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LF and MF observations of the lightning electromagnetic pulse at ionospheric altitudes

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Abstract. For the first time the full ionospheric signature of the lightning electromagnetic pulse (EMP) was measured up to a frequency of 2 MHz. At altitudes below 225 km, the upward-going whistler wave is found to have a nose-whistler wave shape with the fastest propagating frequency (nose frequency) near 80 kHz. The bulk of the EMP energy is at the nose frequency, and there is a sharp upper limit near 175 kHz where the group delay is very long. We believe the group delay is due to a propagation resonance for the whistler mode (slightly non-longitudinal propagation) associated with the low plasma frequencies in the F-layer valley. MF emissions were seen below the F peak, but not above. These results verify earlier speculation that the leading intense edge of the lightning EMP was carried by 50-125 kHz waves. In addition, we present tantalizing evidence for detection of a pulse pair prior to the stroke that is similar to transionospheric pulse pairs (TIPPs) detected in satellite data.

Introduction

A lightning discharge has a complex electromagnetic signature with both near- and far-field effects. Considerable effort has gone into characterizing the signal using ground-based methods [*Uman*, 1987].

Knowledge about the penetration of lightning-generated electromagnetic energy into the ionosphere is much more sparse. The frequency content of these so-called whistler waves is well known [*Helliwell*, 1965], but knowledge about the original ionospheric signal is lost to both high altitude instruments on satellites and distant Earth-bound receivers (e.g. in the other hemisphere).

Whistlers have been used as probes of the plasmasphere since they contain information on both the plasma content along the magnetic field line and the radial location and drift of the guiding structure. Until now little, if any, experimental space-based lightning wave information has been available above about 30 kHz where earlier rocket and satellite work has typically been limited. In this research arena rockets can provide a unique platform for study since, if the lightning activity is high, a vertical profile of the signal properties can be made in a short time.

An earlier rocket-borne experiment provided a clue that intense, high group velocity (V_g) waves above this classic VLF measurement band were part of the ionospheric picture. As reproduced on the cover of the November 1990 issue of *Geophysical Research Letters*, a ms-long precursor pulse was routinely recorded on several instruments prior to the arrival of the 10 kHz waves from a lightning stroke [*Kelley et al.*, 1990]. The arrival time of the precursors corresponded to a V_g consistent with 100 kHz waves.

In this paper we report the first ionospheric observations of the spectrum of lightning-induced electromagnetic waves from ELF through MF bands. These data were obtained on a near vertical path over a very active thunderstorm cell. Data reported here were obtained using a double-probe electric field sensor carried aloft by NASA sounding rocket 36.111, launched from the Wallops Flight Facility in Virginia. Complete waveform information was obtained using a specially designed 4-M sample/sec triggered burst memory [*Baker et al.*, 1996]. Triggering was accomplished using the output of a photodiode-based lightning sensor provided by co-investigators from the University of Washington. In the absence of an optical trigger, e.g., if the optical sensor was saturated, an untriggered data snapshot of up to 512k samples was transmitted. Additional instrumentation was supplied by the University of New Hampshire, the Sodankylä Geophysical Observatory, and the Danish Technical University. More complete results from the full payload instrument complement, including electromagnetic fields in the DC-20 kHz range, will be published subsequently.

Data Presentation

Here we present wave measurements ranging in frequency from 20 kHz to 2 MHz made in two representative height ranges, one above and one below the ionospheric F peak. Although intermittent, on-board probe density measurements and ionosonde data all indicate that the data in Figures 1 and 2 were obtained at the base of the ionospheric F layer and well below the F peak. Figure 1 provides an overview of the electromagnetic field data obtained during the 1.2 ms period captured by the burst memory at that location. The upper plot shows the raw electric field signal, E_{perp},

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detected by a dipole oriented 3.6 degrees from perpendicular to the magnetic field, the character of which is made clear by the spectrograms directly below. The data were filtered from 20 kHz to 2 MHz using 4-pole Butterworth filters and digitized with 12-bit resolution at 4-M samples/sec. The 20-kHz cutoff avoids saturation on the peak in the signal strength, and separate data channels provided continuous waveform data up to 20 kHz. Within the two-decade passband, the electronic response is linear and uniform in frequency. A broadband magnetic search coil displayed the same character as the more sensitive electric field detector.

