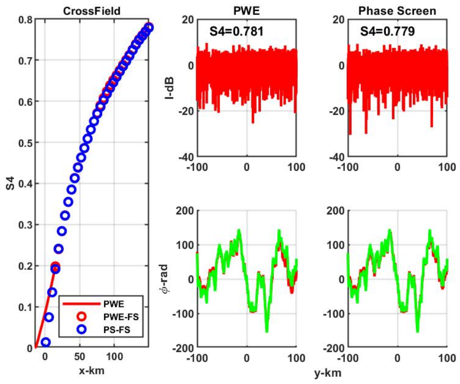

Figure 2 Left frame S4 index from 3D calculation (red) and phase screen (blue). Right frames intensity and phase in observation plane. Green at phase screen.

The more diverse structure in the auroral zone remains to be characterized along with sporadic-E and structure induced by ionospheric heating. Beyond that stochastic structure characterization needs to be integrated into the assimilation of data from evolving GNSS receiving networks. A recent book collection of review articles “The Dynamic Ionosphere: A System Approach to Ionospheric Irregularity” treats the subject directly [73]. The paper “Scintillation Modeling” by Materrasi, Alfonsi, Spogli, and Forti is particularly relevant.

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