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Paul J. Jacobsmeyer
Chief

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Self-Focusing Instabilities Induced by OTH Radars

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13. ABSTRACT *(Maximum 200 words)*

Soviet OTH experiments have found that field-aligned ionospheric plasma density striations develop roughly 1 minute after turn-on of an OTH radar with 90 dbw ERP. A theoretical development of self-focusing instabilities predicts a threshold of 87 dbw under daytime conditions. Nighttime conditions lead to appreciably higher threshold (up to 120 dbw). Since the instability exponentiation time is long (1-10 sec), short OTH coherent integration times can limit growth to 1-2 e-foldings which should not degrade OTH signal processing.

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Abstract

Soviet OTH experiments have found that field-aligned ionospheric plasma density striations develop roughly 1 minute after turn-on of an OTH radar with 90 dbw ERP. A theoretical development of self-focusing instabilities predicts a threshold of 87 dbw under daytime conditions. Nighttime conditions lead to appreciably higher threshold (up to 120 dbw). Since the instability exponentiation time is long (1-10 sec), short OTH coherent integration times can limit growth to 1-2 e-foldings which should not degrade OTH signal processing.

Contents

1 INTRODUCTION

One of the unexpected phenomena of high-power ionospheric modification research was the appearance of artifical Spread-F[1,2]. This has come to be understood in terms of a self-focusing instability [3-5] which creates ionosphere striations deleterious to OTH signal processing. At the simplest level, the instability results from the coupling of three processes. First, it is well-known that radiowaves will be refracted into regions of relatively higher index of refraction. In a plasma, the index of refraction n is related to the electron density n_e via

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2} \equiv 1 - \frac{4\pi n_e e^2}{m\omega^2}. \quad (1)$$

Thus regions of higher refractive index correspond to regions of lower electron density. Second, the higher intensities produced by refraction preferentially heat the high-index, low-density regions. Third, the higher pressure associated with heating pushes plasma out of the low-density region, amplifying the refractive effect.

The question naturally arises: Is the power flux of an OTH radar sufficient to trigger self-focusing instabilities? An unequivocal affirmative answer is given by the experimental results of Novozhilov and Savel'yev[6]. Figure 1 sketches the geometry of their experiment. Figure 2, reproduced from their paper, shows fast amplitude scintillations developing 2 minutes after the OTH was turned on. Phase fluctuations between receivers spaced by several hundred meters increased in amplitude and became more rapid. Further measurements[6] determined that the scale size of ionospheric striations was $\approx$ 300 m and that the spread arrival angles at the diagnostic receiver increased from $\pm$ 0.3° to $\pm$1°. According to Novozhilov and Savel'yev, the HF electric field in the ionosphere was $E_o \approx (0.1)E_p$ where E_p is the plasma field defined by Gurevich[7]

$$E_p^2 = \frac{3T_e m_e}{e^2}\delta\omega^2, \qquad \delta = \frac{2m_e}{M_i}. \quad (2)$$

Here δ denotes the average fractional energy lost by an electron in an electron-ion collision. We shall argue below that self-focusing instabilities are

