AGU PUBLICATIONS

Electromagnetic Detection of ELF/VLF Signals Emitted by Geminids 2017 Meteors

Samaneh Aghelpasand[1], Parvin Howaida[2], Mehran Ahadi[3]

[1] Alzahra University, Department of Physics, Tehran, Iran

[2] Institute for Research in Fundamental Sciences (IPM), School of Astronomy, Tehran, Iran

[3] Amirkabir University of Technology, Department of Physics and Energy Engineering, Tehran, Iran

Corresponding author: Samaneh Aghelpasand (S.Aghelpasand@student.alzahra.ac.ir and Samane.aghelpasand@gmail.com)

Key Points:

- 1. Challenges in associating ELF/VLF signals with meteors due to noise from lightning and man-made sources hinder direct link establishment.
- 2. Studies suggest different models to explain audible sounds from meteors, including the Photoacoustic and Electrophonic effects.
- 3. Meteor detection in ELF/VLF bands during the Geminids meteor shower involved analyzing spectrograms to correlate radio with visual.

Abstract

Skywatchers have been fascinated by ’meteors’ radiant glow for years. Early reports show that the sounds of these luminous meteors have been recorded, a rare occurrence due to ’sound’s slower speed compared to light. Astronomers studying meteors suggest that ionized tails can produce electromagnetic waves and their investigations show it is in ELF and VLF bands, causing nearby metal objects to vibrate and create audible sounds, known as the Electrophonic effect. These waves travel at the speed of light, confirmed by various measurements. This study details the detection of such signals during the 2017 Geminids meteor shower using a loop antenna and SuperSID monitor, distinguishing signals from local and natural noise. Factors affecting data recording are also discussed. These findings shed light on an overlooked aspect of meteor observations, guiding future research in this field.

Plain Language Summary

Researchers have discovered that meteors can create sounds that people can hear. They believe that when meteors pass by, they produce electromagnetic waves that make nearby metal objects vibrate and create noises. By using special equipment during the 2017 Geminids meteor shower, we were able to identify and separate these signals from other background noises. This finding reveals a new and interesting aspect of meteor observations, providing direction for future studies in this area.

1 Introduction

When observing bright meteors, it has been reported that a sound is heard, which is believed to be produced by the meteors themselves (Halley, 1714) and Blagdon (1784) did the first scientific study on this phenomenon. However, considering that light travels faster than sound, this phenomenon seems strange. Based on the Electrophonic effect, meteors generate EM waves that can be converted into audible sounds by metal objects near observers (Keay, 1980). Many researchers, such as Keay (1980), and Beech et al. (1995), have extensively studied the relationship between meteors and EM signals, particularly in the ELF/VLF range, aiming to connect these signals with observable meteor events. Keay (1991) established criteria for perceiving electrophonic sound, suggesting a minimum fireball brightness and duration needed for these EM signals to be heard. Beech et al. (1995), Garaj et al. (1999), and Price and Blum (2000) recorded ELF/VLF signals related to meteor events, attempting to correlate these signals with visual records but faced challenges in clear association due to various factors such as equipment limitations and timing issues. Studies encountered difficulties distinguishing genuine meteor-related ELF/VLF signals from the prevalent background ELF/VLF noise caused by lightning and man-made sources like naval transmissions and power line harmonic radiation.

Price and Blum (2000) reported detecting ELF/VLF signals alongside fireballs during the 1999 Leonid meteor storm. However, they faced challenges in definitively associating these ELF/VLF signals with specific fireball occurrences due to timing discrepancies in their optical records. They noted that the general occurrence of ELF/VLF signals was more prevalent during the peak of the meteor storm. Additionally, they argued that the ELF/VLF signals they detected peaked at a frequency distinct from those typically associated with lightning, suggesting an alternate source, possibly fainter meteors. Despite these observations, they could not establish a direct link between the recorded ELF/VLF signals and individual fireball events.

Recently, Spalding et al. (2017) proposed that intense modulated light at frequencies ≥ 40 Hz can generate simultaneous sounds by heating common dielectric materials such as hair, clothing, and leaves through radiation. This heating results in small pressure oscillations in the air contacting the absorbers, known as the Photoacoustic effect. According to their calculations, meteors with a brightness of −12 dB can generate audible sound at around ~25 dB. However, this effect can not explain the sounds from fainter meteors.

Kelley and Price (2017) proposed a model that can explain the sound from fainter meteors. They used data from Arecibo's radar system for their model. Their model conveys that the head echo caused by the plasma of the meteor produces an electric current perpendicular to the meteor's track, generating a Hall current that extends to the E region of the ionosphere above the observer. This large current can generate ELF/VLF signals to the ground and cause the Electrophonic effect. This model predicts that any meteor with dense enough plasma to be detected at GHz frequency by radar as a head echo should be able to produce electrophonic sound audible by the human ear within a range of 100 km.

Our study analyzes 'meteors' direct ELF/VLF emissions during the peak of the Geminids meteor shower 2017, known for its elevated ZHR (Zenithal Hourly Rate), which is usually about 100 meteors per hour. Our methodology involves identifying the meteor's frequency-time diagram (spectrogram) amidst other recognized local and natural noises in these frequency bands. By comparing visual meteor observations and radio-based detections, an attempt is made to identify specific spectrogram patterns related to meteors. Section 2 provides a detailed description of the observational setup and data acquisition. Section 3 presents the spectrograms of other ELF/VLF sources that, in the case of meteor detection, are considered as noise. Section 4 shares our results regarding meteor detection. Finally, section 5 discusses the challenges related to the detection of meteors.

2 The Observational Setup and Data Acquisition

For this observation, The SuperSID monitor (Figure 1), provided by Stanford University, was employed as the receiver within the ELF/VLF frequency ranges. This device is primarily designed to identify alterations in the Earth's ionosphere resulting from solar flares and similar disruptions. However, since SuperSID is capable of capturing emissions within ELF/VLF spectrum, the device can also be utilized to receive signals from various sources, including meteors.

