GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 3, PAGES 317-320, FEBRUARY 1, 2000

Diffraction model of ionospheric irregularity-induced heater-wave pattern detected on the WIND satellite

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Abstract.
High frequency (HF) radiation from the HAARP and SURA ionospheric heaters transmitted through the underdense ionosphere and received by the WIND satellite show the presence of strong spatial structure in the radiation pattern. A simple model based on the combination of ionospheric irregularities and interference effects has been developed to account for the observations. The analysis demonstrates the utility of satellite receptions as probes of ionospheric irregularities created or enhanced by powerful HF radio waves.

Introduction

A new class of ionospheric heating experiments have been recently initiated, first using the newly constructed HAARP ionospheric heating facility [*Rodriguez et al.*, 1998], subsequently the SURA facility [*Rodriguez et al.*, 1999a; *Tokarev et al.*, 1999] and most recently the combined HAARP and HIPAS heaters [*Rodriguez et al.*, 1999b]. In these experiments the frequency of the transmitted signals exceeds the critical plasma frequency of the F-peak. The HF radiation is received by detector on the WIND satellite [*Bougeret et al.*, 1995]. Figure 1, taken from *Rodriguez et al.* [1999a], shows the signal amplitude received by the 8925 kHz channel on the wave detector on WIND for SURA transmissions at the same frequency and in a CW mode, when the overhead critical frequency was 6300 kHz. The spiky structure of the signal is similar to previous measurements using the HAARP transmitter at low power [*Rodriguez et al.*, 1998]. In this letter we explain the observed signal pattern with a simple theoretical model that combines the effect of irregularities in the ionosphere with diffraction analysis in the wave propagation after encountering the F-peak.

Paper number 1999GL003675.
0094-8276/00/1999GL003675$05.00

Theoretical Model

One possible source of irregularities is the thermal self-focusing instability of the high-powered HF radio waves [*Litvak*, 1970; *Perkins and Valeo*, 1974; *Gurevich*, 1978; *Bernhardt and Duncan* 1982; *Guzdar et al.* 1998; *Gondarenko et al.* 1999]. Also pre-existing natural irregularities can seed the underdense thermal self-focusing instability [*Guzdar et al.* 1996]. In this letter we focus on the consequence of the natural or wave-

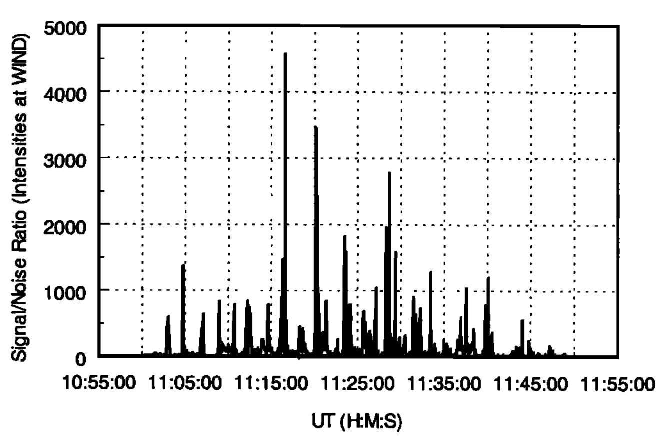

Figure 1. WAVES receiver measurement of the SURA radiated power at 8925 kHz.

enhanced irregularities on the far-field wave pattern of the electromagnetic HF wave. The theoretical model has two key assumptions. The first assumption is that the HF beam breaks up into a number of smaller filaments forming a relatively regular lattice due to the self-focusing instability or pre-existing irregularities enhanced by self-focusing. The second assumption is that once the radiation passes the F-peak, each filament of the lattice becomes an independent transmitter, whose radiation propagates freely in the low density plasma with phase determined by its phase when exiting the F-peak.