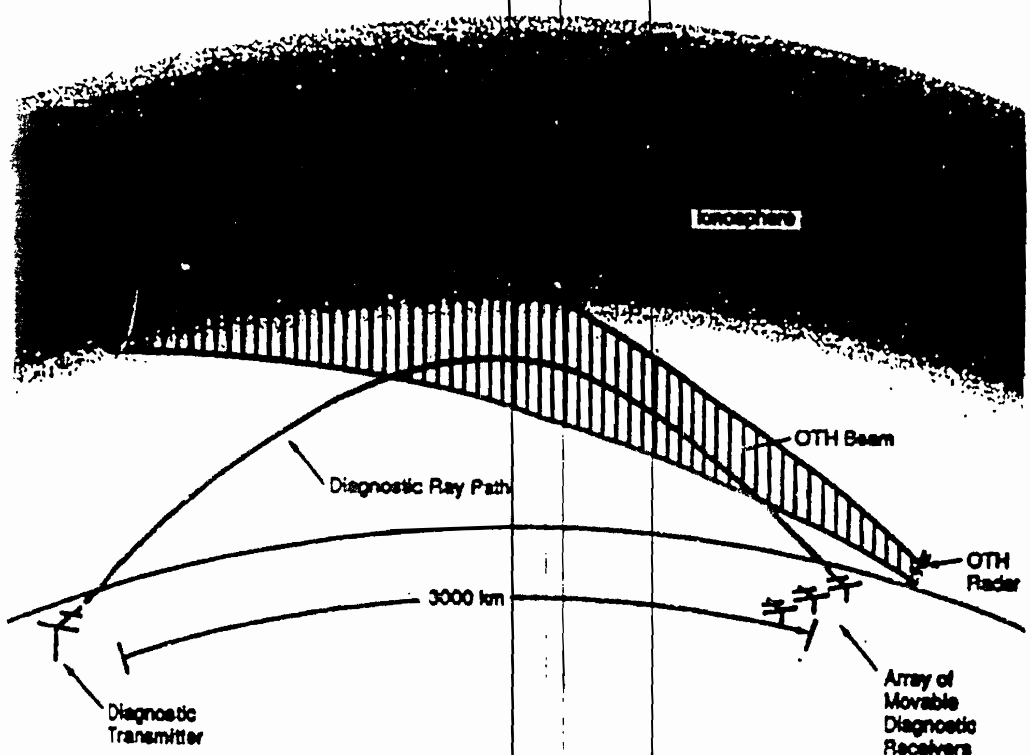

Figure 1. Geometry of the Novozhilov and Savel'yev experiment, performed near 1500 h, April 17, 1975. The OTH frequency ν was not reported; it slightly exceeds the MUF. We assume $\nu \approx 30$ MHz appropriate to daytime conditions; the diagnostic frequency was then about 25 MHz.

