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THE INFLUENCE OF LOCALIZED PRECIPITATION-INDUCED D-REGION IONIZATION ENHANCEMENTS ON SUBIONOSPHERIC VLF PROPAGATION

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Abstract. A two-dimensional mode propagation model has been used to investigate the effect of localized ionospheric perturbations on the propagation of VLF radio waves in the earth-ionosphere waveguide. Computations have been performed for the NSS transmissions at 22.3 kHz from Annapolis, Maryland to Eights Station, Antarctica, where anomalous short-duration signal amplitude changes, in coincidence with whistlers, were first noted. The calculations suggest that two ionization regions, one very near the transmitter and another near the receiver, may need to be present at the same time in order to obtain the large amplitude increases (>3 dB) that are observed to occur on occasion. It is suggested that the former is due to transmitter-induced electron precipitation, while the latter is due to precipitation associated with the whistler. We also find that small amplitude changes can be obtained under less restrictive ionospheric perturbation conditions.

Introduction

Short-duration ($\leq$ 30 s) nighttime perturbations of the amplitude and phase of subionospherically-propagating signals from VLF transmitters have been correlated with the occurrence of whistlers [Helliwell et al., 1973; Lohrey and Kaiser, 1979] and other transient magnetospheric VLF emissions [Dingle and Carpenter, 1981]. Information on the characteristics of this phenomenon (the "Trimpi" effect) has come mainly from observations of VLF propagation to Antarctica, first at Eights Station and, more recently, at Siple and Palmer Stations. Statistics compiled by Carpenter and LaBelle [1982] on events at Palmer ($L \approx 2.3$) suggest a preference for the equinoctial periods and indicate that they can occur at all nighttime hours, but most frequently between midnight and dawn following magnetic storms. Also, large amplitude whistlers were more likely to cause effects than small amplitude whistlers.

A schematic illustration of the effects believed to be taking place in the ionosphere and magnetosphere during whistler-associated VLF perturbations is presented in Figure 1. In this figure, a whistler induces precipitation into the ionosphere at either or both duct end points by gyroresonant pitch-angle scattering interactions with trapped energetic electrons. The precipitation, hence the ion production, would be short-lived ($\sim$ 1s), but the ionospheric density perturbation could persist for several tens of seconds as determined by the ionospheric time constant $\tau(\equiv[2\alpha N]^{-1})$. The observed recovery times are consistent with reasonable estimates of the effective recombination coefficient α and the electron density N in the height range of interest. Thus, patches of enhanced ionization would endure for this interval below the normal nighttime ionospheric reflecting height ($\sim$85-87 km) for VLF propagation, if the precipitated electrons were sufficiently energetic ($E > 40$ keV). Electron precipitation bursts have been detected at subauroral latitudes [Rosenberg et al., 1971, 1981; Foster and Rosenberg, 1976; Helliwell et al., 1980; Siren et al., 1980], but not as yet in the type of event considered here.

Localized depressions of the reflecting height of the ionosphere caused by electron precipitation would alter the propagation characteristics of the earth-ionosphere waveguide and could lead to VLF signal perturbations [Crombie, 1964]. In this letter we discuss the application of a quantitative model of waveguide propagation [Tolstoy et al., 1981] to predict the location and extent of localized ionosphere perturbation regions that can account for the observed effects. It is important to note, especially with regard to amplitude perturbations, that signal increases as well as decreases, of as much as 6 dB, can occur [Helliwell et al., 1973].

The VLF Wave Propagation Model

A two-dimensional model for VLF wave propagation which is based upon the Budden-Wait full wave waveguide mode approach [Budden, 1961a, b; Wait, 1970] has been employed. This model was developed at the Naval Ocean Systems Center, San Diego, and supplied to us through the courtesy of J. Ferguson.

