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Ionospheric Induced Scintillation: A Space Weather Enigma

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The effect of scintillation on radio signals whose propagation path involves the Earth's ionosphere is analogous to the allies of World War II receiving radio messages that had passed through the Enigma machine. In both these cases, man-made information has been encrypted and transmitted via radio. The two encryption methods are shown in Figure 1. The right panel shows a World War II Enigma machine used extensively by German U-boats to convey encrypted messages transmitted by radio [*Perera*, 2010]. The left panel gives an extreme example of a mapping of ionospheric irregularities at 3 m, which creates very severe scintillation on radio communications through this ionospheric region [*Fejer*, 1996]. In addition, the task of formally deciphering the encrypted signal is a monumental task as time is of the essence and old information quickly becomes redundant.

Deciphering the Enigma signal involved inferring the number of "wheels," their settings, and the number and placement of cables in the patchboard in the Enigma Box [*Kasparek et al.*, 1984]. The more wheels there are, the deeper the level of encryption is. Continuing the analogy, the ionosphere introduces irregularities over a signal path's Fresnel zone. As the dynamic range of these irregularity scales increases and their amplitude increases, the ionospheric encryption deepens. Ionospheric scintillation is observed over many orders of magnitude of frequency of the radio spectrum and impacts almost all user frequencies. Conventional radio communication began at lower frequencies, and as technology evolved, the busiest frequencies migrated upward. The World War II Enigma messages were mostly carried by radio communications below 30 MHz, especially those from the submarine squadrons, which typically used 2 to 18 MHz. Hence, in principle, these Enigma messages potentially had a further level of encryption from the ionosphere.

Two classes of radio communications are strongly influenced by the ionosphere: long-distance HF (3–30 MHz) and satellite signals (mostly from 300 MHz to tens of gigahertz). Long-distance HF communications include a variety of military, government, and civilian services, notably those of disaster response groups such as radio amateurs. HF users employ voice and relatively low bit rate digital signals. Satellite signals include high-volume civilian and military communications and position/navigation/time (PNT) services such as GPS. Other than satellite signals, most transmissions above 30 MHz are intended as line-of-sight local broadcasts, and the ionosphere has limited impact on them.

Radio waves may propagate through the ionosphere or may be reflected from the ionosphere. In each scenario, the radio wave does not propagate as a narrow "laser"-like beam but as a cone of spreading radio energy over a path whose cross section depends on the radio wavelength; on leaving the ionosphere the radio wave is focused on a receiver through diffraction. Long-range World War II submarine-to-mainland Enigma radio communications would be susceptible to this same diffraction propagation.

Unfortunately, the ionosphere is a very poor diffraction grating. The ionosphere can introduce variations in the refractive index over the cross-sectional area of the signal's Fresnel zone and, consequently, introduce differential retardations of the wavelets that eventually reach the receiver. (This was already appreciated during World War II but was a lesser issue in the receiving of radio signals than the Enigma encryption.) As a result of the ionospheric effects, the receiver now integrates these differing wavelets, creating an interference effect that leads to a signal that in the worst case has faded below receiver sensitivity. Fades as large as 20 dB are known. Another effect is the radio receiver may lose phase synchronization lock, a consequence of being unable to decipher the signal continuously. Such a loss of lock is analogous to the situation in which the receiver of an Enigma message has lost the current Enigma key and hence cannot use the device to play back the message [*Perera*, 2010]. This results in a loss of information as the receiver attempts to resynchronize with the original encoded message sequence. To date, the mitigation strategies for these ionospheric effects typically involve finding alternative frequencies that are less impacted by scintillation.