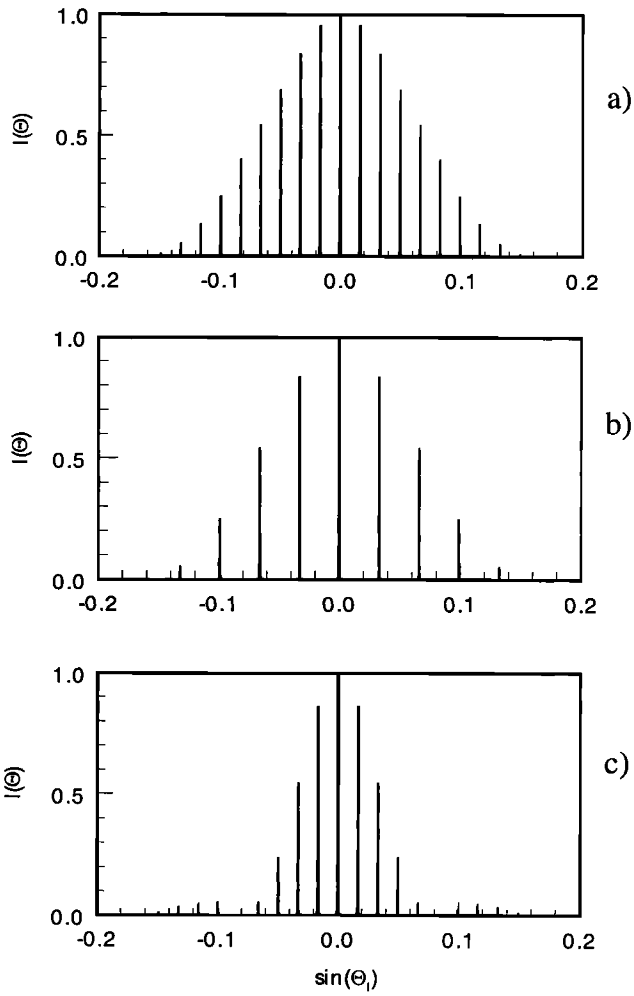

Figure 3. Diffraction pattern for (a) $a = 0.1$ *km*, and $d = 1.0$ *km*, (b) $a = 0.1$ *km*, and $d = 0.5$ *km*, and (c) $a = 0.2$ *km*, and $d = 1.0$ *km*.

Propagation Model

A simple diffraction model is used to follow the HF radiation once it exits the F-peak. A schematic of the model is shown in Figure 2. The irregularities in the ionosphere are modelled by a transmission grating with transparent widths (slit) of $2a$ and the separation between the center of two slits of $2d$. In reality, the transmission through the ionosphere consists of waves propagating through the low density transparent field aligned filaments, and through the plasma between the depleted channels. It is the difference in the phases between the two regions which gives rise to a diffraction pattern so that the constant background that arises from the semi-transparent nature of the ionosphere is removed by the present model. In reality, there is a distribution in the widths of the filaments and spacing between the filaments as well as curvature of the incident beam. Also if wave-enhanced self-focusing occurs, the "optical" path of the heater wave through the filaments with depleted density would vary from filament to filament. All these different physical effects which can introduce different path-lengths of the wave propagation in filaments are modelled by introducing a random phase for the wave at the slits. The angular distribution of the far-field amplitude of a monochromatic wave incident on a transmission grating with N slits and random phases ϕ_n at each slit is

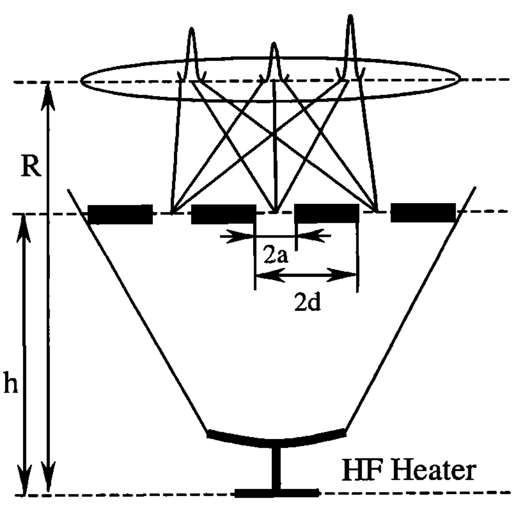

Figure 2. Schematic of heater, ionospheric irregularity and far-field diffraction pattern.

$$E(\theta) = \frac{ia}{\lambda}\frac{sin(kasin\theta)}{kasin\theta}\sum \exp[2ikd(n-1)sin\theta + i\phi_n] \tag{1}$$

Here $k = \omega/c$ is the wavenumber of the heater wave with frequency ω, and the summation is over the number of the filaments N. We assume that $2Nd = L$, where L is the size of the irradiated spot in the F region. If we assume that the random phases ϕ_n are zero, the summmation can be readily done to yield the well-known formula for the intensity of an N slit diffraction pattern

$$I(\theta) \propto \left(\frac{sin(kasin\theta)}{kasin\theta}\right)^2 \left(\frac{sin(kNdsin\theta)}{kdsin\theta}\right)^2 \tag{2}$$

This expression shows that there are basically three characteristic scalelengths: (1) the width of the primary maxima is $(\lambda/2Nd)R$, where R is the radial distance from the heater source and λ is the heater wave-