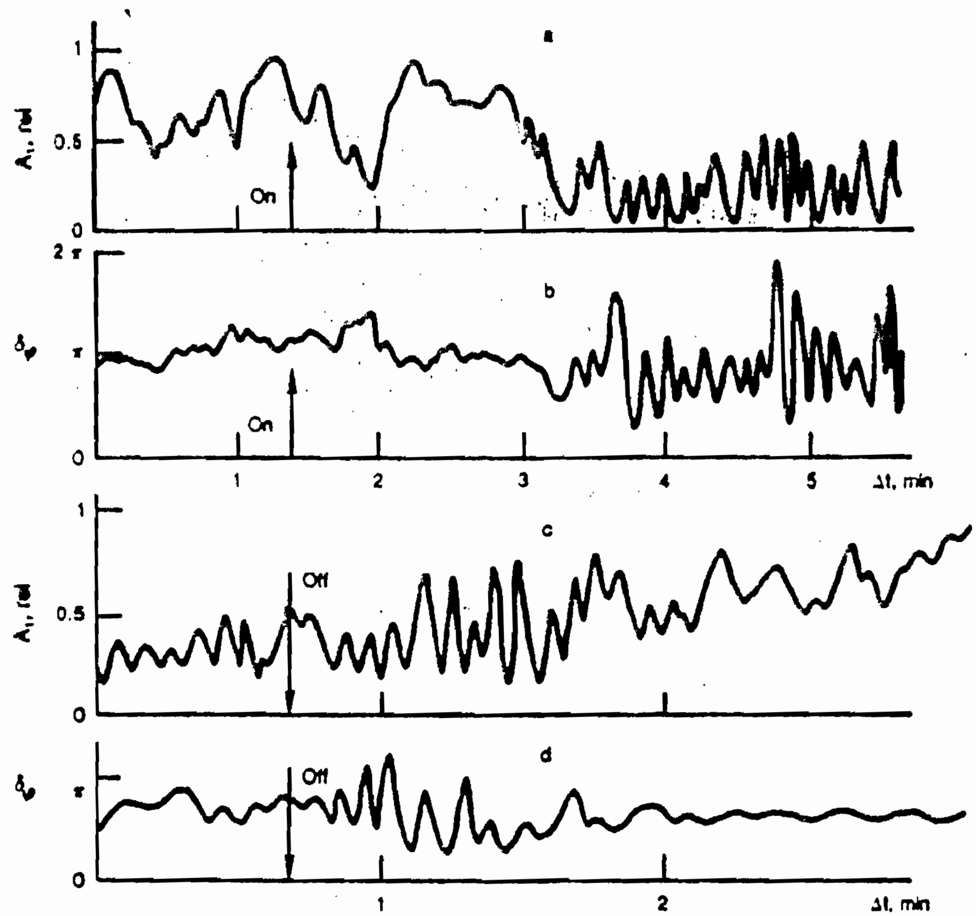

Figure 2. Results of Novozhilov and Savel'yev experiment. a) Amplitude scintillation commences ≈ 2 min. after OTH turn-on. b) Phase fluctuations between two receivers spaced by several hundred meters commence ~ 2 min. after OTH turn-on. c) and d) Amplitude and phase fluctuations decay ≈ 1 min. after OTH turn-off.

most virulent when the electron collision frequency is high which occurs when plasma density is high, electron temperature low, and electron-ion collisions dominate electron-neutral collisions. For an O^+ plasma, one has $\delta = 7 \cdot 10^{-5}$ and the power flux through the ionospheric plasma for the Novozkilov-Savel'yev experiment was

$$F_e \approx (0.1)^2 \frac{c}{4\pi} E_p^2 \approx 10^{-4} \text{ Watts/m}^2 \tag{3}$$

where we have assumed $T_e \approx 1000°K$ and a frequency $\nu \approx 30$ MHz for daytime OTH operation.

2 OTH RAY TRAJECTORIES AND IONOSPHERIC POWER FLUX

Let us employ ray-tracing to estimate the power flux of an OTH radar based on a simple parabolic model of the electron density below the peak of the F-region. Hence the plasma frequency profile is

$$\omega_p^2 = \omega_{p,max}^2[1 - (\frac{z}{z_o})^2] \tag{4}$$

where $\omega_{p,\mathrm{max}}$ denotes the maximum plasma frequency and $z_o \approx 100$ km. From the simplified-but-adequate dispersion relation

$$\begin{aligned} \omega^2 &= \omega_p^2 + (k_h^2 + k_z^2)c^2 \\ &= \omega_p^2 + \omega^2\cos^2\theta + c^2 k_z^2, \end{aligned} \tag{5}$$

one can compute horizontal and vertical group velocities

$$V_h = c\ \cos\theta \quad V_z = c\left[\sin^2\theta - \frac{\omega_{p,max}^2}{\omega^2}\left(1 - \frac{z^2}{z_o^2}\right)\right]^{1/2}. \tag{6}$$

Here θ denotes the initial elevation angle of the ray. From the ray equation in the ionosphere

$$dR = \frac{V_h dz}{V_z} = \frac{\omega\cos\theta dz}{\omega_{p,max}\left[\frac{z^2}{z_o^2} - 1 + \frac{\omega^2\sin^2\theta}{\omega_{p,max}^2}\right]^{1/2}}, \tag{7}$$

one can compute the relation between range R, ionospheric height z, and initial launch angle θ. For a ray that is still ascending, one can integrate (7) to obtain

$$R^+ = \frac{H}{\tan\theta} + \frac{z_o\cos\theta\ \omega}{\omega_{p,max}}\ ln\left\{\frac{1 + \frac{\omega\sin\theta}{\omega_{p,max}}}{\frac{z}{z_o} + \left[(\frac{z}{z_o})^2 - 1 + \frac{\omega^2\sin^2\theta}{\omega_{p,max}^2}\right]^{1/2}}\right\} \tag{8}$$

in a flat-earth approximation which is adequate for our estimate of the power flux. Here, Hz 200 km denotes the altitude of the lower boundary of the F-region (i.e. $z = -z_o$). The peak F-region plasma density occurs at an altitude $H + z_o$.

