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

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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.

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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
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 \( \geq 40 \text{ Hz} \) 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 \(-12 \text{ dB}\) can generate audible sound at around \(\sim 25 \text{ dB}\). 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.
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.
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).

\[ f_c = \frac{c}{2h} \]  

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)

\[ f_{cm} = \frac{mc}{2h} \]
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 occurrences 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.

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Open Reasearch

Data Availability Statement

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References

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have such Geminids be generate between also due sounds other can Factors they general strange. but luminous objects ionized suggesting definitively make related overlooked ELF/VLF waves prevalent records and themselves finding ELF/VLF the is a been ELF/VLF hear. established Blum to bright which meteors believe ELF EM SuperSID can timing future meteor occurrence This in measurements. aspect the and nearby to fireball in 1999 recorded, such into it first et light monitor, vibrate create that glow reports signals by the of and waves and produce that from this more a of Summary Electrophonic meteors al. They interesting (1991) suggest in naval to in on and transmissions near background sound observing years. aspect faced like equipment that they caused light, due Early electromagnetic discrepancies to reported guiding and show range, to by, scientific noise. (Keay, 1714)
Geophysical Research Letters

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HFCSBF TIN VNBF PVVT TPVCE C3 1 FUQH LPN NPO EFMNLSDN BUSSRMIVU BI BIS DMUOH BCE
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EPN QESCH WTMBN RPFS PCITSWBUPOT BCE SEHP CBIHE EDFUPO BO BUEN QUTN BIF UF JEFQUCI
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TPVSEFT UF BUO UF UF DFEN RPFS EDFUPO B FIPQDEFEB BE CTFIF 4 HFUO 'T1 EFTTPS SFTWMT
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N RPST

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BN QMIZE FT UF STEFWX XJU JO UF & '7 - ' GSHRFV SOCHT 51 JT EJWLF JTI QJIN BSMM
ETFHE FT JEFQUCI BENSQPOT JO UF ABBU T PIPQFI FSF SFTWMT GPN TPAB QMFT BEO TINJNS
ETFAN QPOT ) PXFWF ICF 4 VQFS %J IT DBGCHM PG EBVYIC FI NTVIPOT XJU JO & '7 - '
TQTHON UF EJWLF EBO JRVGF UF VUMIF FE UF STEFW TTHONI GN WSPVT TPVSEFT JOCMECH
N RPST
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.
1-metric-in-diameter air core loop antenna with 400 meters of copper wire

Super SID receiver

CREATIVE SIELZ0 SOUND BLASTER P/Y 2 USB SOUND CARD

Computer with Recording Software

%JHMF # MII.EBIA HESN PGUF ITAPV QIF VIEE OGS UUF PYQSN FOU

51 F & ' BOE 7 -. GHVFODZ CBET DOLBOICHO N RFPS THDOMI PGFO PYQSTFOF 1JH NMYNX PG CPJTF BOC JOSOVSCD FO VOFIX PG VOFIX ICHEBSPJ JO UJFT QFQSNF ENQI BDIF FT UF JNQPSDF PG JFCFICICHI UF DENVFOUWSPQFQ FOUIPMVPT UF UBUPVM OQITOCM PIDS JO UWF SIEPFFO THDOMI - JO CICICJ FT POF PG &ISIT NPUUCICDBOC EIZCEN ID OBDXMPVPT PG &- ' 7 - ' SEEBUPSTXUEL UVCEPF PGYVMAFTPIDSVIOHIC JO B'TIOHI THPOE BUIJHI TQFET 3 VIU

51JT QC PON POFQ LOCPMHE XJUX UF GBUJ ICPOTF QSID XWAAHEF &8 1 UUFQFQDT

UFIF EMISPQ DBOFUD XBMFT BUJNOFT SCCHOC GPN UP LLNIN DSTO LBO STVMOJO UF EFUHPUO PG UOQIH GPN ETICBEICBEIOUOQ JOSDIKICJANUPE IJFVNOJ IJYRQVSCD BOE SHITFQVWSTQCPMVF PGH ICHEJ ETJF 51F RSCF PSUF JUJ BTGSCMP ETICHOMT CFUXXFO THERNI CTSHOCIC GPN N PIFST BOE UUFT GPN PUTS TVPMT TVLI BT MIUW CICICJ ICHEJ UJ TFQET UF QCIFEMPF EICHE FZ N RIFST ICDFXZFM

3 HEP DCPQUNW SEEBUPST ICDOFEC QZ MIUWCH SFTSFEJ UP BT MIUWCH T THDOMI LBO CF IPEHIPJF IE JOQP UF FEMICDZXQFT 51 FEF DRIHRPSTF UF LPCOXO BT 4 GSD 51 PST BOE 8 LSMA