Figure 1: The Super SID receiver used in this experiment

Given that meteor signals can originate from any direction in the sky rather than just from the apparent radiant of the meteor shower, employing an omnidirectional antenna is essential. Small loop antennas, with a perimeter much smaller than a wavelength, tend to exhibit a more omnidirectional radiation pattern (Stutzman and Thiele, 2012). Therefore, a 1-meter-in-diameter air core loop antenna with 400 meters of insulated copper wire is fabricated to detect signals within the ELF/VLF ranges (Figure 2). Furthermore, an external sound card and a computer are utilized to save the data from the receiver. An overview diagram of the setup is provided in Figure 3.

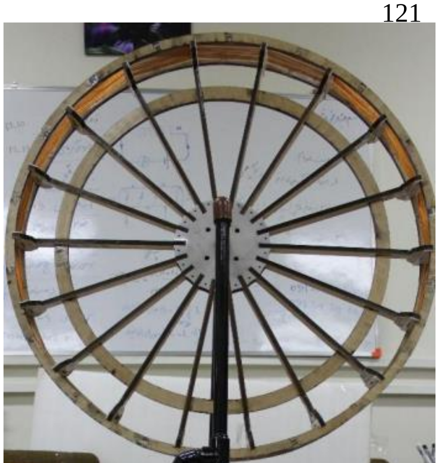

Figure 2: The 1-meter-in-diameter air core loop antenna with 400 meters of copper wire used in this experiment

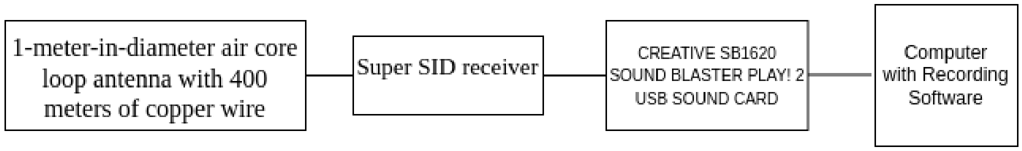

Figure 3: Block diagram of the setup used for the experiment

The observation was conducted in a remote location in Semnan, Iran, with a latitude of 34.76° and a longitude of 52.17°. This location provides an ideal environment for minimizing unwanted noise and interference during the observations. Its remote nature allows for the capture and study of natural phenomena without the influence of human-generated disturbances, leading to more accurate and reliable data collection and analysis. The observation and recording took place between 10:30 PM, Dec 13th, 2017, and 12:45 AM, Dec 14th, 2017, at the peak of the Geminids meteor shower. Many events were recorded during this time, along with a background hum noise. However, when compared to city noises, the data appears significantly cleaner.

3 Distinguishing Meteor Signals in Spectrogram Amidst Unwanted Radiations

The ELF and VLF frequency bands containing meteor signals often experience high levels of noise and interference. The variety of unwanted radiators in this spectrum emphasizes the importance of identifying the different environmental sources that could possibly occur in the recorded signals. Lightning is one of 'Earth's most significant and dynamic natural sources of ELF/VLF radiations, with hundreds of pulses occurring in a single second at high speeds (Rust, 1988). This phenomenon, coupled with the Earth-ionospheric waveguide (EIWG) that reflects these electromagnetic waves at altitudes ranging from 50 to 150 kilometers, can result in the detection of lightning from distant locations, further increasing noise levels in this frequency range and registering various types of lightning discharges. Therefore, it is crucial to distinguish between signals originating from meteors and those from other sources, such as lightning, to identify and study the signals produced by meteors accurately.

Radio continuum radiation generated by lightning, referred to as lightning's signal, can be categorized into three distinct types. These categories are known as Sferic, Chorus, and Whistler (Volland, 1995). Each type represents a specific pattern in the spectrogram and provides valuable insights into the nature and behavior of these electromagnetic phenomena.

3.1. Sferics

Sferics are distinct pulses of thunder and lightning that travel through the EIWG without undergoing significant attenuation. These electromagnetic signals can travel long distances, reaching several kilometers (Potter, 1951). Their spectrograms are characterized by their sharp decay and energy spread across various frequencies, originating in the vicinity of thunder and lightning occurrences. Figure 4 depicts the spectrogram of various sferics radiations above 5 kHz, visible as random parallel vertical lines. The horizontal lines represent the noise created by inductive fields from power lines in the vicinity of the receiving equipment.

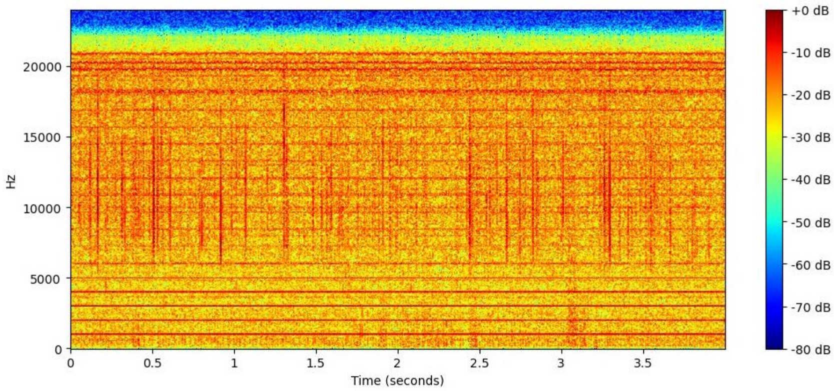

Figure 4: Sferics spectrogram (random vertical orange sharp lines) detected by the equipment used in this experiment

3.1.2. Tweeks

A specific type of atmospheric phenomenon, tweeks, involves the refraction of certain Sferics through various ionosphere layers. This process provides valuable information about the 'ionosphere's electron density, reflection height, and the distances traveled by the reflected wave(Hiroyo et al., 2003). Spectrogram patterns of these refracted Sferics can be used to analyze these properties. The cutoff frequency of the EIWG, around 1.8 kHz (Budden, 1961), causes noticeable dispersion in these waves. Reflection by the lower ionosphere renders them valuable for studying altitudes below 100 km.

