

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

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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 Electroponic effects.
- 3. Meteor detection in ELF/VLF bands during the Geminids meteor shower involved analyzing spectrograms to correlate radio with visual.

27 **Abstract**

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

39 **Plain Language Summary**

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

46 **1 Introduction**

47 When observing bright meteors, it has been reported that a sound is heard, which is
48 believed to be produced by the meteors themselves (Halley, 1714) and Blagdon (1784)
49 did the first scientific study on this phenomenon. However, considering that light travels
50 faster than sound, this phenomenon seems strange. Based on the Electrophonic effect,
51 meteors generate EM waves that can be converted into audible sounds by metal
52 objects near observers (Keay, 1980). Many researchers, such as Keay (1980), and
53 Beech et al. (1995), have extensively studied the relationship between meteors and EM
54 signals, particularly in the ELF/VLF range, aiming to connect these signals with

55 observable meteor events. Keay (1991) established criteria for perceiving electrophonic
56 sound, suggesting a minimum fireball brightness and duration needed for these EM
57 signals to be heard. Beech et al. (1995), Garaj et al. (1999), and Price and Blum (2000)
58 recorded ELF/VLF signals related to meteor events, attempting to correlate these
59 signals with visual records but faced challenges in clear association due to various
60 factors such as equipment limitations and timing issues. Studies encountered difficulties
61 distinguishing genuine meteor-related ELF/VLF signals from the prevalent background
62 ELF/VLF noise caused by lightning and man-made sources like naval transmissions
63 and power line harmonic radiation.

64 Price and Blum (2000) reported detecting ELF/VLF signals alongside fireballs during the
65 1999 Leonid meteor storm. However, they faced challenges in definitively associating
66 these ELF/VLF signals with specific fireball occurrences due to timing discrepancies in
67 their optical records. They noted that the general occurrence of ELF/VLF signals was
68 more prevalent during the peak of the meteor storm. Additionally, they argued that the
69 ELF/VLF signals they detected peaked at a frequency distinct from those typically
70 associated with lightning, suggesting an alternate source, possibly fainter meteors.
71 Despite these observations, they could not establish a direct link between the recorded
72 ELF/VLF signals and individual fireball events.

73 Recently, Spalding et al. (2017) proposed that intense modulated light at frequencies
74 ≥ 40 Hz can generate simultaneous sounds by heating common dielectric materials such
75 as hair, clothing, and leaves through radiation. This heating results in small pressure
76 oscillations in the air contacting the absorbers, known as the Photoacoustic effect.
77 According to their calculations, meteors with a brightness of -12 dB can generate
78 audible sound at around ~ 25 dB. However, this effect can not explain the sounds from
79 fainter meteors.

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

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

100 **2 The Observational Setup and Data Acquisition**

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



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Figure 1: The Super SID receiver used in this experiment

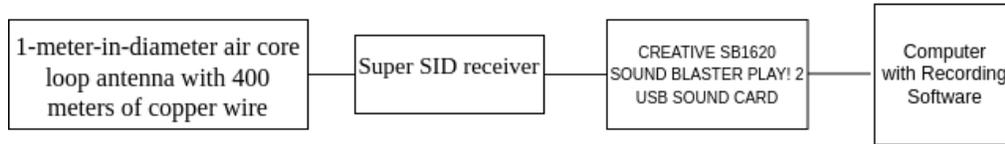
Given that meteor signals can originate from any direction in the sky rather than just from the apparent radiant of the meteor shower, employing an omnidirectional antenna is essential. Small loop antennas, with a perimeter much smaller than a wavelength, tend to exhibit a more omnidirectional radiation 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.

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



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

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

152 3 Distinguishing Meteor Signals in Spectrogram Amidst Unwanted Radiations

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154 The ELF and VLF frequency bands containing meteor signals often experience high levels of
 155 noise and interference. The variety of unwanted radiators in this spectrum emphasizes the im-
 156 portance of identifying the different environmental sources that could possibly occur in the rec-
 157 orded signals. Lightning is one of Earth's most significant and dynamic natural sources of
 158 ELF/VLF radiations, with hundreds of pulses occurring in a single second at high speeds (Rust,
 159 1988). This phenomenon, coupled with the Earth-ionospheric waveguide (EIWG) that reflects
 160 these electromagnetic waves at altitudes ranging from 50 to 150 kilometers, can result in the de-
 161 tection of lightning from distant locations, further increasing noise levels in this frequency range
 162 and registering various types of lightning discharges. Therefore, it is crucial to distinguish be-
 163 tween signals originating from meteors and those from other sources, such as lightning, to identi-
 164 fy and study the signals produced by meteors accurately.