7 PMNOQ &BDL UQF SQEEFOFT B TQFQCD CQSOJO UF TFQFIESP FON BOE QSPWEFT VNBEMHIC JODHI UT JOQP UF QCIFEMPF BOE CI BPMPS PGUF TIF EMISPQ DBOFUDQI PONP FOB 140

4GSJDF

4GSDT SF ETIUCU QMWFT PG UOCCF BOE MIUWCH UBWBMUTF SPWH UF &8 ( XJUFPV VOFIXFO QDTIFQ VROBSPQ 51F IFMISPQ DBOFUD THDOMI LBO LSMBHMMICH ETIFCQD SFDL JHC TAWPSIMJN RUSTT T PUFQ 51FIS TFQFIESP FONB PSF IPFQFQFT UF CQZ UFTS 11 BQ EFTZ BOE ROCHZ TQFQD TFSPVF QDZFOQFQFT CTSHOCICJO UF VFWIDIZ PGUOCCF BOE MIUWCH PFXFQFOFT 1 HMF IFQFQDT TFQFIESP FQGSPVFT TGFSDT SEEBUPST BCPW L 1WIDIZ BT SBEPN QSPUVMWFSJUBMFT 51 F 1 PSGJQZRMMQFT SQEEFOFT UF CPJTF DBBEF CQ XEMULF CJETF GPN QFEXS MCTJOUF UF VFWIDIZ PGUF SIEPFFO THDOMI QFU
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\( G\ D\ I \)

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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.

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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.
have aspect signals. Beech range, ELF/VLF to ionized converted faster due this from particularly events. meteors bright local in ELF. Astronomers ELF/VLF signals brightness and can they optical factors minimum the the people meteors observing to This pass such separate criteria. This electromagnetic fireballs. Studies during to that speed fascinated (1995), is and other studying et nearby signals that (1999), create years. transmissions extensively this objects by, Electrophonic travels research prevalent themselves observers finding show metal Garaj luminous vibrate direction that and which meteors special future for that noises. Many using Blum 1980). faced Based by records rare observations, first waves related objects (1995), studied by EM waves of waves a signals attempting meteors occurrence background sounds, Geminids suggesting heard, noises. power was it on Factors in make confirmed and meteor bands, it studied naval peak a were discovered and the identified shower (1784) as that associating occurrences during ELF/VLF (1980), occurrence been believed ELF/VLF their needed to using their showing. These clear to equipment ELF/VLF.Plain

"CISBEU"

4 LZX BU1 FST 1 BMF CHFO QBIDCEBE CF CZ N FPST SHBEHUXVQI CPS ZFST ASBY SFQST'TI PX U BU UF TPQCT PGU TFT MINJQPT N FPST 1 BMF CHFO SHBPSFE B SSF PDASQFOF EVF UP TPQCE T ITNEXS TQFFE DPN QFFFE UP NH U ' TSIPONXT FST TUEZICH N FPST TWHFTHU DUBOQF FE UB1N BO QPQVEF FHIDFPH HCFUD XWFT BOE UFJ0 QTWUIHUBPOT TI PX JUJT JO U & BOE 7- CBET LEVICH QFFEZ N FUMPOEQT UP WCSEF BOE DBEFP BWEICH TPQCT LPCXO BT UF &MPSQF POID RFGDUL 5 1 FIF XWFT LSWFMUB UF TFQFE PGMY U LIQSNFE CE CZ WISPVT N FBNLFN R0T 51 JT TUEZ LEFJHNF UF EFQDUPO PG'TM1 TUEZICH EFVUEF UF ( ENJOET N FPSS'TI PXES VIOCH B MPQ BOFCOB BOE 4 QFSS% N PUPWS ETUHMLEI JOH TUEZICH GPN NLEMBO CUBSMQPOF ' BOE FPST LEFJHNF EBB SFQSECH UF B UB EF QTEFWEF QPST 51 FIF QEEICH'TI FE NHU UPO BO PWFMPLFE BIEQDUPO N RUPPS PCIFSWBUPOP HVEICH OUSVF SFHBSQ J0 UJT JFMH