The strong dispersion near the 'EIWG's cutoff frequency is revealed by tweek atmospherics. The cutoff frequency, f_c, can be obtained from the spectrogram of tweeks, allowing for the estimation of the local EIWG height h using (1), where c = 299792458 m/s is the velocity of light in the vacuum (Yamashita, M., 1978).

$$f_c=c/2h \tag{1}$$

Distinct electromagnetic radiation patterns known as modes—transverse electric (TE) and transverse magnetic (TM)—are propagated within the EIWG. Each mode can have various orders and propagates only above its corresponding cutoff frequency to satisfy the boundary conditions of the waveguide. The cutoff frequency of the *m*th mode is represented by: (Budden, 1961)

$$f_{cm}=\mathrm{mc}/2\mathrm{h} \tag{2}$$

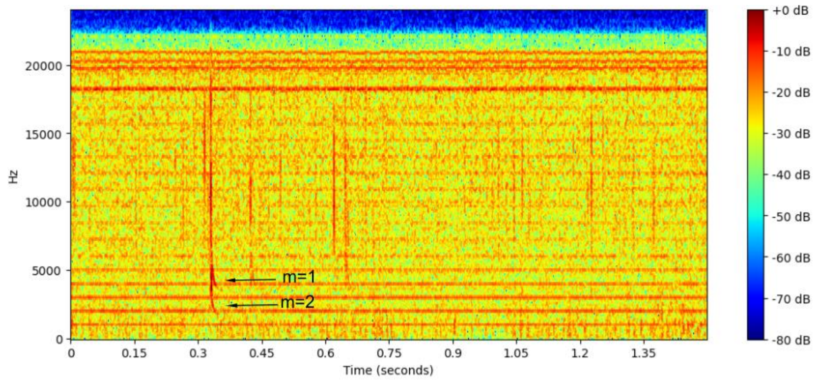

Figure 5: tweeks spectrogram detected by the equipment used in this experiment

Approximately ~6000 sferics and ~491 tweeks were recorded during our observation. Among the tweeks, instances were observed with m=1 and m=2 propagation modes, with 80% of occurrences attributed to m=1 and 20% to m=2; no higher modes were detected. The average cutoff frequency for m=1 was approximately ~2.3 kHz, while for m=2, it was around ~4 kHz, leading to an estimate of the ionospheric reflection height to be about ~70 km. It is worth noting that other types of lightning signals were not detected during our observation, therefore we omitted their explanation.

3.4. Meteors

The distinction between meteor signals and other noise sources also involves analyzing spectrum characteristics in addition to identifying lightning patterns. Meteor signals exhibit their highest intensity below 2 kilohertz, primarily in the ELF range, while lightning signals reach their maximum intensity beyond that, mainly in the VLF range. This difference serves as a significant criterion for the differentiation. (Price & Blum, 2000)

4 Meteor Detection

Our goal was to pinpoint a distinctive signal in the ELF/VLF band, characterized by three specific features. Initially, it had to be distinguishable from recognized signals like different types of lightning signals (sferics, tweeks, etc.). Secondly, it was expected to exhibit random pulses over time. Lastly, this signal was required to show a correlation with the visual observational data and prior studies.

Based on previous ELF/VLF observations of the Geminids conducted by astronomers in Iran in 2011 (Lashkari et al., 2011), it was reported that the detected meteors had frequencies ranging from several Hz to 2 KHz and exhibited properties mentioned earlier. We sought similar spectrogram patterns in our observations. The durations of meteor signals during their occurrence are random, and most of them match with the visual observations. Some occurences could belong to meteors that were too weak to produce visible light or were missed by the team and were considered to be errors. Figure 6 shows a sample of the signals we acquired using the setup, with the accepted meteor signatures identified. We also detected several signals stronger than the meteors, as shown in Figure 7, that we could not find their pattern reported in the literature to the best of our knowledge, which are highly likely to be originated from fireballs or bolides.

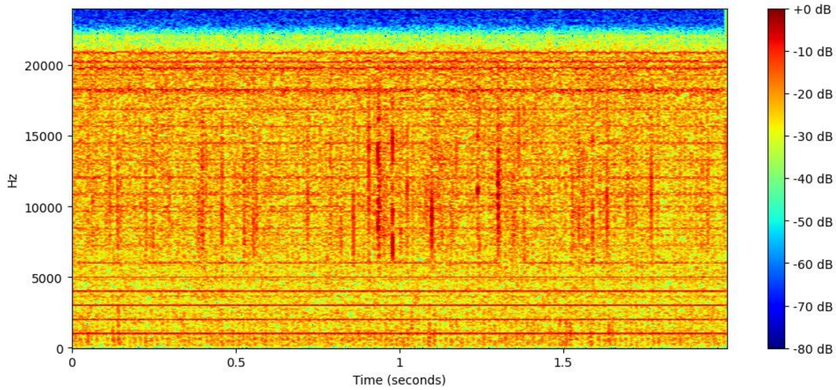

Figure 6: Spectrogram of some meteor signatures matching with visual observations and previous studies

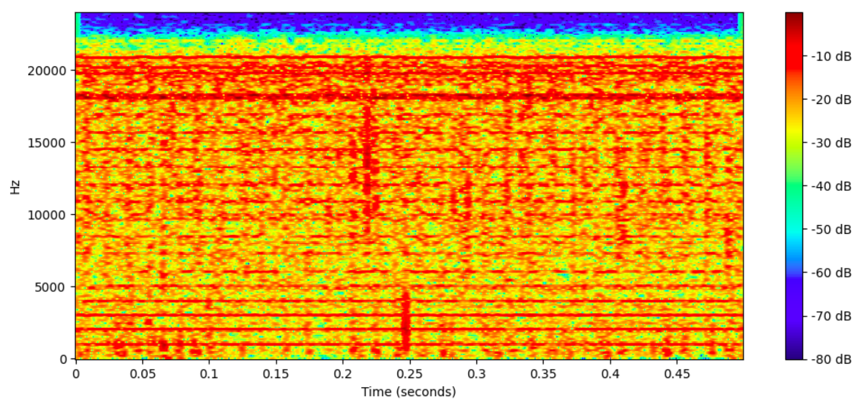

Figure 7: Spectrogram of signatures likely related to fireballs or bolides

5 Conclusions

Examining meteor radio observations provides valuable insights into the mechanism of EM wave production in the 'Earth's ionosphere. Meteors, being the only objects consistently entering the Earth's ionosphere and producing electromagnetic waves, contribute to an improved understanding of the ionosphere across different locations and seasons. Through increased observations, a more comprehensive understanding of meteor features can be achieved by examining various meteor showers, enabling the identification of correlations such as velocity, distance, and occurrence rate.