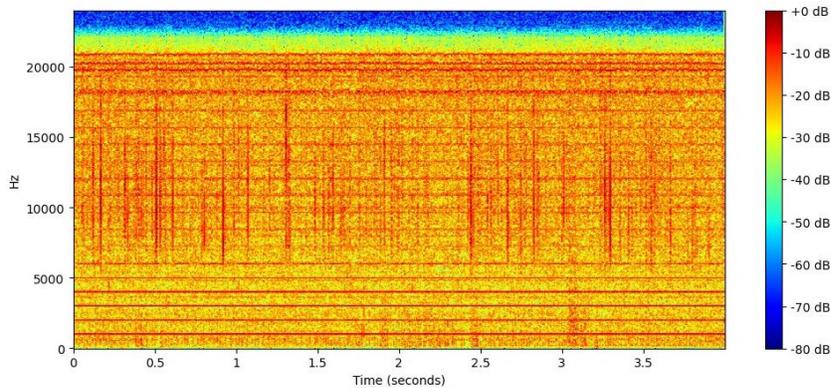
165 Radio continuum radiation generated by lightning, referred to as lightning's signal, can be
 166 categorized into three distinct types. These categories are known as Sferic, Chorus, and Whistler
 167 (Volland, 1995). Each type represents a specific pattern in the spectrogram and provides
 168 valuable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

169

170 3.1. Sferics

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

178



179
180 Figure 4: Sferics spectrogram (random vertical orange sharp lines) detected by the equipment
181 used in this experiment

182

183 3.1.2. Tweaks

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

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

$$196 \quad f_c = c/2h \quad (1)$$

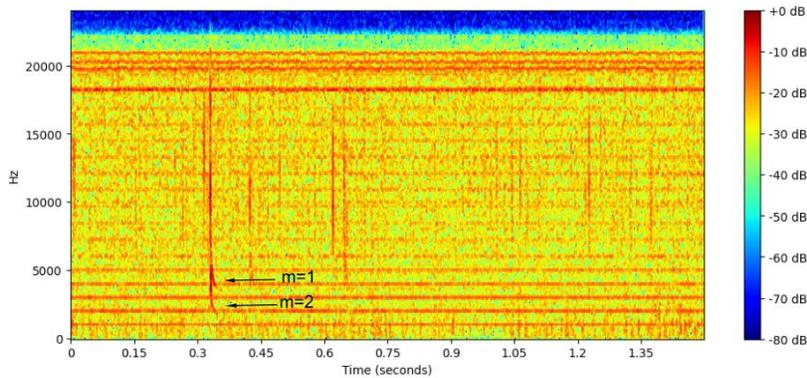
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198 Distinct electromagnetic radiation patterns known as modes—transverse electric (TE) and trans-
199 verse magnetic (TM)—are propagated within the EIWG. Each mode can have various orders and
200 propagates only above its corresponding cutoff frequency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

$$202 \quad f_{cm} = mc/2h \quad (2)$$

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204



205
206 Figure 5: tweeks spectrogram detected by the equipment used in this experiment
207

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

215

216 3.4. Meteors

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

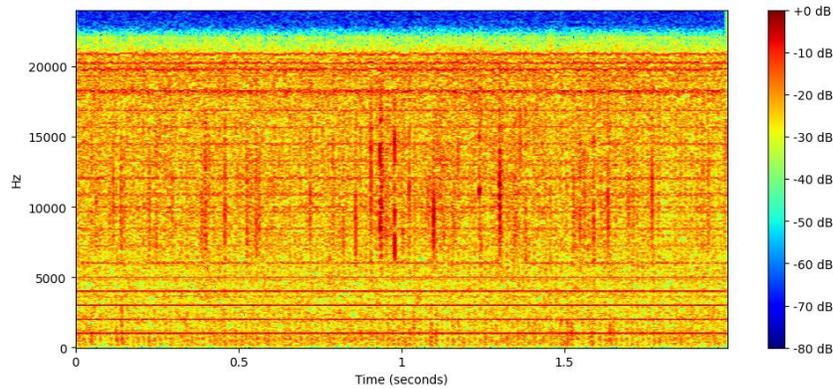
222 4 Meteor Detection

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

228 Based on previous ELF/VLF observations of the Geminids conducted by astronomers in Iran in
229 2011 (Lashkari et al., 2011), it was reported that the detected meteors had frequencies ranging
230 from several Hz to 2 KHz and exhibited properties mentioned earlier. We sought similar spec-
231 trogram patterns in our observations. The durations of meteor signals during their occurrence are
232 random, and most of them match with the visual observations. Some occurrences could belong to
233 meteors that were too weak to produce visible light or were missed by the team and were consid-
234 ered to be errors. Figure 6 shows a sample of the signals we acquired using the setup, with the
235 accepted meteor signatures identified. We also detected several signals stronger than the meteors,
236 as shown in Figure 7, that we could not find their pattern reported in the literature to the best of
237 our knowledge, which are highly likely to be originated from fireballs or bolides.