At a fixed range, Equation (8) relates the ray height in the ionosphere z to launch elevation angle θ. It is straightforward to generalize Equation (8) for descending rays that have reflected from the height where

$$(\frac{z}{z_o})^2 = 1 - \frac{\omega^2 \sin^2\theta}{\omega_{p,max}^2}. \quad (9)$$

The range formula for descending rays is

$$R^- = \frac{H}{\tan\theta} + \frac{z_o \cos\theta\omega}{\omega_{p,max}} ln \left\{ \frac{(1 + \frac{\omega\sin\theta}{\omega_{p,max}})[\frac{z}{z_o} + (\frac{z^2}{z_o^2} - 1 + \frac{\omega^2\sin^2\theta}{\omega_{p,max}^2})^{1/2}]}{1 - \frac{\omega^2\sin^2\theta}{\omega_{p,max}^2}} \right\}. \quad (10)$$

When one sets $z/z_o = 1$, one can determine the total horizontal distance ΔR_{ion} travelled by the ray in the ionosphere

$$\Delta R_{\text{ion}} = \frac{z_o\cos\theta\omega}{\omega_{p,max}} ln \left\{ \frac{(1 + \frac{\omega\sin\theta}{\omega_{p,max}})^2}{1 - \frac{\omega^2\sin\theta}{\omega_{p,max}^2}} \right\} \quad (11)$$

$$= \frac{2z_o}{\tan\theta}(\frac{\omega\sin\theta}{\omega_{p,max}})^2 \qquad \frac{\omega\sin\theta}{\omega_{p,max}} << 1. \quad (12)$$

For most long-range OTH operations, which utilize low rays, form (12) is valid. The range R at which the ray strikes the earth is

$$R(\theta) = \frac{2H}{\tan\theta} + \Delta R_{\text{ion}}. \quad (13)$$

Using the characteristic values H $\approx$ 200 km, $z_o \approx$ 100 km, one finds that the contribution of ΔR_{ion} to (13) is small when $(\omega\sin\theta/\omega_{p,max}) \ll 1$. Thus to a good approximation

$$\tan\theta \approx \frac{2H}{R}. \quad (14)$$

Let us note that because the denominator of the logarithm in Equation (11) diverges as $\sin\theta \rightarrow \omega_{p,max}/\omega$, there are two θ values corresponding to a given range, the low-ray which has $(\omega\sin\theta/\omega_{p,max}) \ll 1$ and a high ray with $\sin\theta \approx \omega_{p,max}/\omega$, independent of range. Since all high rays correspond to a very small interval in elevation angle θ, the power launched onto high rays is negligable. Thus, we need to consider only low rays in estimates of ionospheric power density and Equations (12) and (14) are good approximations.

The power density in the ionosphere at a range R_{ion} follows from the formula

$$F_o = \frac{1}{R_{ion}} \left(\frac{\partial^2 P}{\partial\phi\partial\theta}\right) \left[\left|\frac{d\theta^+}{dz}\right| + \left|\frac{d\theta^-}{dz}\right| \right]_{\tan\theta = H/R_{ion}} \tag{15}$$

where $(\partial^2 P/\partial\phi\partial\theta)$ is the transmitter beam pattern in azimuthal angle ϕ and elevation angle θ and

$$\frac{d\theta^+}{dz} = -\frac{(\frac{\partial R^+}{\partial z})_\theta}{(\frac{\partial R^+}{\partial \theta})_z} \tag{16}$$

with an evident generalization for the contribution from descending rays. Following our approximation for low rays, one finds

$$\left|\frac{d\theta^+}{dz}\right| + \left|\frac{d\theta^-}{dz}\right| \approx \frac{2\sin\theta\cos\theta}{H} \left(\frac{\omega \sin\theta}{\omega_{p,max}}\right) \frac{1}{[\frac{z^2}{z_o^2} - 1 + \frac{\omega^2 \sin^2\theta}{\omega_{p,max}^2}]^{1/2}} \tag{17}$$

$$\approx \frac{2}{R_{ion}} \left(\frac{\omega \sin\theta}{\omega_{p,max}}\right) \frac{1}{[\frac{z^2}{z_o^2} - 1 + \frac{\omega^2 \sin^2\theta}{\omega_{p,max}^2}]^{1/2}}. \tag{18}$$