We utilized a setup consisting of the SuperSID receiver and a fabricated loop antenna. The setup is operated in a remote location where the local ionosphere was never studied before to minimize the noises and interferences to ensure a high-quality recording. The signal is recorded in parallel with logging the visual appearances of the meteors. The recordings were analyzed considering the known patterns of different potential interference and noise sources, and the possible meteor EM radiations were identified.

There is still no clear explanation as to why meteors can produce EM waves in these specific frequencies and why we can hear their hissing sound but not the electromagnetic waves related to lightning. This field of study is ongoing and requires dedicated observations with improved setups to progress further.

Acknowledgments

We are grateful to Stanford University for providing the receiver used in this study. We would also like to express our sincere gratitude to Prof. Jack Gallimore, Amir Kayone Lashkari, and Prof. Morris Cohen for their invaluable assistance and support throughout this project.

Open Reasearch

Data Availability Statement

The data used in this study was collected independently using a dedicated antenna and receiver. The collected data has been stored as WAV files and is publicly archived in the Zenodo repository at https://zenodo.org/records/10818759. The analysis was conducted using Python 3.11.5, and the Jupyter notebook used to plot the spectrograms is available in the Zenodo repository at https://zenodo.org/doi/10.5281/zenodo.10818599. Additionally, the executed notebook is available for public access in the Binder repository at https://mybinder.org/v2/zenodo/10.5281/zenodo.10903958/. It is possible to reproduce the data visualizations presented in this article by modifying the time range and file repository.

References

1. Halley, E. (1714), An account of several extraordinary meteors or lights in the sky, *Philosophical Transactions of the Royal Society of London*, 29, 159–164. doi:10.1098/rstl.1714.0018

2. Blagdon, C. (1784), An account of some late fiery meteors; with observations. *Philosophical Transactions of the Royal Society of London,* 74 , 201–232. https://www.jstor.org/stable/106587?seq=1

3. Keay, CS. (1980), Anomalous sounds from the entry of meteor fireballs. *Science*, 210(4465), 11-5. doi:10.1126/science.210.4465.11. PMID: 17751127.

4. Beech, M., Brown, P., & Jones, J. (1995), VLF detection of fireballs. *Earth, Moon, and Planets*, 68, 181-188. doi:10.1007/BF00671507.

5. Keay, C. S. L. (1991), Meteor fireball sounds identified. *Lunar and Planetary Inst., Asteroids, Comets, Meteors,* 297-300. https://adsabs.harvard.edu/full/1992acm..proc..297K

6. Garaj, S., Vinković, D., Zgrablić, G., Kovacic, D., Gradecak, S., Biliskov, N., Grbac, N., & Andreic, Z. (1999), Observational detection of meteor-produced VLF electromagnetic radiation. *Fizika A*. urn:nbn:hr:217:524298

7. Price, C., & Blum, M. (2000), ELF/VLF radiation produced by the 1999 Leonid meteors. *Earth, Moon, and Planets*, 82-83, 545-554. doi:10.1023/A:1017033320782.

8. Spalding, R.& Tencer, J., Sweatt, W., Conley, B., Hogan, R., Boslough, M., Gonzales, G., & Spuný, P. (2017), Photoacoustic Sounds from Meteors. *Scientific Reports* 7, 41251. doi:10.1038/srep41251

9. Kelley, M., & Price, C. (2017). On the electrophonic generation of audio frequency sound by meteors. Meteor-Generated Audio Frequency Sound. *Geophysical Research Letters*, 44. doi:10.1002/2017GL072911.

10. Rust, W. (1989), The Lightning Discharge. Martin A. Uman. *Academic Press, San Diego, CA*, 1987. xii, 377 pp., illus. $49. *International Geophysics Series*, 39. *Science (New York, N.Y.)*. 242. 1713-4. doi:10.1126/science.242.4886.1713.

11. Volland, H. (Ed.). (1995). Handbook of Atmospheric Electrodynamics, *CRC Press*, 3. doi:10.1201/9780203713297

12. Potter, R. K. (1951), Analysis of Audio-Frequency Atmospherics. *Proceedings of the IRE*, 39, 1067-1069, doi:10.1109/JRPROC.1951.273750.

13. Ohya, H., Nishino, M., Murayama, Y., & Igarashi, K. (2003). Equivalent electron density at reflection heights of tweek atmospherics in the low- middle latitude D-region ionosphere. *Earth Planets Space*. 55. 627-635. doi:10.1186/BF03352469.

