ELF/VLF RADIATION
PRODUCED BY THE 1999 LEONID METEORS

COLIN PRICE AND MOSHE BLUM
Department of Geophysics and Planetary Science, Tel Aviv University, Ramat Aviv
69978, ISRAEL
E-mail: cprice@flash.tau.ac.il

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Abstract. For more than 200 years large meteors entering the atmosphere have been observed to produce audible sounds simultaneously with the optical flash. Since sound waves travel much slower that visible light, the only explanation was that electromagnetic waves produced by the meteors induce a vibration in a transducer close to the observer, producing an audible sound, known as electrophonics. To check this hypothesis, continuous measurements of low frequency electromagnetic waves were performed during the Leonids meteor storm on the night of 18 November, 1999. The analyses of the data indicate distinct electromagnetic pulses produced by the incoming meteors. Many of the weaker incoming meteors that could not be seen visibly were also detected electromagnetically, with a peak rate of approximately 15,000 meteors per hour occurring at the peak of the storm, nearly 50 times the visible rate.

Keywords: Electrophonics, ELF, Leonids 1999, meteors, radio waves, VLF

1. Introduction

For generations there have been claims that meteors entering the earth's atmosphere produce an audible sound simultaneously with the optical signature produced by the incoming meteor (Blagdon, 1784; Udden, 1917; Romig and Lamar, 1963; Andres *et al.*, 1969; Keay, 1980; Keay, 1993). It was difficult to explain these sounds being produced by shock waves or other acoustic signals produced by the meteorite itself, since given the distance of the meteor from the observer, there should always be a time delay between the optical and audible signals. However, if the meteor produced an electromagnetic wave in the audible frequencies, then this wave would reach the observer at the same instance as the visible light (Hawkins, 1958; Beech *et al.*, 1995). This low frequency wave could induce oscillations, vibrations, and sounds from many objects near the observer. Hence, any electrically conducting body (plants, hair, wires, metal sheets, speakers, fences, spectacles, etc.) could vibrate at audible frequencies, giving the observer the perception that the sound was produced by the meteor (Udden, 1917). This phenomenon is known as electrophonics. It is interesting to note that some observations mention sounds being heard before any optical flash in the sky (Nininger, 1939; Keay, 1980), allowing the observers to focus their attention in a particular direction before seeing the meteor burning up in the atmosphere.

We have tested this hypothesis by attempting to measure the ELF/VLF radiation from the meteors during the 1999 Leonid meteor storm. Here, we report a strong increase of VLF detections with unusual spectral signature that coincide with the peak of the storm.

2. Measurements

During the Leonids meteor storm on 18 November, 1999, electromagnetic measurements were continuously recorded to try and detect these radio waves produced by meteors. Since the best viewing location for the 1999 meteor shower was the Middle East, we were ideally located for this task. A permanent field site for observing ELF/VLF signals is located at the Desert Research Institute of Ben-Gurion University, at Sde Boker in the Negev Desert (30 N, 34 E). The antenna is designed to pick up very weak signals in the extremely low frequency (ELF: 100 Hz $< f <$ 3000 Hz) and the very low frequency (VLF: 3 kHz $< f <$ 50 kHz) range for use in lightning research. However, these frequencies are exactly those expected to be produced by meteors (Keay,1980) and, therefore, our setup was ideal for studying the meteor signals. The ELF/VLF antenna is 10 meters high, with two orthogonal triangular loops, each with a baseline of 18 meters, height 9 meters, giving an area of approximately 81 m^2 for each loop. One loop is aligned in the magnetic north-south direction, with the other along the magnetic east-west bearing. The sensitivity of the system in the broadband range (0.1–50 kHz) is 6 μV/meter. The dynamic range of the antenna/preamp set is approximately 100 dB, allowing us to detect lightning discharges from great distances. The data were collected on digital audio tapes (DAT) with GPS timing, to correlate with the optical measurements. The data were later digitized at 100 kHz.

3. Results

Since our antenna is sensitive to both lightning discharges and possible meteor pulses, we needed to differentiate between the lightning and meteor signals. In Figure 1 we see an example of the north-south magnetic field time series, in the 0.1--50 kHz range, produced by a lightning discharge (Figure 1a) and a meteor (Figure 1b) on the night of the meteor storm. There are two distinct differences between the lightning and the meteor signal. First, while the lightning pulse lasts no longer than 1 millisecond, the meteor pulse continues for up to 10 milliseconds. Although this is longer that the lightning pulse, this is much shorter than the duration of the optical meteor trail which can last for seconds. Second, the amplitude of the lightning pulse is much larger than the meteor pulse. These time series are from the same data file and, therefore, the relative amplitudes can be directly compared. It is important to note that at the time of sampling thunderstorms were observed over the Balkans by the Leonid MAC team, but there were no thunderstorms within a 2,000 km radius of the Negev field site.