In this model the conductivity and permittivity of the earth's surface, the lower boundary of the waveguide, may vary according to a worldwide multi-level map of discrete values [Morgan, 1968]. The upper boundary of the waveguide, the ionosphere, is assumed to be parallel to the earth and to be anisotropic, vertically and longitudinally inhomogeneous, dissipative, and diffuse. In particular, the ionosphere is described by an effective permittivity matrix modified for earth curvature and having complex terms. A multipole expansion of the geomagnetic field is included since the field produces anisotropic effects which are significant. The model also allows for arbitrary electron density and collision frequency distributions as a function of

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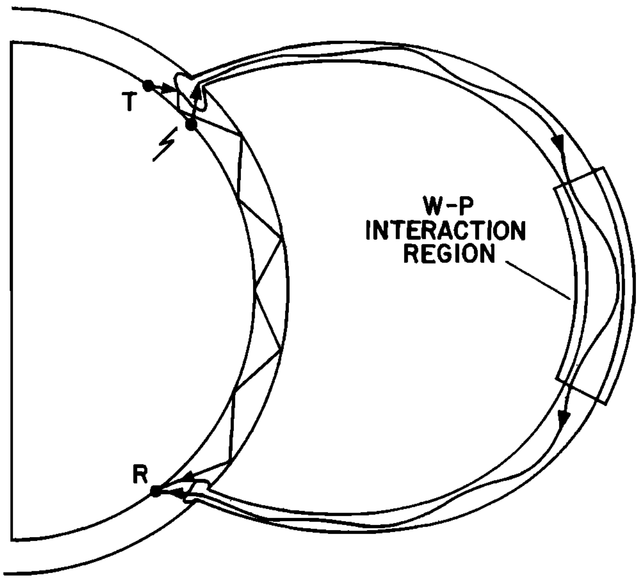

Fig. 1. Schematic illustration of whistler-associated subionospheric VLF perturbations (from Dingle and Carpenter, 1981). A whistler propagating along a field-aligned path in the magnetosphere precipitates electrons into the conjugate hemispheres, thus perturbing the earth-ionosphere waveguide and the properties of signals propagating from a transmitter T to a receiver R . In the general case, the great circle path TR and the whistler duct would not lie in the same meridional plane and the L values of T and R could differ significantly.

height. Exponential profiles for each, appropriate to the nighttime D region, have been used [Ferguson, 1980]. Geophysical conditions transverse to the direction of propagation are assumed to be homogeneous.

The VLF time-harmonic signal propagates as a sum of discrete modes which partially reflect within the earth-ionosphere waveguide. Conditions can vary widely along the path; however, the path is dynamically segmented such that conditions can be regarded as homogeneous (except with regard to height) within each segment. Regions of ionospheric electron density enhancement are introduced into the model by locally modifying the electron density profile. Specifically, the reference reflection height h' is altered at points along the path, resulting in an effective vertical translation (Δh') of the entire density profile.

The present model considers the perturbation regions to represent slowly changing geophysical conditions in the direction of propagation. The shape of the region is not critical because any perturbation can be treated as closely as desired by choosing the segments to be sufficiently small. For convenience, trapezoidal shapes with small slopes were used for Δh' in order to satisfy the requirement that changes of electron density from segment-to-segment be kept small.

Computational Results

The above model has been applied to the NSS (Annapolis, Maryland; 39°N; 76.5°W) to Eights Station (75°S; 77°W) path. At the time of the earliest observations of the perturbation effect (1963) NSS was operated at a frequency of 22.3 kHz [Helliwell et al., 1973]. The computed signal strength of the NSS transmission as a function of distance along this path for a typical (constant) nighttime reflection height h' = 85 km is shown by the solid curve in Figure 2 and subsequent figures. The NSS transmissions at 21.4 kHz to Siple Station (76°S; 84°W), over almost an identical path, show similar behavior.

The NSS signal was modeled as a sum of the five lowest-order modes propagating from the transmitter. Higher-order modes were not required since they attenuated severely over the long range to the receiver. The signal character is such that within 3000 km of the transmitter (as seen in Figure 2) the selected modes are of comparable strength and thus interference is apparent. However, as the undisturbed signal progresses, the third-order mode (second TM) becomes strongly and persistently dominant. Hence, the signal steadily decreases with only minor variations evident in the amplitude pattern.