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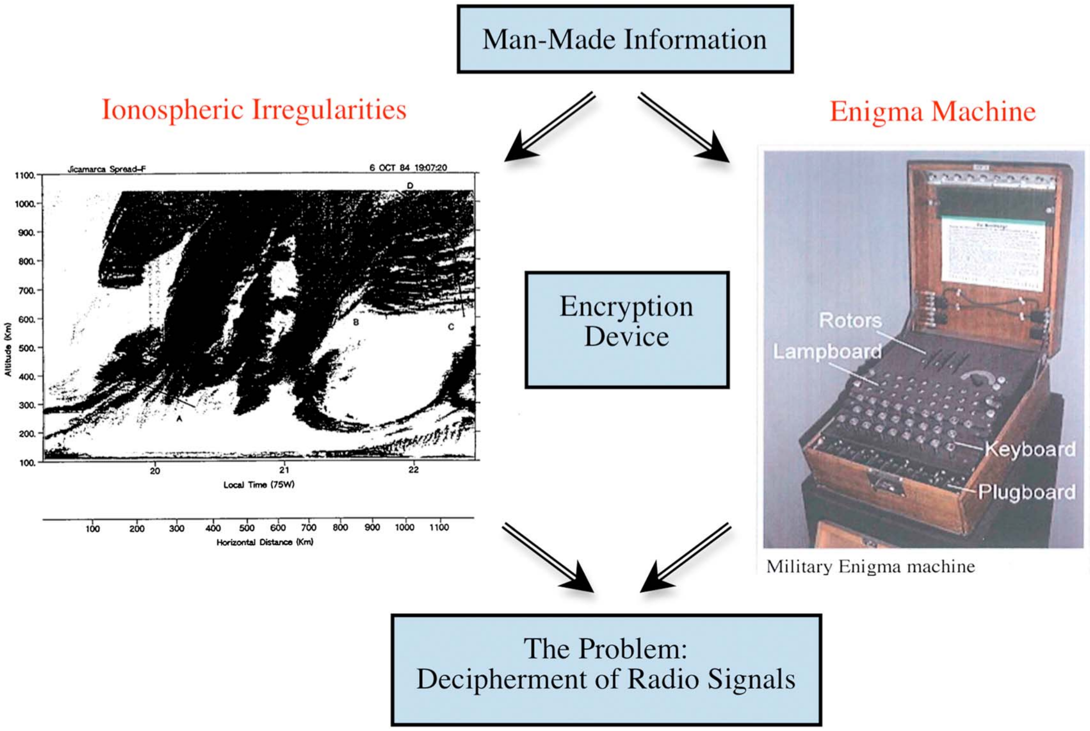


Figure 1. The parallel between (left) radio information lost through encryption after passing through ionospheric irregularities and (right) information encrypted by a World War II Enigma machine. In both cases, real-time decipherment is essential but very difficult to achieve. Courtesy of R. Woodman and D. Hysell.

Scientists are involved in research to understand the fundamental ionospheric processes that lead to the irregularities that form in the ionosphere and confuse the deciphering of radio signals. Observations are made from in situ density probes on satellites (Figure 2, top) and from the ground by radars (Figure 2, bottom) [*Tsunoda et al.*, 1982]. These two techniques are complementary in that the in situ measurements cover a wide range of scale sizes as the sensor crosses the irregularity region while the ground-based radio techniques map the irregularity region at one characteristic scale size. The technology involved in making in situ measurements has become sophisticated enough that the measurements are taken with sufficient cadence to extend their shortest scale size down to that of the ground-based instruments. The in situ analysis problem is compounded by the fact that at whatever scale is investigated, irregularities are present. These irregularities obtained from Fourier analysis of satellite in-track density fluctuations are found to be correlated in a power law distribution according to their irregularity scale. In sharp contrast, theoretical searches for an instability and the associated free-energy source lead to very wavelength-dependent growth rates for specific scales of irregularity formation. The present-day simulations of these instabilities provide growth rates and density structures at a specific frequency, which are a long way from the observed nonhomogeneous 3-D distributions of power-law-related irregularities. An excellent example of this irregularity structure is the equatorial bubble phenomena (Figure 2). Indeed, the present-day physics approach to understanding these structures still lacks the cascade physics needed to generate the power law interscale size relationships observed in the irregularities. An obvious additional impact is that the current understanding of the underlying science is still too primitive to enable reasonable prediction of the effects of scintillations on radio waves. The physics of the irregularity formation suggests that the number of variables that contribute to their growth and subsequent cascade across scale sizes leads to unique manifestations of the irregularity distribution. This unique feature of the ionosphere can well be compared to the day-to-day operation of the Enigma machine in that each day's new setting, the key, corresponds to a new code to be deciphered.