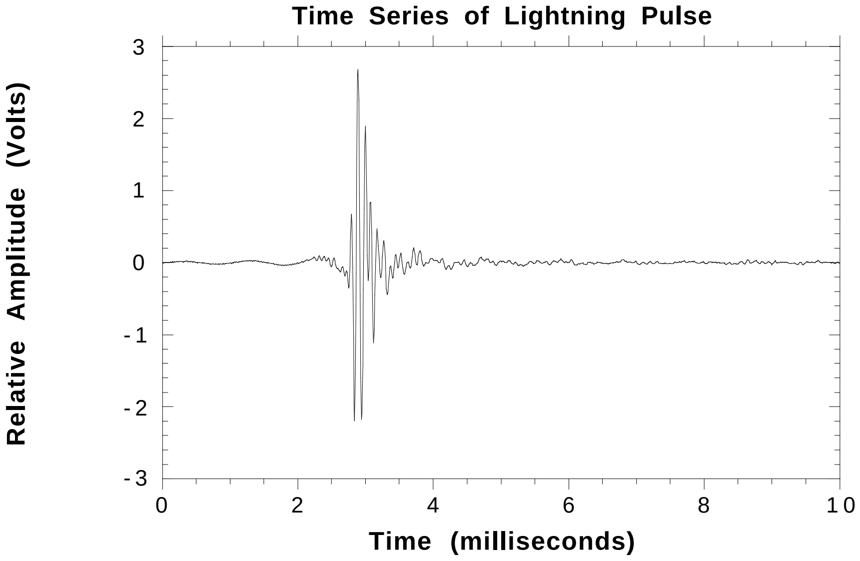

Figure 1a. Time series of lightning on the night of 18 November, 1999.

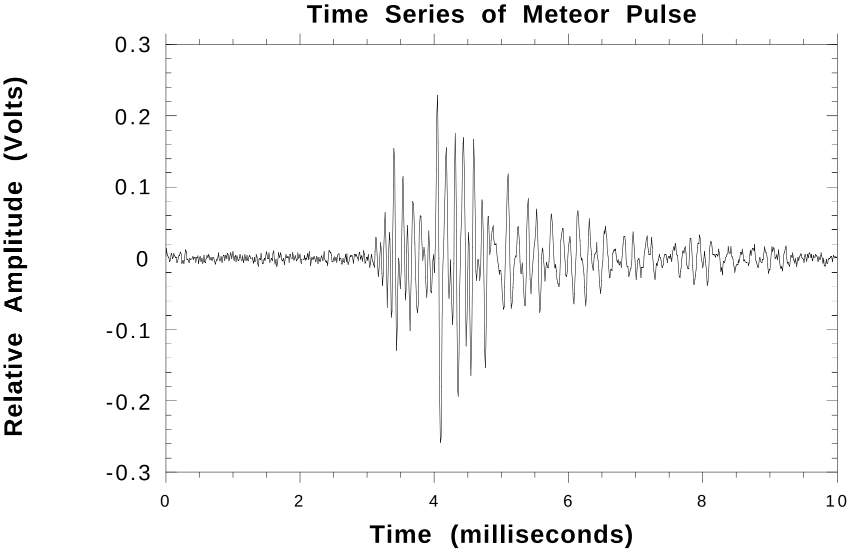

Figure 1b. Time series of a meteor electromagnetic pulses on the night of 18 November, 1999.

In addition to the obvious differences between the lightning and meteor time series, their respective spectra also show significant differences. It is well documented that the spectrum of distant lightning shows a maximum near 6 kHz (Volland, 1982). This is shown from our measurements in the Negev desert during August, 1999, when no precipitation or lightning activity occur in the Middle East (Fig 2a). This spectrum is an average of approximately 35 individual spectra. The maximum around 5 kHz agrees well with measurements of lightning from other parts of the globe. During the night of the Leonids meteor storm (18 November, 1999), very different spectra were obtained due to the incoming meteors (Fig 2b). Here too the spectrum represents an average of approximately 35 events.