Within the context of ray optics, the power flux diverges at the reflection height. Since we shall show that self-focusing instabilities are extended along magnetic field lines for distances ~ 5 km [(see Equation (32)], it is meaningful to compute the average power flux in the ionosphere. We define this as

$$< F_o > = \frac{1}{z_o - z_1} \int_{z_1}^{z_o} dz\, F_o(z) \tag{19}$$

where $z_1 = z_o(1 - \frac{\omega^2 \sin^2\theta}{\omega_{p,max}^2})^{1/2}$ is the reflection height. Again using low ray approximations, one finds that

$$< F_o > = \frac{4}{R_{ion}^2} \frac{\partial^2 P}{\partial\phi\partial\theta} \approx \frac{4}{R_{ion}^2} \frac{P_T}{\Delta\Omega} = \frac{1}{\pi R_{ion}^2}(P_T G) \tag{20}$$

where $(P_T G)$ is the effective radiated power (ERP) and $\Delta\Omega$ estimates the solid angle of the transmitter beam. One can combine (15), (18) and (20) to obtain an expression for the altitude dependent power density,

$$F_o(z) = \frac{1}{2} < F_o > \frac{1}{[1 - (\frac{z_o - z}{\Delta z})]^{1/2}} = \frac{(P_T G)}{2\pi R_{ion}^2} \frac{1}{[(1 - (\frac{z_o - z}{\Delta z})]^{1/2}} \tag{21}$$

where

$$\Delta z \approx z_o \omega^2 \sin^2\theta / 2\omega^2_{p,max} \tag{22}$$

in a low-ray approximation.

Suppose a nominal OTH antenna radiates into an azithumal sector $\Delta\phi \approx 10^\circ$ and has an $\Delta\theta \approx 45^\circ$ beam width in elevation angle. One then finds

$$< F_o >= (30 \frac{\mu\text{watts}}{\text{m}^2}) (\frac{P}{1\text{MW}}) (\frac{10^6 m}{R_{\text{ion}}})^2. \tag{23}$$

From this one deduces that the Soviet transmitter power was $P \approx 10$ MW to agree with (3). The gain of our nominal OTH transmitter is $G = 4\pi/\Delta\Omega \approx 100$. Hence the ERP of the Soviet OTH installation is estimated to be 90 dbw. MITRE's proposed ETB transmitting antenna has an ERP of 95 dbw giving it a power flux of $3 \cdot 10^{-4}$ watts/m^2 at a range of 1500 km. Our theoretical development below places the threshold flux for self-focusing at about 10^{-4} watts/m^2 during daytime conditions. (It will be significantly higher at night).

We conclude this section by noting that OTH-induced self-focusing instabilities have been observed by Soviet researchers and that the power fluxes estimated from their paper agree with those produced by a nominal 10 MW OTH radar with an ERP of 90 dbw. An ETB is proposed to have an ERP of ≈ 95 dbw and a full-capability AOTH system ≈ 97 dbw per transmit beam. Thus, experimentally, one should expect that self-focusing striations could arise in ETB and AOTH systems.

3 SELF-FOCUSING INSTABILITY ANALYSIS

A detailed theoretical analysis of the self-focusing instability has been published by Perkins and Goldman[5]. We shall abstract the essential physics from this paper. It suffices to consider a strong electromagnetic wave propagating horizontally in an underdense, uniform plasma with $\omega > \omega_p$. The geometry of self-focusing striations is field-aligned sheets of density irregularities with a wave vector $\vec{q}$ which lies in the direction $\vec{k}_o \times \vec{B}$, where $\vec{k}_o$ denotes the wave vector of the strong electromagnetic wave and $\vec{B}$ the earth's magnetic field. The density irregularities grow exponentially both spatially along the direction of $\vec{k}_o$ and temporally. Figure 3 gives the coordinate system for our computation. We assume that density perturbations δn and other dependent variables take the form

$$\delta n = \tilde{n}(\xi) e^{iq\eta + \alpha(x - z\tan\beta) + \gamma t}$$

where

$$\begin{aligned} \eta &= x\cos\beta - z\sin\beta \\ \xi &= x\sin\beta + z\cos\beta \end{aligned}$$

and β denotes the angle of the geomagnetic field with respect to vertical. We make the assumption, readily justified a posteriori, that $q \gg \frac{\partial}{\partial z}, \frac{\partial}{\partial x}$.