One slightly positive aspect, however, is that this space weather irregularity problem is an Enigma for another reason. For many significant adverse space weather impacts, the specification and potential for forecast involves understanding the entire heliophysical system (Sun/solar wind/magnetosphere/ionosphere/atmosphere) in extremely coupled ways. In contrast, the radio scintillation type of space

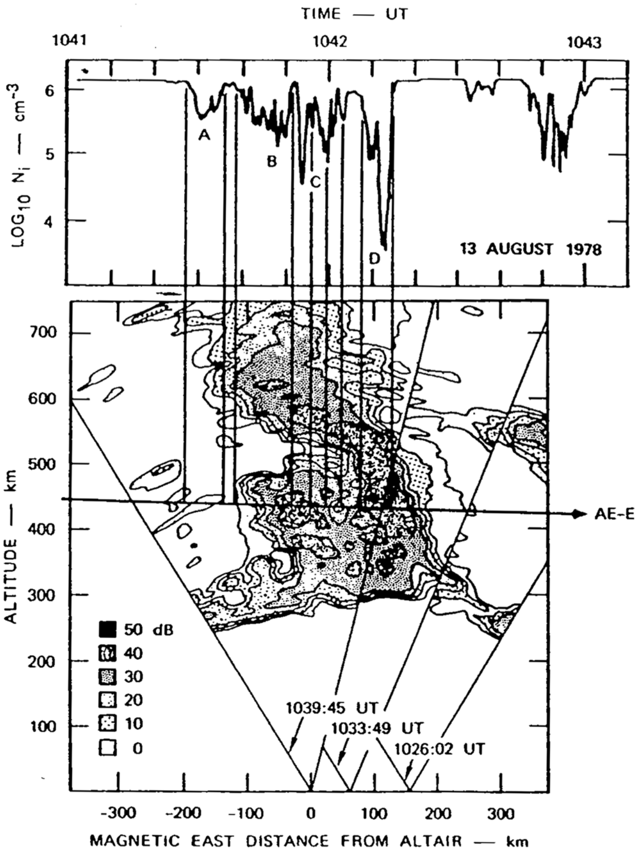
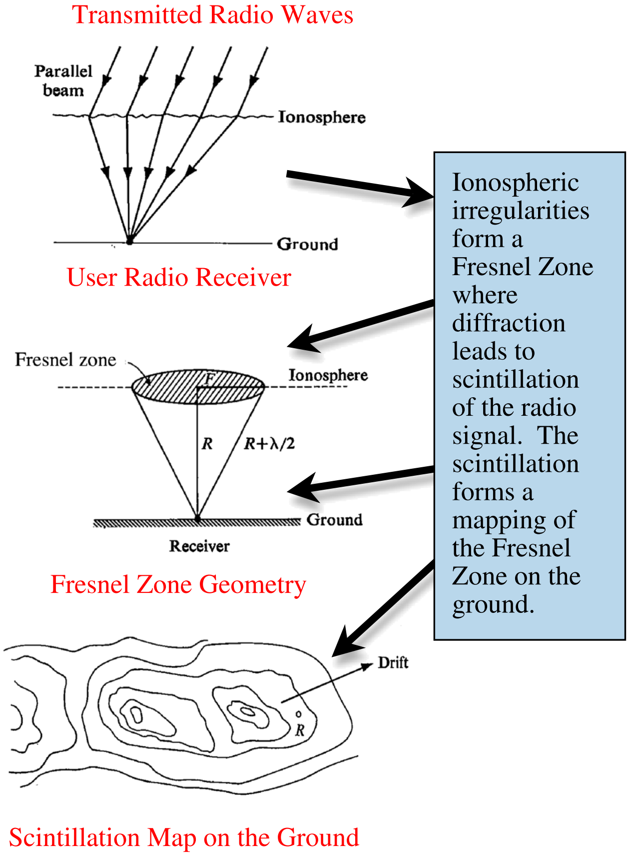


Figure 2. Examples of (top) coordinated observations of the ionospheric electron density irregularities made by the NASA AE-E satellite and (bottom) those made by backscatter power mapping of 1 m irregularities measured by the Advanced Research Project Agency (ARPA) Long-range Tracking and Identification Radar (ALTAIR) over Kwajalein [*Tsunoda et al.*, 1982].

weather is localized in the ionosphere and in many severe cases is independent of other space regions and their dynamics. Of course, there are instances of irregularity formation in which larger-scale couplings occur. An example would be scintillation associated with auroral phenomena and the fades and blackouts of radio signals related to solar flare impacts on the ionosphere. In these cases, the energy source is easily identifiable as a form of the conventional space weather system, but again, the subsequent blooming of the irregularities over spatial and temporal scales is an ionospheric process still to be deciphered. Given that the radio scintillation form of space weather is often characterized as the main ionospheric space weather problem, being able to separate it from the usual chain of causes and effects of space weather regional sequences should be an advantage in finding solutions to the ionospheric irregularities problem of radio wave scintillation.