Unlike the lightning spectra, the meteor spectra shows a minimum near 5kHz, with a large maximum in the ELF range (0.3-1.5 kHz) and an additional weaker maximum around 2 kHz. In the VLF range there appears a weaker, broader maximum between 6-15 kHz. No signal was observed above 20 kHz. The characteristic differences between the lightning and meteor spectra allow for the automatic determination of whether the electromagnetic signal is caused by lightning or by meteors. This enabled us to label the meteor pulses and, therefore, count the number of ELF/VLF meteor signals observed during the night of the 17-18 November, 1999. An example of the dynamic spectrum at the peak of the meteor shower is shown in Figure 3.

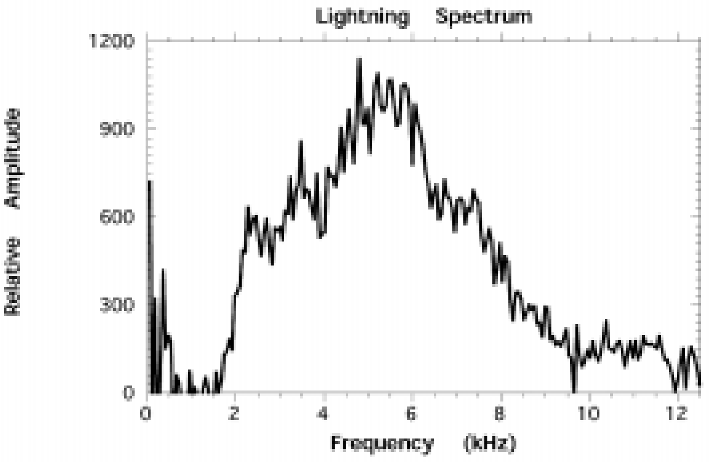

Figure 2a. The mean spectrum of lightning pulses.

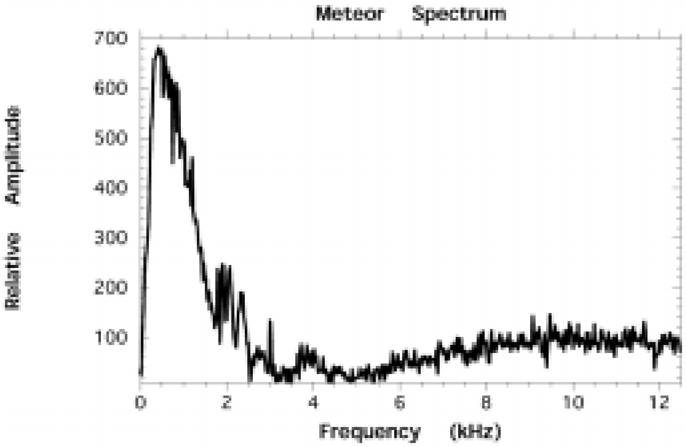

Figure 2b. The mean spectrum of meteor pulses.