14. Budden, K.G. (1961), The wave-guide mode theory of wave propagation. *London Englewood Cliffs N.J: Logos Press; Prentice-Hall.*

15. Yamashita, M. (1978), Propagation of tweek atmospherics. *Journal of Atmospheric and Terrestrial Physics*, 40, 151-156. doi:10.1016/0021-9169(78)90019-3

16. Price, C. & Blum, M. (2000). ELF/VLF radiation produced by the 1999 Leonid meteors. *Earth Moon and Planets*. 82-83. 545-554. doi:10.1023/A:1017033320782

17. Lashkari, A.K., Zeinali, M.M., & Taraz, M.(2015), Detecting of ELF/VLF signals generated by GEMINIDS 2011 meteors. *Earth Moon Planets*, 115, 23–30, doi:10.1007/s11038-015-9463-0

18. Helliwell, R.A. (1965), Whistlers and Related Ionospheric Phenomena. *Stanford University Press*

19. Stutzman, W.L, & Thiele, G.A. (2012), Antenna Theory and Design. *John Wiley & Sons*, 80-89

Electromagnetic Detection of ELF/VLF Signals Emitted by Geminids 2017 Meteors

Samaneh Aghelpasand[1], Parvin Howaida[2], Mehran Ahadi[3]

[1] Alzahra University, Department of Physics, Tehran, Iran

[2] Institute for Research in Fundamental Sciences (IPM), School of Astronomy, Tehran, Iran

[3] Amirkabir University of Technology, Department of Physics and Energy Engineering, Tehran, Iran

Corresponding author: Samaneh Aghelpasand (S.Aghelpasand@student.alzahra.ac.ir and Samane.aghelpasand@gmail.com)

Key Points:

1. Challenges in associating ELF/VLF signals with meteors due to noise from lightning and man-made sources hinder direct link establishment.
2. Studies suggest different models to explain audible sounds from meteors, including the Photoacoustic and Electrophonic effects.
3. Meteor detection in ELF/VLF bands during the Geminids meteor shower involved analyzing spectrograms to correlate radio with visual.

Abstract

Skywatchers have been fascinated by ’meteors’ radiant glow for years. Early reports show that the sounds of these luminous meteors have been recorded, a rare occurrence due to ’sound’s slower speed compared to light. Astronomers studying meteors suggest that ionized tails can produce electromagnetic waves and their investigations show it is in ELF and VLF bands, causing nearby metal objects to vibrate and create audible sounds, known as the Electrophonic effect. These waves travel at the speed of light, confirmed by various measurements. This study details the detection of such signals during the 2017 Geminids meteor shower using a loop antenna and SuperSID monitor, distinguishing signals from local and natural noise. Factors affecting data recording are also discussed. These findings shed light on an overlooked aspect of meteor observations, guiding future research in this field.

Plain Language Summary

Researchers have discovered that meteors can create sounds that people can hear. They believe that when meteors pass by, they produce electromagnetic waves that make nearby metal objects vibrate and create noises. By using special equipment during the 2017 Geminids meteor shower, we were able to identify and separate these signals from other background noises. This finding reveals a new and interesting aspect of meteor observations, providing direction for future studies in this area.

1 Introduction

When observing bright meteors, it has been reported that a sound is heard, which is believed to be produced by the meteors themselves (Halley, 1714) and Blagdon (1784) did the first scientific study on this phenomenon. However, considering that light travels faster than sound, this phenomenon seems strange. Based on the Electrophonic effect, meteors generate EM waves that can be converted into audible sounds by metal objects near observers (Keay, 1980). Many researchers, such as Keay (1980), and Beech et al. (1995), have extensively studied the relationship between meteors and EM signals, particularly in the ELF/VLF range, aiming to connect these signals with observable meteor events. Keay (1991) established criteria for perceiving electrophonic sound, suggesting a minimum fireball brightness and duration needed for these EM signals to be heard. Beech et al. (1995), Garaj et al. (1999), and Price and Blum (2000) recorded ELF/VLF signals related to meteor events, attempting to correlate these signals with visual records but faced challenges in clear association due to various factors such as equipment limitations and timing issues. Studies encountered difficulties distinguishing genuine meteor-related ELF/VLF signals from the prevalent background ELF/VLF noise caused by lightning and man-made sources like naval transmissions and power line harmonic radiation.

Price and Blum (2000) reported detecting ELF/VLF signals alongside fireballs during the 1999 Leonid meteor storm. However, they faced challenges in definitively associating these ELF/VLF signals with specific fireball occurrences due to timing discrepancies in their optical records. They noted that the general occurrence of ELF/VLF signals was more prevalent during the peak of the meteor storm. Additionally, they argued that the ELF/VLF signals they detected peaked at a frequency distinct from those typically associated with lightning, suggesting an alternate source, possibly fainter meteors. Despite these observations, they could not establish a direct link between the recorded ELF/VLF signals and individual fireball events.

Recently, Spalding et al. (2017) proposed that intense modulated light at frequencies ≥40 Hz can generate simultaneous sounds by heating common dielectric materials such as hair, clothing, and leaves through radiation. This heating results in small pressure oscillations in the air contacting the absorbers, known as the Photoacoustic effect. According to their calculations, meteors with a brightness of −12 dB can generate audible sound at around ~25 dB. However, this effect can not explain the sounds from fainter meteors.

Kelley and Price (2017) proposed a model that can explain the sound from fainter meteors. They used data from Arecibo's radar system for their model. Their model conveys that the head echo caused by the plasma of the meteor produces an electric current perpendicular to the meteor's track, generating a Hall current that extends to the E region of the ionosphere above the observer. This large current can generate ELF/VLF signals to the ground and cause the Electrophonic effect. This model predicts that any meteor with dense enough plasma to be detected at GHz frequency by radar as a head echo should be able to produce electrophonic sound audible by the human ear within a range of 100 km.

Our study analyzes 'meteors' direct ELF/VLF emissions during the peak of the Geminids meteor shower 2017, known for its elevated ZHR (Zenithal Hourly Rate), which is usually about 100 meteors per hour. Our methodology involves identifying the meteor's frequency-time diagram (spectrogram) amidst other recognized local and natural noises in these frequency bands. By comparing visual meteor observations and radio-based detections, an attempt is made to identify specific spectrogram patterns related to meteors. Section 2 provides a detailed description of the observational setup and data acquisition. Section 3 presents the spectrograms of other ELF/VLF sources that, in the case of meteor detection, are considered as noise. Section 4 shares our results regarding meteor detection. Finally, section 5 discusses the challenges related to the detection of meteors.