Panel 2 of Figure 1 shows two preferred electromagnetic bands, one below about 200 kHz and another above 1 MHz with a clear gap between. The low frequency portion of the data from the channels is expanded in panel 3 where the characteristic "C"-shape of a nose whistler is evident. To our knowledge, this is the first report of a fractional-hop nose whistler observed at ionospheric altitudes. Unlike the classic plasmaspheric nose whistler, however, this fractional-hop nose whistler feature displays a minimum propagation time for a frequency of just under 100 kHz rather than the usual value, which is $\leq$10 kHz. The time scale is also very different, hundreds of microseconds rather than a second or so. As discussed below, we believe that the physical explanation, which involves a local maximum in the group velocity, is similar.

At higher frequencies there are interesting signals as well. Returning to panel 2, about 300μs before the nose frequency arrived, MF signals began and lasted for about 500μs. A one-dimensional full-wave VLF-MF propagation code based on the method in *Young* [1994] shows that any MF signal caused by direct radiation from a stroke should arrive 55μs before the nose frequency caused by that same stroke. Clearly the MF component began to radiate well before the stroke. The lower frequency for the MF signal is 1 MHz, which is about equal to the local plasma frequency. In addition, the signal is highly structured in time and frequency. In frequency the signal is distinctly banded with a separation of roughly 150 kHz. In time there are two very distinct stripes, one slanted down in frequency with time (440-480μs into the snapshot) and the other slanted upward in frequency with time (580-640μs in the snapshot). Between these, another pulse appears at about 540μs (slanted upward in frequency versus time). With these three pulses in mind a fourth can be found at 360μs (slanted downward). These observations are made more clear in the expanded plot presented in Figure 2.

Figure 3 further extends our knowledge of the propagation of a lightning pulse through the ionosphere. These data were obtained later in the flight when the rocket was well above the F peak, and there is not a trace of any signal above about 225 kHz. Apparently, any MF waves in the detector bandwidth have been totally reflected by the high plasma frequency below the rocket. The nose frequency is still evident but a new feature has emerged. Waves with frequencies as high as 225 kHz waves now seem to have caught up to the nose frequency waves. The upper cut-off remains and the trace is indistinct near the cut-off, but the long time delayed waves that formed the top of the "C" are gone. Signals from several AM radio stations can be seen in the plot, particularly the one at 560 kHz. In general, these signals were more evident in the higher altitude data than that taken on the bottomside of the F layer. This is somewhat curious since the instrument gain was constant.

Discussion

Most ionospheric applications of magneto-ionic theory have been discussed for situations in which the plasma frequency is above the electron gyrofrequency. However, this relationship can be reversed in the F-layer valley.

We have studied the Bermuda ionosonde data at the same local time and have found that the E-region density started to decrease dramatically nearly an hour earlier and the peak value had decreased to 10^4 cm^{-3} at the launch time. The density at the E-layer peak decreased very slowly thereafter, indicating a metallic ion layer was present. This shows that recombination of molecular ions had occurred and we are confident that the valley region was very depleted by launch time.

In such a low plasma density case for $0° < \theta < 90°$ there is a resonance at $\omega_p \cos(\theta)$, where θ is the angle between $\mathbf{k}$ and $\mathbf{B}_o$, rather than at the more usual whistler mode cut-off at $\Omega_e \cos(\theta)$. We believe that this explains the upper cut-off in the low frequency spectrogram as due to the plasma frequency limit, and in turn implies that the minimum plasma frequency below the rocket (and above the transition height from free space to whistler mode) is given by the 175 kHz upper limit on the electromagnetic band. This plasma frequency corresponds to a plasma density of only 400 cm^{-3}. The dispersion relation can be solved for V_g as well and its maximum value is in good agreement with the observation of the nose frequency. We have also found the band below 175 kHz to be circular and R mode as expected, assuming that it is propagating upward. The ratio of broadband electric and magnetic fields is about 3×10^7 m/s, indicating an index of refraction of 10. This is most likely an overestimate, though, since we have not corrected for the finite input capacity of the electronics. The dispersion relation indicates that n $\approx$ 3 at the nose frequency.