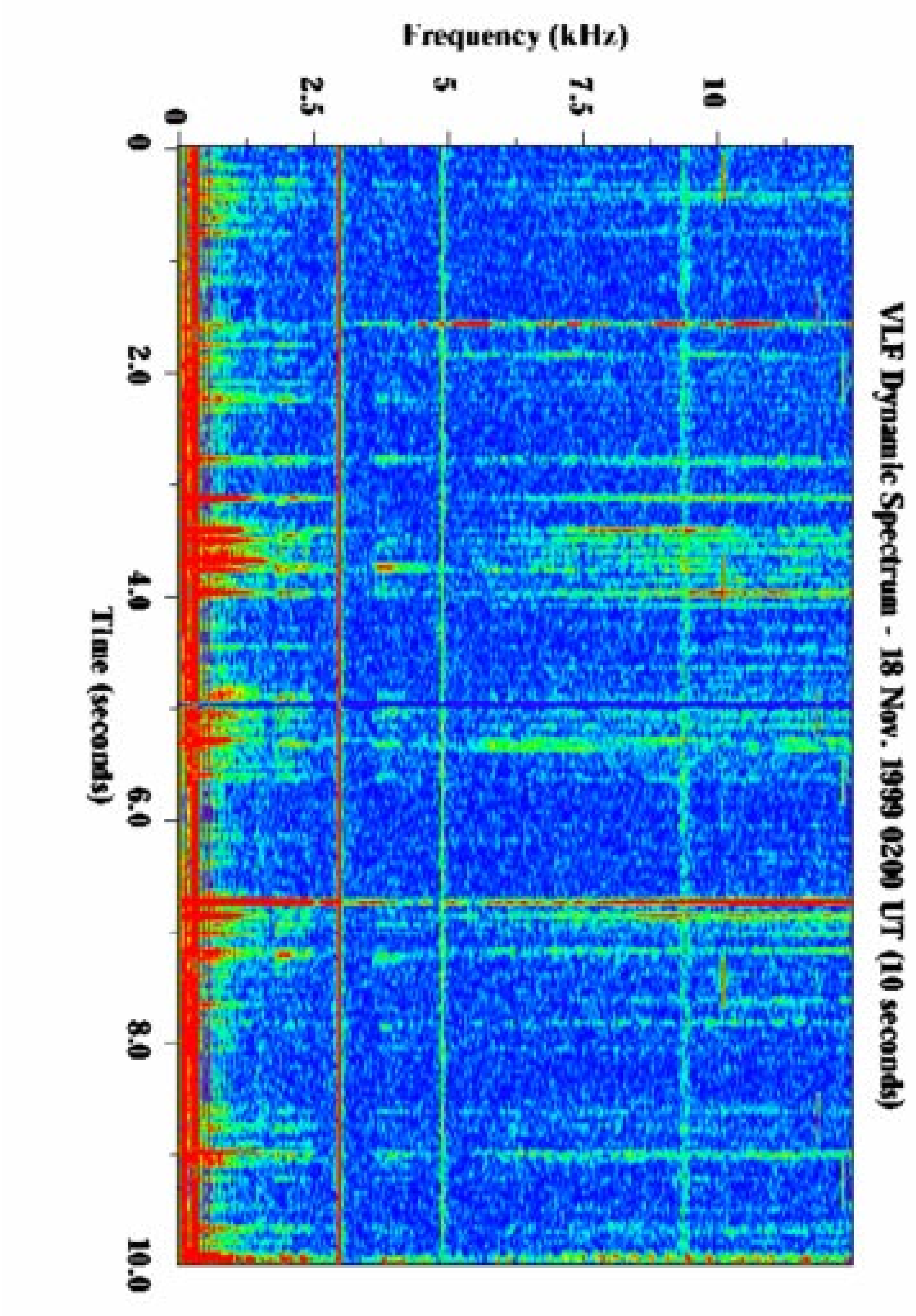

Figure 3. The dynamic spectrum during peak of Leonid meteor shower, around 02:00 UT, 18 August, 1999.

The dynamic spectrum represents only 10 seconds of data, where the spectrum is calculated every 10 milliseconds. The frequency of the 10 millisecond windows is shown on the vertical axis between 0-12.5 kHz, while the color code represents relative amplitude of the signals, red being the largest values. A few features are clearly seen in this 10-second snapshot. The horizontal red lines between 0-0.5 kHz represent the large noise produced by the electric power lines that operate at 50 Hz in Israel, together with all the higher harmonics. The horizontal lines shown at higher frequencies represent the anthropogenic signals from VLF transmitters around the globe, used for navigational purposes. The Russian VLF signals are transmitted in a pulsed format, as can be seen in Figure 3 above 10 kHz. The vertical lines represent the pulses for the individual meteors entering the earth's atmosphere. The mean spectrum of these events is shown in Figure 2b. Up to thirty VLF pulses are observed within this 10-second period. Whether all these VLF pulses are produced by individual meteors, or whether each meteor produces a series of pulses, is still unknown. Correlations with optical measurements will allow us to decipher this uncertainty in the future.

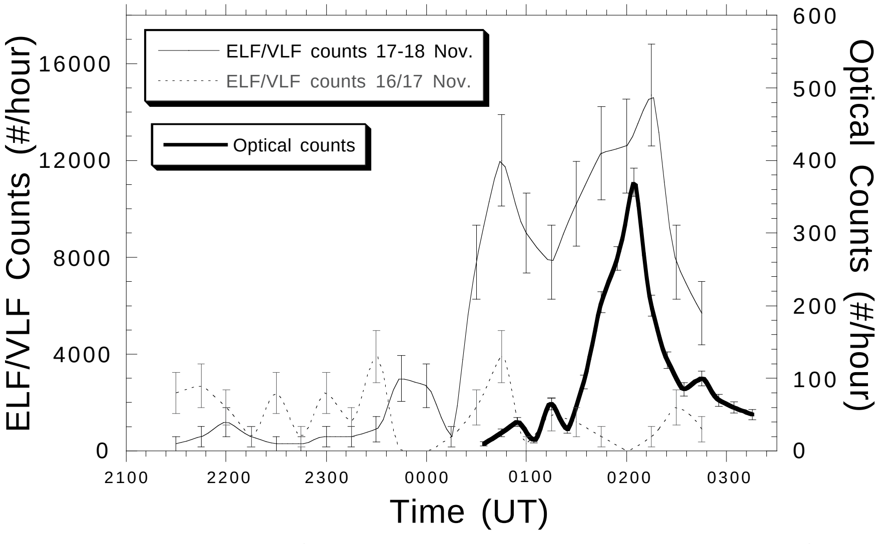

Figure 4. Hourly counts of optically observed meteors during the night of 17-18 November, 1999 (bold line), and the electromagnetically observed meteor counts during the night preceding the meteor shower (16-17 November: dotted line) and the night of the shower (17-18 November: solid thin line).

