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VLF HEATING OF THE LOWER IONOSPHERE

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Abstract. A controlled wave-injection experiment with a 28.5 kHz transmitter having a radiated power of 100 kW has revealed evidence of ionospheric heating by the VLF waves. Calculations indicate that the observed effect can be attributed to the absorption of wave energy in the lower ionosphere, which is estimated to result in a 30% enhancement in the collision frequency at 85 km. This process also represents a new means of direct coupling of lightning energy to the lower ionosphere.

1. Introduction

One of the first [*Tellegen*, 1933] recognized manifestations of ionospheric heating by radio waves was the so-called 'Luxembourg' or 'ionospheric cross-modulation' effect, involving the transfer of modulation from a 'disturbing' wave that locally heats the ionosphere to a second wave that reflects or propagates through the same region [*Budden*, 1985; *Huxley and Ratcliffe*, 1949; *Maslin*, 1975;1976].

We report on a new finding in which the amplitude of the 24.0 kHz NAA transmitter (Maine) signal observed at Palmer Station (PA), Antarctica was found to exhibit the modulation pattern of the 28.5 kHz NAU transmitter (Aguadilla, Puerto Rico), which was being keyed as part of a controlled VLF wave-injection experiment. With the NAA-PA great-circle path crossing within <50 km of the ionosphere the NAU (Figure 1), this result is interpreted as a VLF analog of the ionospheric cross modulation effect.

2. Experimental Results

The purpose of the wave-injection experiment carried out during Spring 1989 was to stimulate the precipitation of electrons from the inner radiation belt, and to detect the associated ionospheric effects as perturbations on subionospheric VLF signal paths observed at Arecibo, Puerto Rico and at Palmer, Antarctica as depicted in Figure 1. The transmitter was keyed nightly for 0335-0350 UT and 0735-0750 UT with a 5-s periodic format (3sON/2sOFF).

Superposed-epoch and spectral analyses of the various signal amplitudes received at Palmer and Arecibo were conducted to search for effects of the 5-s periodicity and the results for 7 May 89 are shown in Figure 2.

In Figure 2a, the NAU-PA signal shows the modulation pattern, together with a 1-s long risetime during which the transmission is increased from 70% to 100%. The NAA-PA signal exhibits a decrease (0.07 dB) simultaneous (analysis indicates <20 ms) with the keying OFF of the NAU signal and also the signal build-up during the first 1-s. The NSS-PA, as well as other transmitter signals (not shown) observed at Palmer, did not show any evidence of 3s ON/2s OFF keying. Signals observed at Arecibo were similarly analyzed but no clear evidence of keying was found.

In Figure 2b, the NAU-PA signal exhibits the 5-s periodicity (0.2 Hz) together with a second harmonic at 0.4 Hz. A clear (>5 dB above background) peak at 0.2 Hz is seen on NAA-PA, while no such peak is found for NSS-PA. Data from other 15-min periods for both before and after 0335-0350 UT were similarly analyzed, and no evidence of spectral peaks (>3 dB above background) were found. Similar analysis on the phase of the NSS-PA and NAA-PA signals did not show any signatures of the NAU keying.

Data from 0335-0350 UT and 0735-0750 UT for two separate one-week periods (5-12 May and 11-17 June 1989) were analyzed. High resolution data were available for all of the days except 10 May 1989. Spectral peaks >5 dB above background at 0.2 Hz were observed on the NAA-PA signal during the 0335-0350 UT periods on 7 May and 13 June and a prominent >3 dB peak was observed at 0.2 Hz on 16 June. There were no other such peaks at any frequency on any other days in either the NAA-PA signal data or in the data of any other signals analyzed. Geomagnetic conditions on these days varied over a range of moderate disturbance levels, with ΣKp=23, 20, and 35 respectively on 6 May, 12 June and 15 June 1989.

A careful analysis of signal strengths at the receiver was used to rule out nonlinearities in the receiver equipment as a source of the cross modulation. The NAU and NAA signals at Palmer were measured with two different receivers sharing a common preamplifier. No evidence of the modulation was found on any of the other signals from both of the receivers and the signal intensities on the days the effect was observed were not unusual. Laboratory tests with duplicate of the receiver used at Palmer showed no evidence for spurious responses at 24.0 kHz due to 28.5 kHz inputs.

3. Theoretical Calculations

It appears that, under certain conditions, the modulation of the NAU signal is transferred to the NAA signal, in a manner similar to the 'Luxembourg' effect [*Budden*, 1985]. The <20 ms synchronism between the NAU-PA and NAA-PA signals is consistent with an overhead heating effect. In this section, we estimate ionospheric heating resulting from the absorption of an upward propagating VLF wave originating from a ground-based transmitter.