Davies [1969] provided an alternative view of the scintillation problem in which both the scientist and radio user are engaged in finding a solution. Figure 3, constructed from *Davies*'s [1969] Figures 13.18, 13.19, and 13.28, summarizes one possible present-day approach. The concept is based upon optical diffraction, in which the ionosphere is a phase screen and the user is the point on the ground that integrates the radio wavelets formed over the Fresnel zone into the received signal. In this scenario, the phase screen is the 2-D ionospheric irregularity representation of the 3-D irregularity distribution. This phase screen then changes as the frequency (wavelength) of the radio wave changes, and consequently, a different signal is obtained. In terms of the Enigma operations, this corresponds to selecting a different initial setting of the Enigma cipher wheels. As indicated in this example, on the ground the radio scintillation depends on the location of the receiver. Hence, if the scintillation were mapped by a distribution of receivers, a 2-D radio signal strength map would be obtained. Indeed, users prior to Davies's work were well aware of the fact that as the ionospheric plasma drifted, radio reception would change, "fade." When a stationary ground-based radio receiver experiences time-changing scintillation, it is responding to both the irregularity evolution over the Fresnel zone and the drift of the ionosphere and its irregularities through the Fresnel zone. One implication is that if a network of receivers were in place, they would instantly provide a map of the irregularity distribution within the Fresnel zone. With modern-day synchronized software radio technology this same network of receivers could map over a wide range of frequencies. The scale size of the network is related to the size of the Fresnel zone, as suggested in Figure 3. The characteristic horizontal scale associated with the Fresnel phase screen is given as the square root of the product of the distance to the receiver multiplied by the wavelength. Therefore, at 30 MHz and 1.2 GHz, propagating through an equatorial bubble whose phase screen is at a height of 400 km, the Fresnel scales are 2 km and 300 m, respectively. On the ground, receivers distributed spatially over such scales would map at each frequency, the effect of the ionospheric phase screen for radio waves, propagating from satellite to ground.

I am unaware of this experiment having been carried out to date, although the U.S. Air Force Scintillation Network Decision Aid (SCINDA) system [*Carrano et al.*, 2011] is a present-day one-receiver system that could be readily expanded to map the ionospheric phase screen. SCINDA operates at frequencies in the UHF and L band, an example being UHF from 225 to 400 MHz and at GPS L band frequencies. Both signals are generated by satellites either in geosynchronous orbit or in GPS-like orbits. The SCINDA system is primarily deployed at equatorial latitudes where the equatorial bubble phenomena exist. The source and subsequent evolution of these irregularity structures are dependent only on the ionosphere. These structures have the most severe impact on communications of any common ionospheric space weather



Ionospheric irregularities form a Fresnel Zone where diffraction leads to scintillation of the radio signal. The scintillation forms a mapping of the Fresnel Zone on the ground.

Figure 3. Schematic of ionospheric irregularities and relationship to radio scintillation [adapted from *Davies*, 1969]. (top) Diffraction is occurring as radio waves pass through the ionospheric irregularity layer. (middle) These irregularities represent a Fresnel zone, and (bottom) a subsequent mapping of the induced diffraction as a scintillation map is shown.

phenomenon, especially on radio frequencies up to those of the GPS system. This SCINDA bubble scenario is an ideal first step in mapping the irregularity distribution using a network of ground receivers over the Fresnel zone scales.

One result of *Davies*'s [1969] scenario, using present-day computational, communications, and topographic techniques, might be to ask the question as to whether such a sequence of radio scintillation maps could be inverted to identify the characteristics of the ionospheric phase screen. Depending on how the experiment is outlined, the answer is probably yes, but the more salient question then arises as to how this will lead to "deciphering" radio scintillation in a practical operational form.

Once again, returning to the World War II Enigma problem in real time, in spite of the large amounts of human resources, mathematicians, and vast arrays of electromechanical computational engines, limited success was achieved in deciphering the encryption of the Enigma machine in real time. The solution in the 1940s was simply to "acquire" an Enigma machine and its book of settings. This is not a solution to the space weather problem of equatorial scintillations. On the other hand, the ionosphere is always available for monitoring, and the monitoring suggested on the basis of the "optical diffraction" approach has yet to be tested.

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