2 The Observational Setup and Data Acquisition

For this observation, The SuperSID monitor (Figure 1), provided by Stanford University, was employed as the receiver within the ELF/VLF frequency ranges. This device is primarily designed to identify alterations in the Earth's ionosphere resulting from solar flares and similar disruptions. However, since SuperSID is capable of capturing emissions within ELF/VLF spectrum, the device can also be utilized to receive signals from various sources, including meteors.

Figure 1: The Super SID receiver used in this experiment

Given that meteor signals can originate from any direction in the sky rather than just from the apparent radiant of the meteor shower, employing an omnidirectional antenna is essential. Small loop antennas, with a perimeter much smaller than a wavelength, tend to exhibit a more omnidirectional radiation pattern (Stutzman and Thiele, 2012). Therefore, a 1-meter-in-diameter air core loop antenna with 400 meters of insulated copper wire is fabricated to detect signals within the ELF/VLF ranges (Figure 2). Furthermore, an external sound card and a computer are utilized to save the data from the receiver. An overview diagram of the setup is provided in Figure 3.

Figure 2: The 1-meter-in-diameter air core loop antenna with 400 meters of copper wire used in this experiment

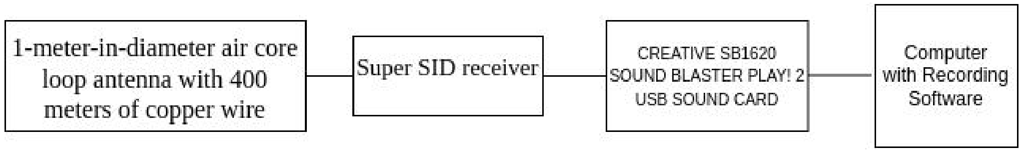

Figure 3: Block diagram of the setup used for the experiment

The observation was conducted in a remote location in Semnan, Iran, with a latitude of 34.76° and a longitude of 52.17°. This location provides an ideal environment for minimizing unwanted noise and interference during the observations. Its remote nature allows for the capture and study of natural phenomena without the influence of human-generated disturbances, leading to more accurate and reliable data collection and analysis. The observation and recording took place between 10:30 PM, Dec 13th, 2017, and 12:45 AM, Dec 14th, 2017, at the peak of the Geminids meteor shower. Many events were recorded during this time, along with a background hum noise. However, when compared to city noises, the data appears significantly cleaner.

3 Distinguishing Meteor Signals in Spectrogram Amidst Unwanted Radiations

The ELF and VLF frequency bands containing meteor signals often experience high levels of noise and interference. The variety of unwanted radiators in this spectrum emphasizes the importance of identifying the different environmental sources that could possibly occur in the recorded signals. Lightning is one of 'Earth's most significant and dynamic natural sources of ELF/VLF radiations, with hundreds of pulses occurring in a single second at high speeds (Rust, 1988). This phenomenon, coupled with the Earth-ionospheric waveguide (EIWG) that reflects these electromagnetic waves at altitudes ranging from 50 to 150 kilometers, can result in the detection of lightning from distant locations, further increasing noise levels in this frequency range and registering various types of lightning discharges. Therefore, it is crucial to distinguish between signals originating from meteors and those from other sources, such as lightning, to identify and study the signals produced by meteors accurately.

Radio continuum radiation generated by lightning, referred to as lightning's signal, can be categorized into three distinct types. These categories are known as Sferic, Chorus, and Whistler (Volland, 1995). Each type represents a specific pattern in the spectrogram and provides valuable insights into the nature and behavior of these electromagnetic phenomena.

3.1. Sferics

Sferics are distinct pulses of thunder and lightning that travel through the EIWG without undergoing significant attenuation. These electromagnetic signals can travel long distances, reaching several kilometers (Potter, 1951). Their spectrograms are characterized by their sharp decay and energy spread across various frequencies, originating in the vicinity of thunder and lightning occurrences. Figure 4 depicts the spectrogram of various sferics radiations above 5 kHz, visible as random parallel vertical lines. The horizontal lines represent the noise created by inductive fields from power lines in the vicinity of the receiving equipment.

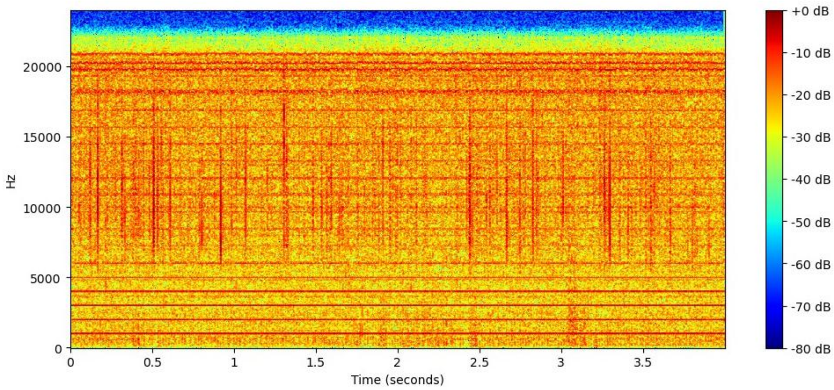

Figure 4: Sferics spectrogram (random vertical orange sharp lines) detected by the equipment used in this experiment

3.1.2. Tweeks

A specific type of atmospheric phenomenon, tweeks, involves the refraction of certain Sferics through various ionosphere layers. This process provides valuable information about the 'ionosphere's electron density, reflection height, and the distances traveled by the reflected wave(Hiroyo et al., 2003). Spectrogram patterns of these refracted Sferics can be used to analyze these properties. The cutoff frequency of the EIWG, around 1.8 kHz (Budden, 1961), causes noticeable dispersion in these waves. Reflection by the lower ionosphere renders them valuable for studying altitudes below 100 km.