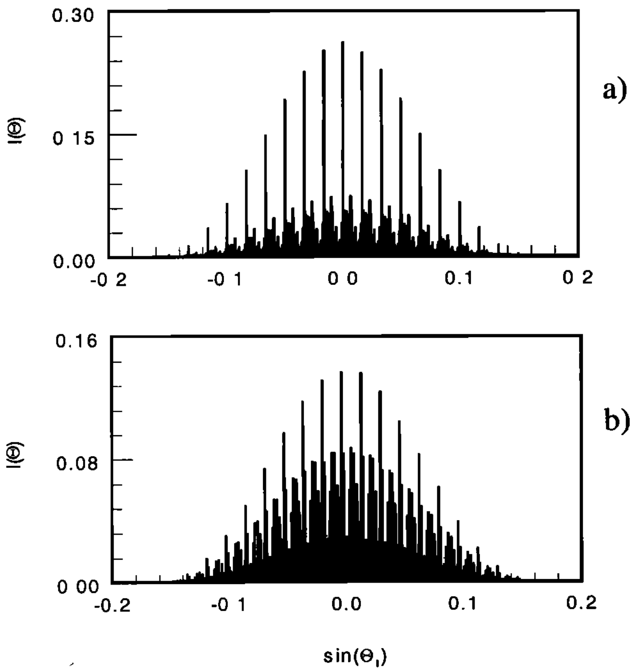

Figure 4. Diffraction pattern for $a = 0.1\ km$, $d = 1.0\ km$, (a) $-2.0 < \phi_n < 2.0$, and (b) $-\pi < \phi_n < \pi$.

length, (2) the distance between the primary maxima is $(\lambda/2d)R$, and (3) the envelope width is $(\lambda/2a)R$. In Figure 3a-3c the diffraction pattern for three different values of a and d are shown. The patterns are plotted in the angular interval $-\pi/60 < \theta < \pi/60$ for the incident wave frequency $f = \omega/2\pi = 8.9\ MHz$. Figure 3a is for $a = 0.1\ km$ and $d = 1.0\ km$. Figure 3b illustrates the case when the inter-filament distance is reduced to $d = 0.5\ km$, but the filament width is unchanged ($a = 0.1\ km$). In Figure 3c the filament width is increased to $a = 0.2\ km$ for $d = 1.0\ km$. What is clear is that dramatic changes in the pattern occur when the inter-filament distance and the filament widths are changed by a factor of two. Since the diffraction pattern is a Fourier transform of the sine of the angle θ, the envelope scale is a measure of the filament width ($2a$), and the inter-filament distance ($2d$) controls the number of primary lines. The case that qualitatively matches the observations in Figure 1a of *Rodriguez et al.* [1999a] is the diffraction pattern in Figure 3a.

There are other features that need to be explained. In the observations there is low-level noise between the primary lines as well as a distinct asymmetry in the angular distribution about the peak intensity. We now address these two features. If we introduce random phases with a uniform distribution between $-2.0 < \phi_n < 2.0$, then the diffraction pattern looks like that shown in Figure 4a. The secondary noise like-feature readily appears. The computed pattern has a very high wavenumber character to it. In examining Equation (1), the random phases can arise from nonuniform separation of equal-sized filaments or filaments with unequal sizes separated by the same distances or unequal sized filaments separated by unequal spacing. None of these three scenarios can be distinguished from each other. However, the magnitude of the noise is very sensitve to the choice of the window in which the phases ϕ_n are chosen. Figure 4b shows the diffraction pattern for the case when the phase ϕ_n varies in the range $[-\pi, \pi]$. The noise level is significantly enhanced. Thus, since the observed level of the noise in Figure 1 is small, it indicates that the fluctuation in the filament size or the inter-filament separation is significantly smaller than the average size ($2a$) or inter-filament distance ($2d$).

The "effective" diffraction grating is two-dimensional (2D)in reality. However the basic characteristic scale-lengths are well represented by our 1D model and this has been the main focus of this letter. The full two-dimensional study will be reported in the future. One possible explanation of the asymmetry of the peak intensity of the observed pattern can be attributed to the trajectory of the satellite relative throught the 2D diffraction pattern. We can assume that during the period of observation the satellite is stationary as the pattern sweeps past it due to the rotation of the earth. As the earth rotates the satellite traces a path through this two-dimensional diffraction pattern. If the beam is not circular, as is the case, there will be an asymmetry in the diffraction pattern sampled by the satellite. Also the "chaotic" structure of the secondary signal spikes can be a manifestation of the satellite path through the two-dimensional pattern.