Single depression regions, placed along the great circle path either within 3000 km of the receiver or within 6000 km of the transmitter, were then examined for their effect on signal amplitude. Approximately 60 regions, with lengths from 1000 to 4000 km and depths (Δh') up to 4 km, were tested. All regions located at distances greater than 1500 km from the transmitter, including regions located over the receiver, were found to result in signal amplitude decreases of $\leq$ 2 dB at the location of Eights. Two examples, given by the dashed and dash-dot curves, are illustrated in Figure 2. These amplitude plots were of the same character as the undisturbed case, i.e., with the third-order mode (second TM) strongly dominant at far field.

Single depression regions located nearer to the transmitter (Figure 3) led to stronger exci-

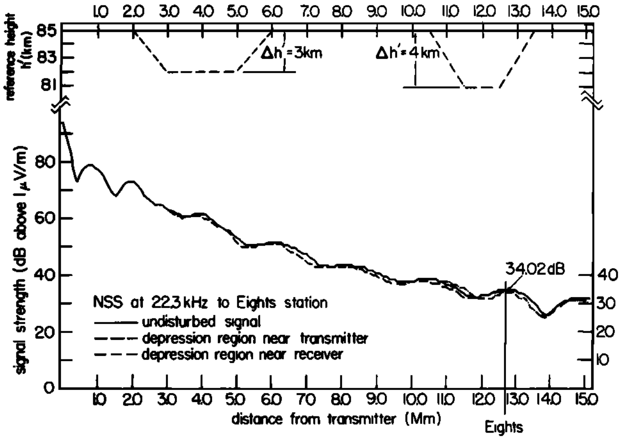

Fig. 2. Signal strength of transmissions along the great circle path from NSS (Annapolis, Maryland) to Eights Station, Antarctica. The solid curve is for a constant reference height h' of 85 km for the entire path. Modifications to the undisturbed signal introduced by a single depression region (of the dimensions indicated) located either near the transmitter or near the receiver are illustrated.

tation and a lower attenuation rate for the second-order mode (first TM). These produced two strong interfering modes (second- and third-order) resulting in a highly oscillatory amplitude curve which persisted out to the receiver. Although larger amplitude variations were obtained for these cases, all resulted in signal decreases at Eights.

To obtain amplitude increases at Eights of 4-6 dB, as have been observed, it was necessary to consider multiple perturbed regions. By combining a perturbed region very near the transmitter (to initiate the strong, persistent mode interference pattern) with a region located near the receiver as shown, for example, in Figure 4, the observed effects could be reproduced.

Discussion

As described above for the NSS to Eights Station path, two ionospheric perturbation regions, one located very near the transmitter and one near the receiver, are required in order to model large amplitude increases at the receiver. An enhanced ionization region located near the receiver (L ≈ 4.1 in this case) could be caused by whistler-induced precipitation, as has already been suggested. However, a perturbed region confined to the vicinity of the transmitter (L ≈ 2.7) would not be consistent, in general, with whistler-induced precipitation as its origin, but might be caused by the transmitter itself.

An indication that D-region ionization enhancements may be located near VLF transmitters comes from a recent report by Inan [1981] which suggests the possibility of an extensive precipitation zone about a transmitting station. The size of the zone is shown to depend on station location, operating frequency, and radiated power. Precipitation induced by the NSS transmitter with the spatial distribution, energy spectrum, and fluxes suggested in Inan [1981] is more than adequate to produce the required D-region enhancement. Some experimental evidence for the significance of VLF transmitters in precipitating electrons, based on satellite particle and wave data, has recently been presented by Imhof et al. [1981].