The equations governing self-focusing instabilities are

$$\begin{aligned} \tilde{F} &= - F_o(\xi)\frac{\omega_p^2 \Delta}{\omega_o c} \int_{-\infty}^{x} \sin[\frac{q^2(x - x')}{2k_o}] e^{-\alpha(x - x')}\, dx' \qquad (24) \\ &= - F_o(\xi)\frac{\omega_p^2 \Delta}{2\omega_o c\alpha} (\frac{2\epsilon}{1 + \epsilon^2}) \end{aligned}$$

$$\gamma\Delta = 2D\frac{\partial^2 \Delta}{\partial \xi^2} + D\frac{\partial^2 \tau}{\partial \xi^2} \qquad (25)$$

$$K\frac{\partial^2}{\partial \xi^2}\tau + \frac{\omega_p^2 \nu_e}{T\omega_o^2 c}\tilde{F} = 0 \qquad (26)$$

Here we use the definition $\tau = \tilde{T}/T, \Delta = \tilde{n}/n$, and

$$\epsilon = \frac{q^2}{2k_o\alpha}, \quad K = 3.16Tn/m\nu_e, \quad D = T/M\nu_{in}. \qquad (27)$$

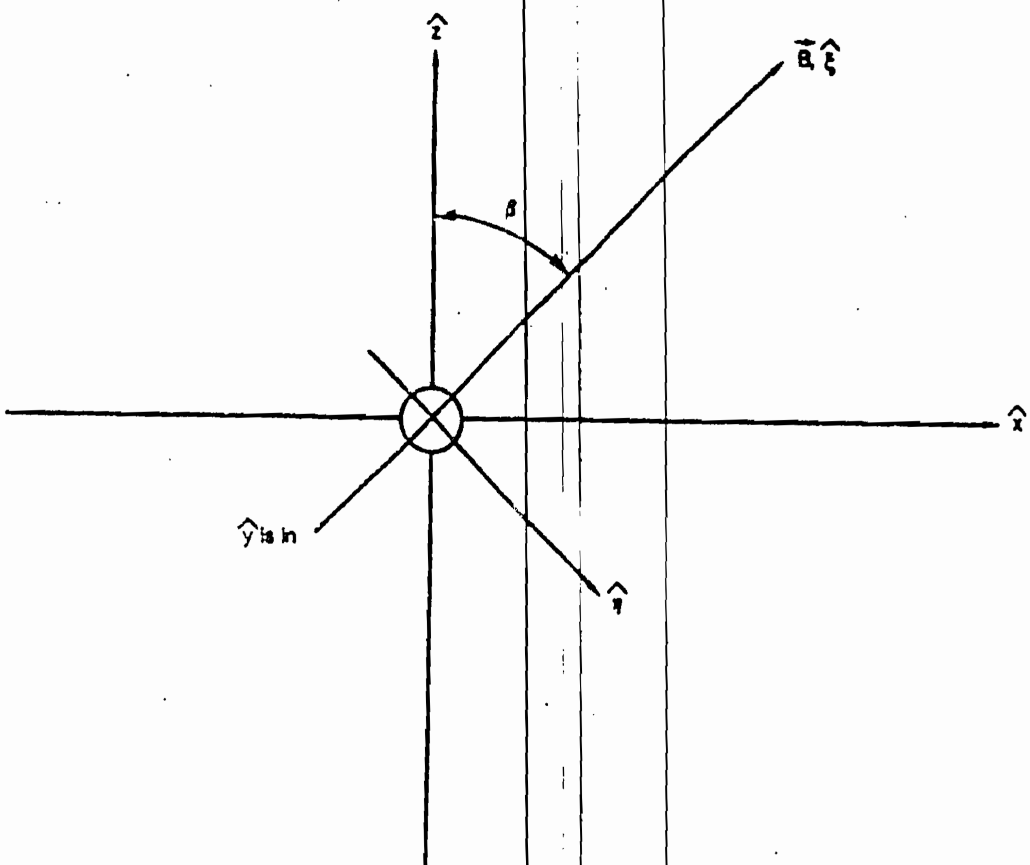

Figure 3. Coordinate system for self-focusing instability calculations. The intense wave propagates in the x direction.