Figure 3 shows the real (μ) and imaginary ($\alpha c/\omega$) parts of the refractive index computed by using the general magnetoionic expression [*Budden*, 1985] and the modified collision frequency obtained using the relation between the change in the collision frequency $\Delta\nu$ and the absorbed wave power U as given by *Maslin*[1976]. Typical exponential night-

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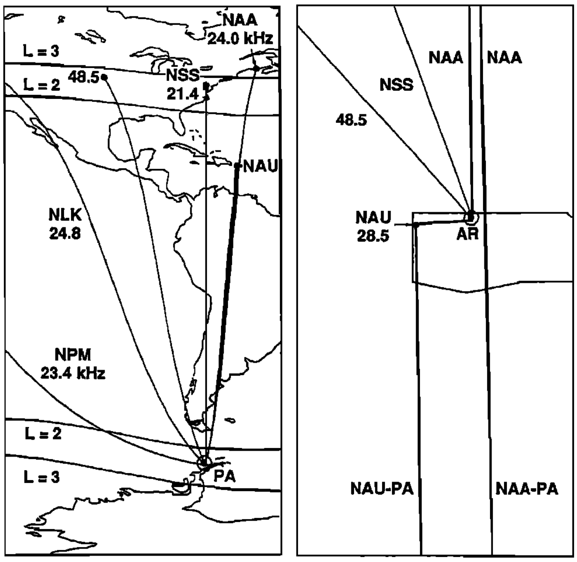

Fig. 1. Observation geometry at Arecibo (AR), Puerto Rico (right) and at Palmer (PA) Station, Antarctica (left). At both sites, signals from 6-10 VLF transmitters are routinely observed although only selected propagation paths are shown above. The NAA-PA path crosses within <50 km of the NAU transmitter as seen in the right hand panel. The loci of the foot of the $L = 2$ and $L = 3$ field lines at 100 km altitude is also shown for reference. The NLK and the NPM transmitters are located respectively at (48°N,122°W) and (21°N,158°W). The number associated with each transmitter is the operation frequency in kHz.

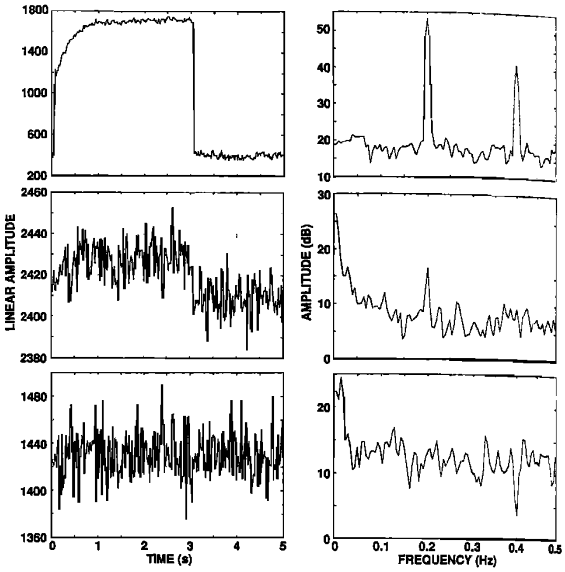

Fig. 2. (a) The left hand panel shows superposition of 180 5-s segments from the 0335-0350 UT period on 7 May 89 for NAU-PA (top), NAA-PA (middle), and NSS-PA (bottom) signals. The vertical axis shows amplitude (A) in linear arbitrary units, with $A = 0$ being absence of signal. (b) The right hand panel shows power spectra of the 15-min data for the period 0335-0350 UT for NAU-PA (top), NAA-PA (middle), and NSS-PA (bottom) signals.

time ambient electron density and collision frequency profiles were assumed for altitudes <100 km with N$\simeq$40 cm^{-3} and ν=5.82$\times$10^5 s^{-1} at 85 km [*Wait and Spies*, 1964]. The radiated power for the 28.5 kHz NAU transmitter was taken to be 100 kW giving 2.1$\times$10^{-6} W/m^2 at 45° elevation and at 70 km for each of the two wave modes (ordinary and extraordinary).

Results in Figure 3 show that the extraordinary wave is evanescent and is absorbed above ~90 km altitude, with α high and $\mu \ll 1$. The resulting heating ($\Delta\nu$) is not large in this relatively high density region and subionospheric VLF waves that reflect at 85 km are not likely to be significantly perturbed.