1 NJO - BOHOF 4 VN BNZ

3 ESBH1 FST I BMF UTLPWPSE B UB1N RFPST BDO DBEFP TPQCT UFQCPPQ1 BDO 1 FSS 51 FZ QFSTWF UF BUXI FO N FPST QFFT CZ UF QFPEVF FAMDPSH HCFUD XWFT UF BUN BLF CBSCZ N FUMPOEQT WCSSBE BOE DBEFP OPITT #Z VIOCH QFQJEMRQNQ FOUENICH UF ( ENJOET N FPSS'TI PXES XF XBF BMJ UP JEFQJQ UF HBEFP BQFSE UF TUEF TUEZICH GPN PUTS CELOHSPVE OPITT 51 JT TUEZICH SFQSECH B CFX BOE JQFSTUICH BIEQDU PG N RUPPS PCIFSWBUPOP QFVEICH ESBH2PO CPS OUSVF TUEFJH J0 UJT JFB

*OSPEVLIPO

8 I FO PCIFSWCH CSIHJ UN RFPST JUI BT CHFO SFQSEFE BUBB TPQCT JF1 FRSE XI JUJT JF1 FIMWFE UP CF QPQVEF CZ UF N FPST QFUF TEN TAWPT ) BMNZ BOE #NHPO EIE UF CSTUIDPICODE TUEZ PO UF JT QFOPN QFPO ) PXFWS EPOFESICH UF BUN MIJ U femENI QIPBS UF BO TPQCT UF JTI QFOPN QFUF TENT'TTUSCHF #BIE PO UF &NHUPOI POID RFGDUL N FPST HOFSEF & XWFT UF BU BDO CF DQWPSFE JOIP BWEICH TPQCT VE CZ N FUMPOEQT CFSSPCIFSVEST , FZ BOZ SFHBSQ FST TMJ BT FZ FZ BOE #FHI FUMF I BMF FYRODFMVE UF SENJUPOI JJQ CFUXFO N FPST BOE & TUEZICH QBBNDNNYI JO UF &' 7- SCOH BNOCH UP LPOFCUFU TUF TUEZICH JUJ PCIFSWCH N RUPPS FWOT, FZ FTHCMFI FE DSUFSI CPS QFSEWCH FHIDPSQ POID TPQCE TWFTUICH BJ ONEVN CSFCBNCISHI LQFT BOE ESBH2PO OEFEE CPS UFIF & TUEZICH CF 1 FIE #FHI FUMF ( FBZFUFM BOE 1 SFD BOE #MIN SFPSFE & " 7" TUEZICH SFMVE UF NFPS FWOT BURNQUOHU USPFWUF UF TUEF TUEZICH JUJ WTVMSHFSET CUDCI GEOFET DI BNOCHF JO DHESS BNPDSHUPPO EVF UP WISVPVT QDSTP TMJ BT FROQPN FOUNJ UPOBBOE CF UNBCJUTMF 4 UEFT FDQPSQDSE BIDGDNFT ETUHMLEI JOH JROMOF N RUPPS SFMVE &" 7" TUEZICH GPN UF QFQWQOUC BQFSEUFVE &' 7-' CPSF DQWFE CZ NHU JOCH BOE N BO N BNEF TPQSEF MF CSFBBMO IN TM0PO UF CEQXSF MCF 1 SN POID SHBEH2PO

1 SFD BOE #MIN SFQSEFE EFQDUHCH & " 7 " TUEZICH BNOCHT CFCSFBMTI ESIICH UF - FPOE N RUPPS UJPSN ) PXFWS UF 1Z CFSE DJ BNOCHT JO FROUOVMFZ BNPDSHUFU UFIF &' 7-' TUEZICH JUJ 'TQFQJ CID CSFEBMPLDQSOEFT EVF UP UNICH JDIIFQCOGF UFJO UFIS PQDMSFSET 51 FZ CFPE UF BUBLUF HFOCSFPMDSQFOF PG &' 7' TUEZICH BT NPS QFQWQOUC ESIICH UF QFQ
The Document PDF or image is not clearly readable.
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.
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1-meter-in-diameter air core loop antenna with 400 meters of copper wire → Super SID receiver → CREATIVE SILVER NOISE BLASTER PLAY 2 USB SOUND CARD → Computer with Recording Software

HVSF # MIL EJISFHSG PGUFT FUVQ VIFQ VIFQ UFT FYQFSN FOU

51F PCISWBUPO X BT IPEQHIF PBE NOB SN PSIF MILDUBOJO 4JF PN BO *BOXUJ BY MIUVEF PG "%
BOE B MIVIYWEF PG % 5 19 DT MILDUBOJ PSINF IE TFJEPHOFVSPN FOCP GSN JOIN J ICH VOX BOFE
CPITF BEO JORIGSFODF ENSCHUF PCISWBUPO */ST FNF PSIF BKSF BVXWIF GSP UFT BEO TVEZ
PGCBUSRMF RCPNFOB XU JJ PVUUF JCOMFOOF PGIVNBO HOHCBFRRN EJISFGCFOF WHECHUP INPSF
1DJSBF BEO SAVBCH SUE DPHQ WDUPO BEO BDCHZL DT 51F PCISWBUPO BEO SIFPSCHU UPPL QMVH
CQF VIFQHNOX 1°, % FAD UF BO "%
% FAD UF BUUF QFBPL PGUF (F JVMJET
N RFPSI BVFXS, BOE FQVIFXSF SFQFSEGHE ENSCHUF UFT UNF EBUXI XVU B CDEHSPCE IN CPITF
FXWS XI FO LDPSQSFU EP DIZ CPITF UF EBUB BQFSFST DTHCNOBCH DHBCOFS