To a good approximation $\omega_s = k_s c$, since $\omega_s^2 \gg \omega_p^2$.

Let us briefly describe the physics content of each equation. Equation (24) gives the intensity fluctuations $\tilde{F}$ at x resulting from phase perturbations caused by index of refraction fluctuations at x'. Equation (1) links the index of refraction to density. Equation (26) governs electron temperature fluctuations resulting from differential heating due to intensity fluctuations. The dominant limitation on temperature fluctuations comes from electron heat conduction along magnetic field lines to a constant temperature bath. This makes sense if the strong beam $F_o(\xi)$ is spatially limited along the magnetic field. Equations (25) states that plasma density fluctuations arise because ions diffuse through neutrals along the geometric field, the diffusion being driven by electron temperature fluctuations.

Straightforward algebra combines Equations (24) - (26) into the eigenvalue equation

$$\Delta - \frac{2D}{\alpha}\frac{\partial^2 \Delta}{\partial \xi^2} = \Lambda \Theta(\xi)\Delta \tag{28}$$

where from (15)-(18)

$$\Lambda = \frac{\omega_p^2 \nu_e^2 \pi e^2 < F_o >}{M \nu_{in} \gamma \omega_o^2 (3.16) T \alpha C^2} \left(\frac{2\epsilon}{\epsilon^2 + 1}\right) \tag{29}$$

$$\Theta = \begin{cases} \left(\frac{\xi}{\xi_o}\right)^3 \frac{1}{(1-\frac{\xi}{\xi_o})^{1/2}} & \xi < \xi_o \\ 0 & \xi > \xi_o \end{cases} \tag{30}$$

$$\xi_o = \frac{z_o}{2}\frac{\omega_o^2 \sin^2\theta}{\omega_{p,max}^2 \cos\beta} = \frac{\Delta z}{\cos\beta} \approx 20 \text{ km} \left(\frac{1000 \text{ km}}{R_{\text{ion}}}\right)^2 \tag{31}$$

and the electron density is to be evaluated at a point where $\omega_p^2 = \omega_o^2 \sin^2\theta$.

Let us rescale the z-variable according to

$$\begin{aligned} \xi_o - \xi &= U_o u \\ U_o = \left(\frac{2D}{\gamma}\right)^{1/2} &= 3\text{km} \left(\frac{T}{10^3 K}\right)^{1/2} \left(\frac{10^{-1}\text{sec}}{\gamma}\right)^{1/2} \left(\frac{1\text{Hz}}{\nu_{in}}\right)^{1/2}. \end{aligned} \tag{32}$$

Note that ξ_o is appreciably longer than U_o, so (28) can be adequately approximated by

$$\frac{\partial^2 \Delta}{\partial u^2} - \Delta = -\frac{\lambda \Delta}{u^{1/2}} \tag{33}$$

where $0 < u < \infty$, and

$$\lambda = \Lambda(\xi_o/U_o)^{1/2} \tag{34}$$

is an eigenvalue of order unity. The boundary conditions for (32) are

$$\frac{1}{\Delta}\frac{\partial\Delta}{\partial u} = 1 \; ; \quad u = 0 \tag{35}$$

$$\frac{1}{\Delta}\frac{\partial\Delta}{\partial u} = -1 \quad u \to \infty. \tag{36}$$

Thus the critical flux for self-focusing instabilities is

$$< F_o > = F_c \equiv \left(\frac{3.16\lambda}{\pi}\right) \frac{M \, \nu_{in} \gamma \, \omega_p^3 \, T \, \alpha c^2}{\omega_{ce}^3 \nu_e^3 e^2} \left(\frac{U_o}{\xi_o}\right)^{1/2} \left(\frac{\epsilon^2+1}{2\epsilon}\right). \tag{37}$$