For the whistler-mode wave, α peaks around 85 km altitude where X$\simeq$Z, and μ becomes increasingly large as the wave enters the ionosphere. The wave power density is reduced by ~10 dB, and the absorbed energy produces an ~30% enhancement in ν (or Z) near 85 km. The resulting increase of ~1 km in the VLF reflection height (height at which $\omega_p^2/\nu \simeq 2.5 \times 10^5$ [*Wait and Spies*, 1964]) is generally consistent with an amplitude increase (less attenuation) as observed (Figure 2a). However, we note that both amplitude increases and decreases are observed on the NAA-PA signal in whistler-induced electron precipitation (Trimpi) events, in which case the enhanced secondary ionization generally leads to a decrease in the nighttime reflection height. Crude models have been used to interpret Trimpi events (amplitude changes of 0.1-1.3 dB) at Palmer as ~1-2 km decreases in the VLF reflection height [*Inan et al.*, 1985]. However, a full waveguide

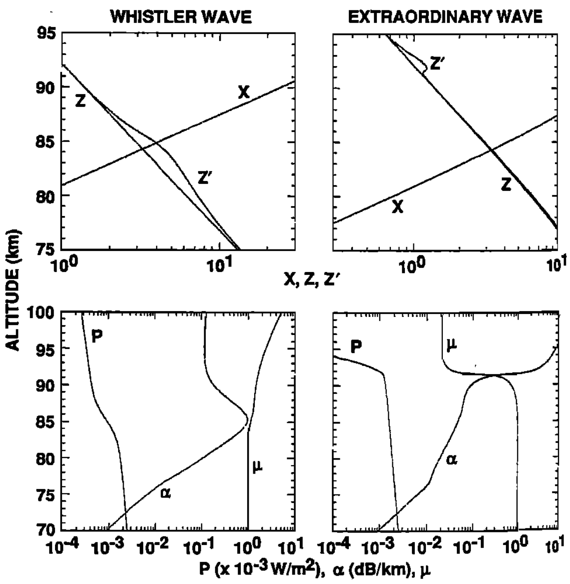

Fig. 3. Computed results for typical ambient conditions. For both the whistler mode and the extraordinary wave, the wave power density $P(h)$, attenuation constant α, and refractive index μ are shown in the lower panels. The upper panels show $X(h)$, $Z(h)$, ($X = \omega_p^2/\omega^2$, with ω_p and ω being the electron plasma and wave frequencies respectively, and $Z = \nu/\omega$ with ν being the average collision frequency for electrons) and the normalized modified collision frequency $Z'(h)$.

modal analysis is needed in order to make useful comparisons.

For given U, the average energy increase per electron, and the resulting $\Delta\nu$, is inversely proportional to number density [*Maslin*, 1976]. Calculations for a D-region a factor of 10 more tenous compared to that in Figure 3 show the extraordinary wave to be heavily absorbed above 95 km, leading to 50% increase in ν at ~98 km. The α for the whistler-mode peaks at ~90 km, resulting in $\Delta\nu$ of 60% at 85 km and ~100% at ~89 km.

That the heating effect is observed only on certain days can partly be attributed to variations in the ambient density and partly to other factors not considered above. A better estimate of $Z'(h)$ can be obtained with an iterative computation, noting that as the medium (i.e., ν) is modified, U is changed. Such a correction would lead to higher U at lower lights, and thus lower P and $\Delta\nu$ at 85 km. However, much of the whistler mode absorption of the whistler mode occurs near 85 km (Figure 3), so that the correction in $Z'(h)$ is likely to be small.

The reflection of the upgoing whistler-mode wave has also not been accounted for. The reflected signal would interfere with the upgoing signal and lead to some maxima and minima in $U(h)$ [*Maslin*, 1975], although this effect is not likely to be significant since the reflected wave traverses the region of high absorption once again and is substantially weakened. The wave power transmitted beyond the reflection height is generally small, so that the theoretical estimates given in Figure 3 for altitudes >85 km are inaccurate.

4. Heating as a Function of Input Wave Frequency

The frequency dependence of heating shown in Figure 4 indicates that the perturbation at 85 km is maximum for 50-60 kHz, with heating decreasing rapidly beyond 60 kHz to <10% for > #300 kHz. There is a broader maximum for the 80 km altitude with $\Delta\nu \simeq 20\%$ for 4-90 kHz.