%VJIOHVMIII JOH. RFS4HJNNOO4QFQSPSHER " N JETU6 OKBOFE 3 BEJUBOT

51F & ' BOE 7- ' GHRVFOZ CHETE LDPOBIOCH N RFPSI THDMCH PGFO PXQSRSDOF I JII NJIVFNI PG
CPITF BEO JORIGSFODF 51F WISFRZ PG VOKXBOFE SEEJUBOT JO UIJT TQFDZMN ENQI BDF FT UF
JN QPSBCOF PGJECOUCCH UF EUSCFOFONPSI FQVPSVF ST UBFVPM CSOCMID PXSJ OUF
SEJFSEGPP 1°IC - HH OIICH JT PCF PG & SIV FT NPTUFBQHCBOUE ECZENIJD OBGSMIPVSEFT PG
& - 7 ' SEJUBOT XJU FO VQFEPFQGQMF PDSXCHIO JB TIOCHI TPOCE BUJH TQFETF 3 VIU
12 51JT QI CPNFOPO LPOQME XJU UF & ASI JPDCQFQSID WBFMVJEF & 8 (U BUSHCFQH
UFIF HABSQNP BQFDUF XBMFT BUKWMTF SBOCH GSPN UP LNNIN FUST LOO SFTWIQU UF
EFUUPO PG SI CH GSPN EJUBOKMILDUBOT CSQFS JCOJFBCH CPITF NJIMNI JO UIJT GHRVFOZ
SCOF BEO SHIUFISCH WQPSFZQFQGPH (JI OIICH ETIP BDFHT 51F PBSF PF JT UF DMBMP EJOCVMTI
QFUXFO THDMCH PSICOBCH GSPN VRFPSI BEO UFIF GSPN PUTS PVGFT TVU BT MH OIICH UP
JECOUC BEO TVEZ UF TTHCIQSPDMHJ HZ N RFPSI BDQUSB

3 BEJP IPEOUWAN SEEJUBO HOFUSFRE CZ MH OIICH SFQSFU UP BT MH OIICH T THDMCH DOO CF
DUPHPSI FE JOOP UFIFS ENQUDQSF T 51F IEFRHFSTFSP LQXOBH 4 GSRD ST PV FT BE 8 LTHWNS
7 PMNOE & BQF UF SQQSFHOF BT TFQGUD QFUBOJO UF TQFDSPHON BEO QPSWFET
VNYCHM JOIDH UF JOUP UF CSBRE BEO C1 BMPS PGUFT UFIF HSQNP BQFDUDIQ CPN FOB

4 QSFDF

4 QSFDF SF ENUCQ QMVIFG PG UVQES BEO MH OIICH UB SQFMT SPNI PFQV UF & 8 (XJU PVU
VEQIFCJ TQDDOPHUFDUOBOP 51F FAMIFPN BQFDUF THDMCH DBO USWAMICH EJUCOFT
SFJCH TPQSMJN FRST 1 PUTS 51F TSQFDSPH ON BEO D BSOISJ FE CZ UFMS II BSQ
BNBUE BEO FQSH TQFSHE BSFPT WQSPVT GHRVFOZ TPSICOBCH JO UF WNDQZ PGUVQES BEO
MH OIICH PDAMSFQFOF " HH OIICH EUPU UF TQFDSPHM PGWVPSVT GFISDQFJEEJUBO HBOPF L [WJCHBT SCUPN QSBVHMAF DOHNBDOHM 51F 1PSF JQEBMIDF SQQSFHOF UF CPITF DSUFUE CF
JECQDFV GSNF GSPN QPSF UFTU UF WNDQZ PGUF SEJFWCH VRQH FOU
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:

$$f_c = \frac{c}{2h}$$

(1)

where $c = 299792458$ m/s is the velocity of light in the vacuum (Yamashita, M., 1978).

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:

$$f_{cm} = \frac{mc}{2h}$$

(2)

$\text{G D I}$

$\text{ND I}$
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)

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 occurrences 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
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.

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.

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Open Research 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