One can cast (37) into practical units and obtain

$$F_c = \left(0.3 \, \frac{\mu \text{ watts}}{m^2}\right) \left(\frac{n_{max}}{n}\right)^2 \left(\frac{10^6 \text{cm}^{-3}}{n_{max}}\right)^{3/2} \left(\frac{25\text{km}}{\alpha^{-1}}\right) \left(\frac{100\text{km}}{z_o}\right)^{1/2}$$

$$\left(\frac{T}{10^3 K}\right)^{4.25} \left(\frac{\gamma}{10^{-1}\text{sec}}\right)^{3/4} \left(\frac{\nu_{in}}{1\text{Hz}}\right)^{3/4} \frac{(\cos\beta)^{1/2}}{\sin^2\theta} \left(\frac{\epsilon^2+1}{2\epsilon}\right) \tag{38}$$

where we have used $\omega_c \sin\theta = \omega_p$. For representative OTH operations, one has

$$\sin\theta \approx 0.2 \tag{39}$$

$$n/n_{max} \approx 0.5.$$

Assuming all other factors are unity, one obtains

$$F_c \approx 1.5 \cdot 10^{-4} \frac{\text{watts}}{m^2} \tag{40}$$

in good accord with observations. A spatial growth rate of $\alpha \gtrsim (25\text{km})^{-1}$ is needed to attain nonlinear striations for representative paths in the ionosphere. Further note that the critical flux is minimum for striation wavelengths given by $\epsilon = 1$, corresponding to $\lambda_{perp} = 2\pi/q \approx 1.2\text{km}(\alpha^{-1}/25\text{km})^{1/2}$. Again there is agreement Novozhilov and Savel'yev.

In evaluating (38), we assumed an exponentiation time of 10 sec to obtain a modestly large number of e-foldings in one minute in agreement with the experimental data of Figure 2. Similarly, the spatial growth length of 25 km is moderately small compared to the distance a ray spends in the ionosphere.

4 DISCUSSION

When will self-focusing instabilities affect OTH operations? OTH radars continuously transmit power into an angular sector with FM modulation which provides range resolution upon processing. The FM nature of the signal plays no role in self-focussing instabilities. One sees from (20) that an ERP at 87 dbw is required to exceed threshold value (38,40) during high-density, low-T_e daytime conditions. Noting that, for OTH operations, $f^2 \propto n_{max}$ it follows from (37) that $F_c \propto f^{-3}$. In other words, the instability becomes appreciably less important at night. It is also stabilized by high electron temperatures, often, but not always, a feature of daytime ionospheres. High temperatures reduce the electron-ion collision frequency which diminishes resistive heating and increases electron thermal conductivity, both stabilizing effects. Lastly, one notes that growth times are near 10 sec, comparable to the planned OTH coherent integration times. One can certainly tolerate one e-folding of fluctuations, so rapid beam switching will defeat self-focusing instablilities near threshold. The Advanced Over-the-Horizon radar (AOTH) plans exceed the threshold flux by a factor of 10, reducing the growth time to ~ 1 sec under daytime conditions. In operational terms, self-focussing instabilities will limit the coherent integration time τ_{coh} of an OTH radar. A reasonable supposition that 5 (or less) e-foldings of ambient density fluctuations can be tolerated. The ERP at which self-focussing is predicted to degrade OTH performance can be estimated by using $\gamma = 5/\tau_{coh}$ in (38) and then using (20).

The planned ERP of 95 dbw for the Experimental Test Bed radar (ETB) should be well into the regime where self-focusing arises in daytime conditions. ETB should be able to investigate self-focusing instabilities. From a practical point-of-view, one may not need the full ERP of 97 dbw for a single AOTH beam in daytime conditions because target cross-sections increase with frequency in the 6-30 MHz region. As the frequency falls from 30 MHz to 6 MHz, the threshold ERP increases from 87 dbw to 120 dbw, so AOTH is predicted to be free of self-focusing instabilities in nighttime when target cross-sections are low. Experiments are needed on an ETB radar to validate these projections.

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