The ray tracing program, Tracer [*Argo et al.*, 1992], developed at Los Alamos National Laboratory, was used to understand the MF behavior with some success. Using a nominal plasma profile, we have launched L- and R-mode waves at stratospheric heights and followed their group delays in several frequency ranges between 1-2 MHz. As these waves propagate upward into the

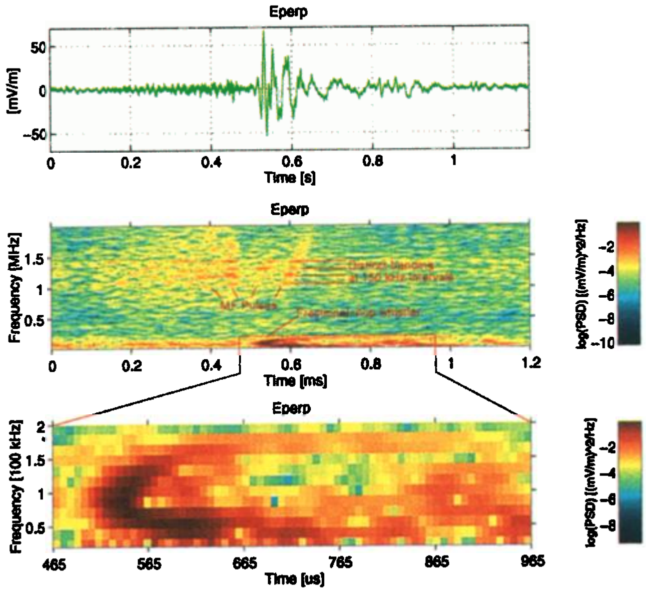

Figure 1. Electric field data taken at 195 km with a 20-kHz to 2-MHz bandwidth receiver. A nose whistler is detected by both sensors at times between 0.5 ms and 0.7 ms and at frequencies below 175 kHz. A deadband exists between 175 kHz and 1 MHz, which essentially has no electromagnetic energy. Above the deadband are broadband bursts of energy both before and after the nose frequency arrived.

increasing plasma density, they slow down and are reflected. The higher frequency components penetrate higher and take longer to return to the rocket, hence a reversed frequency-versus-time pattern is produced.

However, the sense of rotation of the electric field detected at the rocket in all four of the MF bands is identical. The first two pulses are clearly upgoing and we find that the wave is polarized in the left-handed sense. A reflected wave will have the same sense of electric field rotation to an *in situ* sensor, so our data is completely consistent with two upgoing L-mode waves

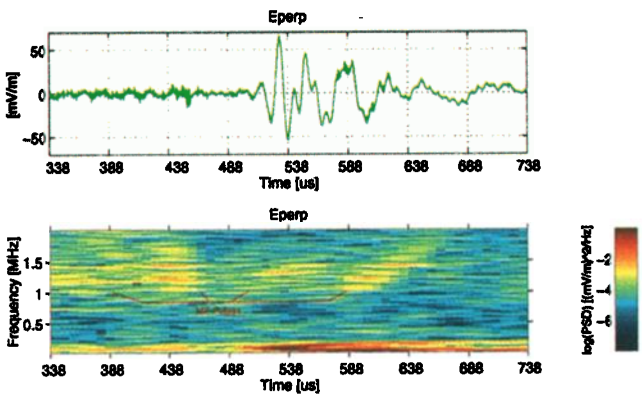

Figure 2. A portion of Figure 1 is presented for a smaller time period. The megahertz components of the spectrogram show four bursts of signal occurring in two pairs, which could be the MF components of TIPPs and their reflections. Times are relative to t=0 in Figure 1.