Discussion

We have developed a simple diffraction model of the wave pattern observed by the WAVES RAD2 receiver on the WIND satellite, when the heater facility at SURA was operated in the continuous mode for 50 minutes. To compare our results with the observations, the time scales given in Figure 1 can be converted to space scale by assuming that the pattern sweeps past the satellite in 40 minutes due to the rotation of the earth. We now show why irregularities of the size of 200 m, separated by 2 km agree with the observed structures. As mentioned earlier, there are three basic scale-lengths obtained from the diffraction model. The first is the primary line-width of the individual spikes, which for the SURA heater is $\approx$ 300 km at 140 R_e. This is in agreement with the 3-4 sec temporal width [*Rodriguez et al.,* 1999a] of the individual spikes which, using the earth's rotation rate, translates into 300 km. The overall envelope is controlled by the size of the irregularities. For 200 m irregularities the envelope width is 23.6 R_e. This is in reasonable agreement with the envelope width of 24 R_e, from Figure 1. Finally, the distance between the primary maxima obtained from the model is 2.36 R_e compared to the average distance between the primary maxima of 1.5 R_e from Figure 1. The low-level of the noise interspersed in the well-defined diffraction pattern indicates that the deviation from the assumed filament size and inter-filament distance are very small. It cannot be stated unambiguously whether the irregularities were present prior to the turning on of the heater or whether these are heater induced or enhanced irregularities. However, based on our earlier work on the nonlinear state of the thermal filaments there is a preferred size of the irregularities for a given heater power density. This suggests that the observed diffraction pattern is caused by heater induced or enhanced thermal filaments and that the observed signal has the potential to be used as a good diagnostic of these irregularities.

Acknowledgments. This work was supported by NSF under the Grant Number ATM-9713719 and ONR.

References

Bougeret, J. -L., M. L. Kaiser, P. J. Kellog, R. Manning, K. Goetz, S. J. Monsoon, N. Monge, L. Friel, C. A. Meetre, C. Perche, L. Sitruk, and S. Hoang, WAVES: the radio and plasma wave investigation on the WIND spacecraft, *Space Sci., Rev., 71*, 231, 1995.

Bernhardt, P. A., and L. M. Duncan, The feedback-diffraction theory of ionospheric heating, *J. Atmos. Terr. Phys., 44*, 1061, 1982.

Bernhardt, P. A., and L. M. Duncan, The theory of ionospheric focused heating, *J. Atmos. Terr. Phys., 49*, 1107, 1987.

Gondarenko, N. A., P. N. Guzdar, G. M. Milikh, A. S. Sharma, K. Papadopoulos, and S. L. Ossakow, Spatio-temporal development of filaments due to the thermal self-focusing instability near the critical surface in ionospheric plasmas, to appear in *Izv. VUZ Radiophys.*, 7, 1999.

Gurevich, A. V., Nonlinear Phenomena in the Ionosphere, Springer-Verlag, New York, 1978.

Guzdar, P. N., P. K. Chaturvedi, K. Papadopolous, M. Keskenin, and S. L. Ossakow, The self-focusing instability in the presence of density irregularities in the ionosphere, *J. Geophys. Res. 101*, 2453, 1996.

Guzdar, P. N., P. K. Chaturvedi, K. Papadopoulos, and S. L. Ossakow, The thermal self-focusing instability near the critical surface in the high-latitude ionosphere, *J. Geophys. Res., 103*, 2231, 1998.

Litvak, A. G., Possibility of self-focusing of electromagnetic waves in the ionosphere, *Izv. VUZ Radiophys., 11*, 814 , 1970.

Perkins, F. W., and E. J. Valeo, Thermal self-focusing of electromagnetic waves in plasmas, *Phys. Rev. Lett., 32*, 1234, 1974.

Rodriguez, P., E. J. Kennedy, M. J. Keskenin, C. L. Siefring, Sa. Basu, M. McCarrick, J. Preston, M. Engebretson, M. L. Kaiser, M. D. Desch, K. Goetz, J. -L. Bougeret, and R. Manning, The WIND-HAARP experiment: initial results of high power radiowave interactions with space plasmas, *Geophys. Res. Lett., 25*, 257, 1998.

Rodriguez, P., M. Keskenin, Y. Tokarev, V. Alimov, Y. Belov, V. L. Frolov, N. Karashtin, G. Komrakov, M. Kaiser, M. Desch, K. Goetz, J. Bougeret, and R. Manning, Evidence of high power HF radiowave self-focusing in the ionosphere: preliminary report of SURA-WIND observation, NRL/MR/ 6750-99-8312, 1999a.

Rodriguez, P., E. J. Kennedy, M. J. Keskenin, Sa. Basu, M. McCarrick, J. Preston, H. Zwi, M. Engebretson, A. Wong, R. Wuerker, M. L. Kaiser, M. D. Desch, K. Goetz, J. -L. Bougeret, and R. Manning, A wave interference experiment with HAARP, HIPAS,and WIND, *Geophys. Res. Lett., 26*, 2351, 1999b.

Tokarev, Yu. V., M. L. Kaiser, P. Rodriguez, V. A. Alimov, Yu. I. Belov, G. N. Boyko, G. P. Komrakov, N. V. Murav'eva, and A. V. Rakhlin, SURA-WIND Radar: Study of non-linear effects to be found during ionosphere sounding by HF radio waves, to appear in *Izv. VUZ Radiophys., 42*, 8, 1999.

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(Received September 15, 1999; revised November 10, 1999; accepted November 29, 1999.)