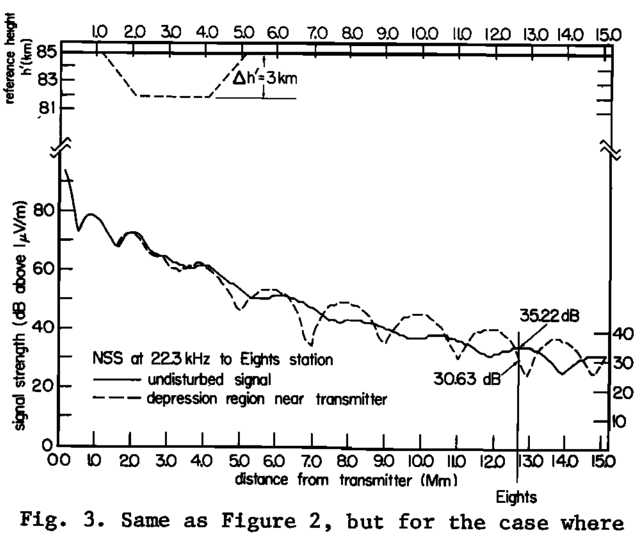

Fig. 3. Same as Figure 2, but for the case where the ionospheric depression region begins within 1500 km of the transmitter. A receiver located at Eights would record an amplitude decrease of 4.5 dB.

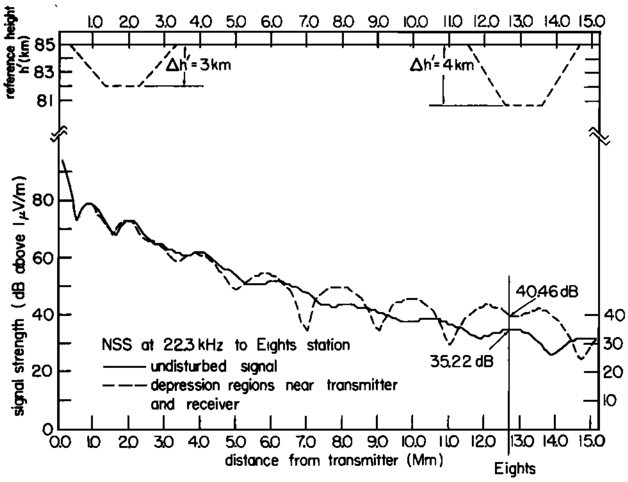

Fig. 4. Same as Figure 2, but for the case where two ionospheric depression regions are present at the same time. A receiver located at Eights would record an amplitude increase of 5.2 dB in this example.

Transmitter-induced precipitation might not be present at all times. However, whistler-associated VLF perturbations usually occur only during intervals of 1-2 hrs over a several-day period following a magnetic storm when the magnetospheric disturbance level is quieting. In the typical situation, the L shells of magnetospheric ducts terminating near the receiver and near the transmitter may differ significantly, but both will lie within the plasmasphere [Helliwell et al., 1973; Carpenter and LaBelle, 1982]. Although parameters such as the cold plasma density and trapped flux level vary with L, the conditions necessary for the occurrence of whistler-induced precipitation may also favor transmitter-induced precipitation at the same time. Thus, it seems plausible to suggest that some whistler-associated VLF amplitude perturbations, particularly those involving significant amplitude increases, are produced in the following manner. Under suitable magnetospheric conditions, a region of the ionosphere in the vicinity of a transmitter is perturbed for some period of time owing to electron precipitation induced by whistler-mode signals from the transmitter in gyroresonance with magnetospheric electrons. As a result, a pattern of strongly interfering modes is set up in the earth-ionosphere waveguide. At irregular intervals, additional whistler-induced precipitation perturbs a region of the ionosphere near the receiver and the propagation characteristics of the waveguide are further altered to produce the observed amplitude effects.

The present results are based on a version of the model which did not consider mode conversion. Also, that version could not handle extreme changes in geophysical conditions, such as are encountered at the Antarctic sea-ice interface. A constant sea-water conductivity value was assumed for the entire path in the calculations of Figures 2-4. A more highly developed model is now in use which allows for realistic ground conductivity and mode conversion, with as many as 15 modes comprising the signal at the sea-ice interface. Calculations which incorporate these changes and which examine depression regions as small as 100 km in longitudinal extent continue to support the initial requirement of a depression region near the transmitter in order to obtain large (4-6 dB) amplitude increases near the receiver.

Further work will concentrate on a quantitative evaluation of changes to the modal structure of subionospheric propagation by transmitter-induced precipitation. Instead of employing the simplified changes to h' represented by the trapezoidal geometries of Figures 2-4, modifications to the electron density profile based on the predictions of Inan [1981] can be incorporated into the VLF propagation model. Calculations will also be performed for other transmitter-receiver paths on which these effects have been observed.

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