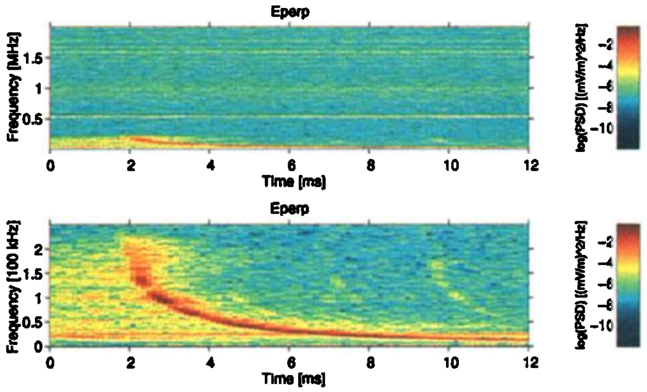

Figure 3. Electric field data for a fractional-hop whistler observed at 359 km, which is above the F peak. The plasma frequency is comparable to or above the electron gyrofrequency. The top panel shows essentially no EM energy above 225 kHz, except for a strong 560 kHz AM transmitter and a few possible weaker channels. The lower frequency information is shown in more detail in the bottom panel. The low frequency components of the whistler are now dispersed over more than 10 ms, but the 50-200 kHz band is dispersed by less than 1 ms.

reflected from the F layer above. Thus, there seem to be two left-handed pulses generated 90μs apart that reflect from the F layer. We wish to reiterate that in our full wave solution, which was initiated by a broadband, linearly-polarized pulse, the MF components we imposed reached the rocket very quickly, less than 60μs before the arrival of the nose frequency. But the first of the upgoing MF waves arrived 150μs before the nose frequency. We conclude that the paired pulses were not generated by the stroke but well before it.

We are very excited by the possibility that this event is of the same class as those causing Transionospheric Pulse Pairs (TIPPS) [*Holden et al.*, 1995]. These are as yet unexplained VHF pulse pairs detected on the Blackbeard satellite that are separated on average by 50μs. About 5% have spacing greater than 70μs. We, of course, are just seeing the medium frequency (MF) tip of the TIPP, but there is no reason we know of to believe TIPPS do not extend to frequencies well below the VHF band detected on Blackbeard. Furthermore, if this hypothesis holds up we may have the first linkage between a TIPP and an actual lightning stroke, a relationship which itself is only a hypothesis at this time. We point out that we have not proven a lightning stroke produced the "C"-shaped signal. It is conceivable that the process generating the TIPP also produced the upward-going waves below 200 kHz. Every effort will be made to resolve this ambiguity.

The pulse pairs are embedded in MF emissions over a 500μs time scale that shows frequency banding, and there seem to be associated VLF signals in the passband below 175 kHz during this time as well, unrelated to the stroke itself.

The instruments flown here are frequency-extended versions of those flown in the 1988 thunderstorm overflight of a smaller thunderstorm cell [*Kelley et al.*, 1990]. In that flight very interesting wave-wave coupling phenomena were observed in the ionosphere in a ms period well before the lower frequency VLF waves arrived. We hypothesized then that the high group velocity waves near 100 kHz would have arrived with the highest energy density in the stroke at the leading edge of the electromagnetic pulse. This hypothesis has been verified by the data presented here. We also note the surprisingly large amplitude of lightning-induced waves in the 50-125 kHz range similar to those reported by *Lanzerotti et al.* [1989] in the Earth ionosphere waveguide. Strokes with this character may be quite an important source of ionospheric modification by lightning.

The time scale over which the lightning EMP retains a localized pulse-like nature is about a hundred microseconds even up to the bottom of the F layer. The energy density in this pulse is about 10^{-14} J/m^3, which is about 1% of the plasma energy density in the F-layer valley. Lower in the ionosphere, the pulse energy density is even larger, perhaps by as much as an order of magnitude, since the VLF portion will not yet be dispersed as has begun in these data. At this level of energy density, nonlinear interactions with the plasma are very likely. This aspect of the data will be addressed in a future publication. Elves, typically observed at lower altitudes, are thought to be due to lightning EMP and have a similar time scale as the wave packets reported here [*Fukunishi et al.*, 1996]. We only detect what remains of the transients after absorption in the D layer, but it seems likely that the energy densities may be high enough to produce D-region optical emissions similar to elves.

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