Previous work on ionospheric cross modulation typically considered 0.2-1 MHz signals, and power levels at 70 km of 10^{-4}-10^{-3} W/m^2 (1-10 MW isotropic radiators on the ground) [*Maslin*, 1975]. Most cases involved $\Delta\nu \ll \nu$, consistent with the result in Figure 4. For comparison, we note that 2.1×10^{-6} W/m^2 at 70 km leads to $\Delta\nu \simeq 0.4\nu$ for 28.5 kHz .

Although simple theory used in past work (assuming $\omega \gg \nu$ and $\Delta\nu \ll \nu$) indicated the cross modulation to be proportional to f^{-2}, it was believed that the theory breaks down between 167 and 90 kHz with 'no cross modulation ever being found for waves of frequency less than 167 kHz' [*Huxley and Ratcliffe*, 1949]. In our work, we consider the full magneto-ionic expression for α that does not require $\omega \gg \nu$. For the VLF range, we find $\Delta\nu$ comparable to ν, indicating that the ionospheric cross modulation effect is more significant than for >200 kHz.

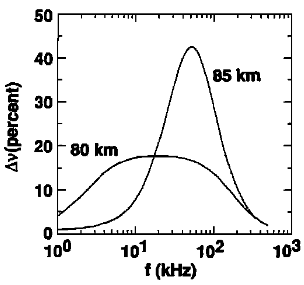

Fig. 4. Frequency dependence. The percentage change in normalized collision frequency (Z') is shown for 80 and 85 km altitudes for the whistler-mode (ordinary) component, for 2.1×10^{-6} W/m^2 at 70 km, and an ambient density profile same as that for Figure 4.

A comparison between HF (>1 MHz) and VLF heating can be made in light of the results of *Barr et al.* [1985] involving the perturbation of subionospheric VLF signal amplitudes by an HF heated patch. Under stable propagation conditions, *Barr et al.* [1985] found typical amplitude perturbations to range from 0.11 dB (nighttime) to 0.025 dB (daytime), comparable to our results, involving a change of 0.07 dB (nighttime). In spite of the genearlly higher radiated powers used for HF experiments, the heating effect is apparently similar to that produced by NAU.

5. Ionospheric Heating Due to Lightning Discharges

The amplitude of the heating wave near 85 km for the case in Figure 3 is ~12 mV/m. Since transient electric fields from lightning of up to 50 mV/m have been observed in the ionosphere [*Kelley et al.*, 1985], localized enhancements in ν should be readily produced in association with lightning discharges, representing a new means of direct modification of the lower ionospheric plasma by lightning. Lightning-associated conductivity changes observed on rockets and balloons [*Kelley et al.*, 1985] can thus be due to the localized heating effects, and some of the observed rapid changes in subionospheric signal amplitudes (early/fast Trimpi events [*Armstrong*, 1983; *Inan et al.*, 1988]) may be caused by modification of the earth-ionosphere waveguide mode structure due to the enhanced ν. However, effects involving slow (10-100 s) recovery are likely to involve other mechanisms (leading to generation of ionization enhancements) operating in conjunction with heating. The subionospheric VLF signatures of lightning-induced heating would be sharp increases (or decreases) in signal amplitude lasting for the duration of the causative radio atmospherics.

6. Summary

Experimental evidence suggests that VLF signals from powerful ground-based transmitters may substantially heat the lower ionosphere. This heating can be detected as amplitude changes on subionospheric VLF signals propagating under the disturbance, in a manner similar to the 'ionospheric cross-modulation' effect previously observed at >200 kHz [*Huxley and Ratcliffe*, 1949], although the heating appears to be more efficient at VLF. Theory indicates that the heating near 85 km is primarily due to the absorption of the whistler-mode wave, resulting in a $\Delta\nu$ of 30% for 100kW radiated power at 28.5 kHz, and is more prominent when the ambient density is lower.

The heating effect reported here also represents a new means of direct electrical coupling between thunderstorms and the lower ionosphere. Measured ionospheric electric fields from lightning are of sufficient magnitude to produce localized heating, suggesting that some of the previously reported anomalous subionospheric VLF responses may be due to this effect.

The ability to substantially heat the lower ionosphere with VLF signals could lead to a new set of controlled experiments to evaluate the effects of ionospheric disturbances of known configuration. Comprehensive [ground-(radars) and rocket-based] measurements are needed in order to fully understand the extent of the effect. Conductivity changes resulting from the heating could possibly be utilized to generate ULF waves. Powerful VLF transmitters and thunderstorm centers may be a continuous source of heating for the overhead ionospheric regions. The possibility of D-region heating by VLF transmitters or lightning leading to the formation of whistler ducts needs to be evaluated.

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