Based on the spectrum shown for the meteors in Figure 2b we used the 1.2 kHz frequency band to automatically identify the presence of a meteor in the dynamic spectrum. As shown above, this is exactly where the lightning signal is weakest. Although the meteor signal is stronger at lower frequencies (0.5 kHz), noise interference from the power line harmonics produces problems deciphering weak meteor signals at these frequencies. Using a specified threshold for the meteor signal at 1.2 kHz, we were able to count the number of electromagnetic pulses produced by the meteors. Since we have six hours of continuous recordings from 21:30 UT on the 17th November through 03:30 UT on the 18th, we were able to produce a time series of the hourly rate of electromagnetic meteor pulses, to compare with the local incident optical meteor observations (Brosch *et al.*, this issue)(Figure4). The ELF/VLF hourly rate obviously depends on the threshold chosen, making our algorithm more or less sensitive to weak pulses.

As is clearly shown using the ELF/VLF method of counting the meteor flux, a peak flux of 15,000 per hour was detected, relative to 350 per hour using optical methods. Therefore, the ELF/VLF method detected nearly 50 times more meteors than the optical method. It should be pointed out that the radio pulse counts were obtained by sampling small segments of data (10 seconds) at 15 minute intervals. This was done to save time in data analysis, since each 10 seconds of ELF/VLF data represents 1 million data points. Analysis at finer temporal resolution will be done in the future. The ELF/VLF count maximum was observed in the sample taken at 02:15 UT, five to ten minutes after the optical peak of the meteor shower. This time correlation confirms that the electromagnetic pulses observed were produced by the incoming meteors. A similar analysis for the previous night (16-17 November, Figure 4) shows no such enhancement of the pulse counts. Although the ELF/VLF antenna observes signals from all directions, and from greater distances than the optical measurements, it is very likely that many weak meteors that cannot be seen optically still produce electromagnetic signals. However, with all the observers in the field during this night, no reports of audible sounds associated with the meteors could be found.

It is possible to estimate the effective area of detection at the peak of the shower, if we know the count rate, and the limiting magnitude of the meteors we detect. It is normally assumed that the limiting magnitude for observing optical meteors is +6.5. However, for the ELF/VLF meteors the limiting magnitude may be higher (smaller meteors). The effective area can be calculated as A = counts / 0.82 x $r^{\Delta m}$ x sin(hr) km^2, where 0.82 (km^{-2} hr^{-1}) is the peak influx of Leonids brighter than +6.5 magnitude (Gural and Jenniskens, this issue), r is the magnitude distribution index of approximately 2.1, hr is the height of the radiant position (70°), and Δm is the magnitude difference between our ELF/VLF limiting magnitude and the standard +6.5 limiting factor for the optical meteors. If we see only the meteors brighter than +6.5 then $\Delta m = 0$, and the effective area is 17,000 km^2. If we manage to detect meteors brighter than +7.5, then our effective area of detection is 36,000 km^2.

The electromagnetic flux rate shows an additional interesting feature not shown in the optical counts. A secondary peak of the shower is shown at 00:45:00 UT, an hour and a half before the optical peak. It is possible that the visible meteors represent only a small subset of the total meteors. From the ELF/VLF counts it appears that there existed a maxima of small sub-visible meteors 90 minutes before the optical peak.

4. Discussion

In addition to the advantage of being able to detect weak meteors, the electromagnetic method of determining the meteor fluxes can also be used during daylight hours, and in all weather conditions. Our measurements provide convincing proof that meteors do produce electromagnetic radiation as they enter the atmosphere, which can explain the sounds heard during observations of large fireballs (electrophonics).

The only theoretical explanation of how these radio waves are produced has been presented by Keay (1993, 1995). However, our measurements challenge the theory with new questions: How do sub-visible and small meteors produce radio signals? The theory applies only to large bolides (fireballs). Why do the radio signals never last more than 10 milliseconds? The theory explains radio signals lasting up to tens of seconds. Why do some people hear sounds before seeing the optical meteor? The theory describes the radio signals produced simultaneously with the bright optical signal. It is clear that more work is needed in this field.

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