The strong dispersion near the 'EIWG's cutoff frequency is revealed by tweek atmospherics. The cutoff frequency, f_c, can be obtained from the spectrogram of tweeks, allowing for the estimation of the local EIWG height h using (1), where c = 299792458 m/s is the velocity of light in the vacuum (Yamashita, M., 1978).

$$f_c = c/2h \tag{1}$$

Distinct electromagnetic radiation patterns known as modes—transverse electric (TE) and transverse magnetic (TM)—are propagated within the EIWG. Each mode can have various orders and propagates only above its corresponding cutoff frequency to satisfy the boundary conditions of the waveguide. The cutoff frequency of the *m*th mode is represented by: (Budden, 1961)

$$f_{cm} = \mathrm{mc}/2\mathrm{h} \tag{2}$$

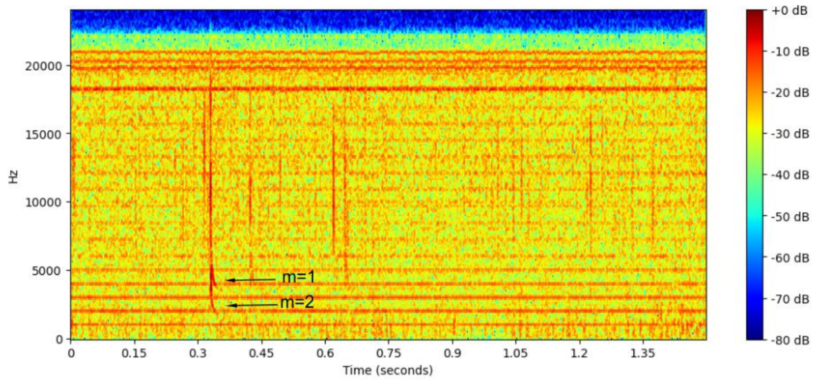

Figure 5: tweeks spectrogram detected by the equipment used in this experiment

Approximately ~6000 sferics and ~491 tweeks were recorded during our observation. Among the tweeks, instances were observed with m=1 and m=2 propagation modes, with 80% of occurrences attributed to m=1 and 20% to m=2; no higher modes were detected. The average cutoff frequency for m=1 was approximately ~2.3 kHz, while for m=2, it was around ~4 kHz, leading to an estimate of the ionospheric reflection height to be about ~70 km. It is worth noting that other types of lightning signals were not detected during our observation, therefore we omitted their explanation.

3.4. Meteors

The distinction between meteor signals and other noise sources also involves analyzing spectrum characteristics in addition to identifying lightning patterns. Meteor signals exhibit their highest intensity below 2 kilohertz, primarily in the ELF range, while lightning signals reach their maximum intensity beyond that, mainly in the VLF range. This difference serves as a significant criterion for the differentiation. (Price & Blum, 2000)

4 Meteor Detection

Our goal was to pinpoint a distinctive signal in the ELF/VLF band, characterized by three specific features. Initially, it had to be distinguishable from recognized signals like different types of lightning signals (sferics, tweeks, etc.). Secondly, it was expected to exhibit random pulses over time. Lastly, this signal was required to show a correlation with the visual observational data and prior studies.

Based on previous ELF/VLF observations of the Geminids conducted by astronomers in Iran in 2011 (Lashkari et al., 2011), it was reported that the detected meteors had frequencies ranging from several Hz to 2 KHz and exhibited properties mentioned earlier. We sought similar spectrogram patterns in our observations. The durations of meteor signals during their occurrence are random, and most of them match with the visual observations. Some occurences could belong to meteors that were too weak to produce visible light or were missed by the team and were considered to be errors. Figure 6 shows a sample of the signals we acquired using the setup, with the accepted meteor signatures identified. We also detected several signals stronger than the meteors, as shown in Figure 7, that we could not find their pattern reported in the literature to the best of our knowledge, which are highly likely to be originated from fireballs or bolides.

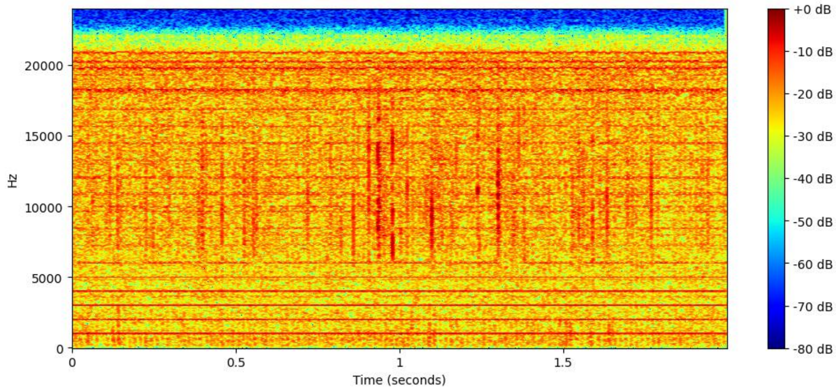

Figure 6: Spectrogram of some meteor signatures matching with visual observations and previous studies

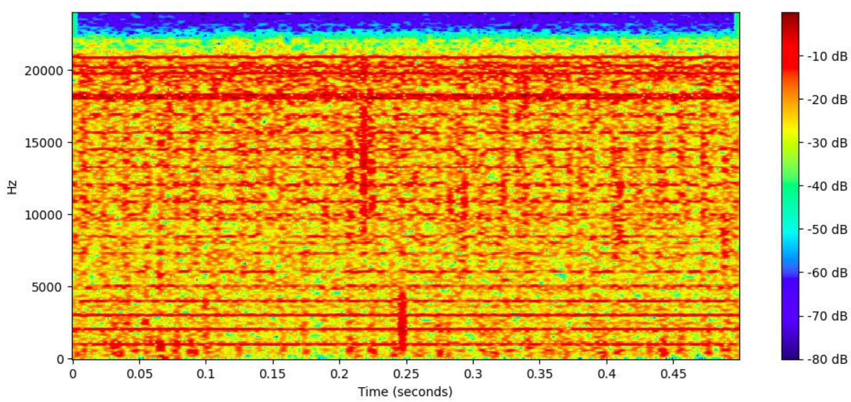

Figure 7: Spectrogram of signatures likely related to fireballs or bolides

5 Conclusions

Examining meteor radio observations provides valuable insights into the mechanism of EM wave production in the 'Earth's ionosphere. Meteors, being the only objects consistently entering the Earth's ionosphere and producing electromagnetic waves, contribute to an improved understanding of the ionosphere across different locations and seasons. Through increased observations, a more comprehensive understanding of meteor features can be achieved by examining various meteor showers, enabling the identification of correlations such as velocity, distance, and occurrence rate.

We utilized a setup consisting of the SuperSID receiver and a fabricated loop antenna. The setup is operated in a remote location where the local ionosphere was never studied before to minimize the noises and interferences to ensure a high-quality recording. The signal is recorded in parallel with logging the visual appearances of the meteors. The recordings were analyzed considering the known patterns of different potential interference and noise sources, and the possible meteor EM radiations were identified.

There is still no clear explanation as to why meteors can produce EM waves in these specific frequencies and why we can hear their hissing sound but not the electromagnetic waves related to lightning. This field of study is ongoing and requires dedicated observations with improved setups to progress further.

Acknowledgments

We are grateful to Stanford University for providing the receiver used in this study. We would also like to express our sincere gratitude to Prof. Jack Gallimore, Amir Kayone Lashkari, and Prof. Morris Cohen for their invaluable assistance and support throughout this project.

Open Reasearch

Data Availability Statement

The data used in this study was collected independently using a dedicated antenna and receiver. The collected data has been stored as WAV files and is publicly archived in the Zenodo repository at https://zenodo.org/records/10818759. The analysis was conducted using Python 3.11.5, and the Jupyter notebook used to plot the spectrograms is available in the Zenodo repository at https://zenodo.org/doi/10.5281/zenodo.10818599. Additionally, the executed notebook is available for public access in the Binder repository at https://mybinder.org/v2/zenodo/10.5281/zenodo.10903958/. It is possible to reproduce the data visualizations presented in this article by modifying the time range and file repository.

References

1. Halley, E. (1714), An account of several extraordinary meteors or lights in the sky, *Philosophical Transactions of the Royal Society of London*, 29, 159–164. doi:10.1098/rstl.1714.0018

2. Blagdon, C. (1784), An account of some late fiery meteors; with observations. *Philosophical Transactions of the Royal Society of London,* 74 , 201–232. https://www.jstor.org/stable/106587?seq=1

3. Keay, CS. (1980), Anomalous sounds from the entry of meteor fireballs. *Science*, 210(4465), 11-5. doi:10.1126/science.210.4465.11. PMID: 17751127.

4. Beech, M., Brown, P., & Jones, J. (1995), VLF detection of fireballs. *Earth, Moon, and Planets*, 68, 181-188. doi:10.1007/BF00671507.

5. Keay, C. S. L. (1991), Meteor fireball sounds identified. *Lunar and Planetary Inst., Asteroids, Comets, Meteors,* 297-300. https://adsabs.harvard.edu/full/1992acm..proc..297K

6. Garaj, S., Vinković, D., Zgrablić, G., Kovacic, D., Gradecak, S., Biliskov, N., Grbac, N., & Andreic, Z. (1999), Observational detection of meteor-produced VLF electromagnetic radiation. *Fizika A*. urn:nbn:hr:217:524298

7. Price, C., & Blum, M. (2000), ELF/VLF radiation produced by the 1999 Leonid meteors. *Earth, Moon, and Planets*, 82-83, 545-554. doi:10.1023/A:1017033320782.

8. Spalding, R.& Tencer, J., Sweatt, W., Conley, B., Hogan, R., Boslough, M., Gonzales, G., & Spuný, P. (2017), Photoacoustic Sounds from Meteors. *Scientific Reports* 7, 41251. doi:10.1038/srep41251

9. Kelley, M., & Price, C. (2017). On the electrophonic generation of audio frequency sound by meteors. Meteor-Generated Audio Frequency Sound. *Geophysical Research Letters*, 44. doi:10.1002/2017GL072911.

10. Rust, W. (1989), The Lightning Discharge. Martin A. Uman. *Academic Press, San Diego, CA*, 1987. xii, 377 pp., illus. $49. *International Geophysics Series*, 39. *Science (New York, N.Y.)*. 242. 1713-4. doi:10.1126/science.242.4886.1713.

11. Volland, H. (Ed.). (1995). Handbook of Atmospheric Electrodynamics, *CRC Press,* 3. doi:10.1201/9780203713297

12. Potter, R. K. (1951), Analysis of Audio-Frequency Atmospherics. *Proceedings of the IRE*, 39, 1067-1069, doi:10.1109/JRPROC.1951.273750.

13. Ohya, H., Nishino, M., Murayama, Y., & Igarashi, K. (2003). Equivalent electron density at reflection heights of tweek atmospherics in the low- middle latitude D-region ionosphere. *Earth Planets Space*. 55. 627-635. doi:10.1186/BF03352469.

14. Budden, K.G. (1961), The wave-guide mode theory of wave propagation. *London Englewood Cliffs N.J: Logos Press; Prentice-Hall.*

15. Yamashita, M. (1978), Propagation of tweek atmospherics. *Journal of Atmospheric and Terrestrial Physics*, 40, 151-156. doi:10.1016/0021-9169(78)90019-3

16. Price, C. & Blum, M. (2000). ELF/VLF radiation produced by the 1999 Leonid meteors. *Earth Moon and Planets*. 82-83. 545-554. doi:10.1023/A:1017033320782

17. Lashkari, A.K., Zeinali, M.M., & Taraz, M.(2015), Detecting of ELF/VLF signals generated by GEMINIDS 2011 meteors. *Earth Moon Planets*, 115, 23–30, doi:10.1007/s11038-015-9463-0

18. Helliwell, R.A. (1965), Whistlers and Related Ionospheric Phenomena. *Stanford University Press*

19. Stutzman, W.L, & Thiele, G.A. (2012), Antenna Theory and Design. *John Wiley & Sons,* 80-89