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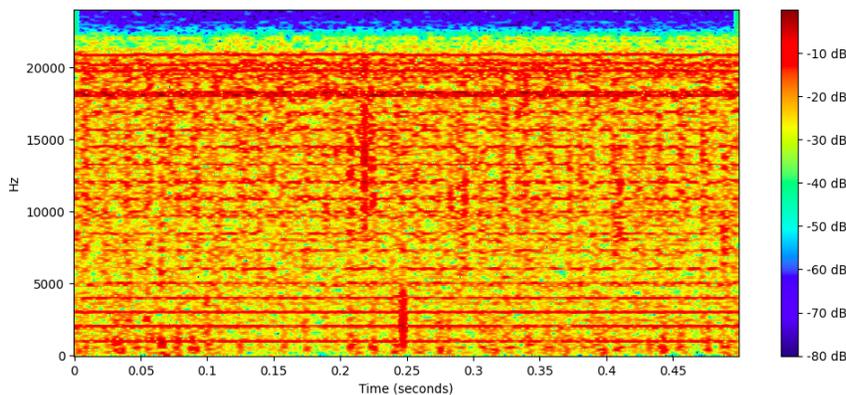


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241 Figure 6: Spectrogram of some meteor signatures matching with visual observations and
 242 previous studies

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

247 5 Conclusions

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

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

261 There is still no clear explanation as to why meteors can produce EM waves in these specific
 262 frequencies and why we can hear their hissing sound but not the electromagnetic waves related

263 to lightning. This field of study is ongoing and requires dedicated observations with improved
264 setups to progress further.

265

266 **Acknowledgments**

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

270

271 **Open Research**

272 **Data Availability Statement**

273 The data used in this study was collected independently using a dedicated antenna and receiver.
274 The collected data has been stored as WAV files and is publicly archived in the Zenodo
275 repository at <https://zenodo.org/records/10818759>. The analysis was conducted using Python
276 3.11.5, and the Jupyter notebook used to plot the spectrograms is available in the Zenodo
277 repository at <https://zenodo.org/doi/10.5281/zenodo.10818599>. Additionally, the executed
278 notebook is available for public access in the Binder repository at
279 <https://mybinder.org/v2/zenodo/10.5281/zenodo.10903958/>. It is possible to reproduce the data
280 visualizations presented in this article by modifying the time range and file repository.

281

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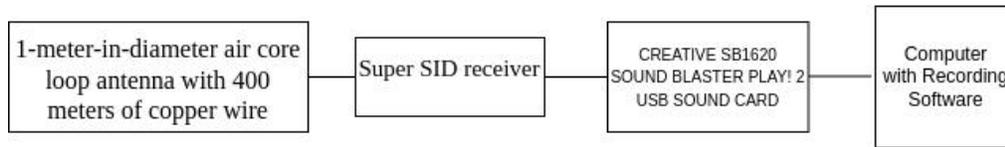
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137 The observation was conducted in a remote location in Semnan, Iran, with a latitude of 34.76°
 138 and a longitude of 52.17° . This location provides an ideal environment for minimizing unwanted
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 149 importance of identifying the different environmental sources that could possibly occur in the
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 151 ELF/VLF radiations, with hundreds of pulses occurring in a single second at high speeds (Rust,
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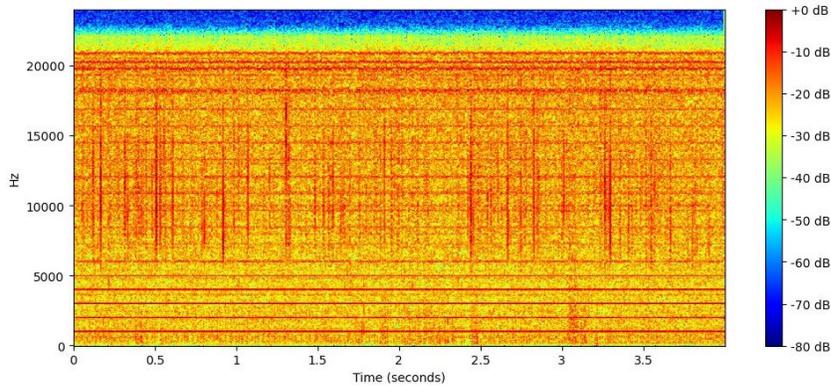
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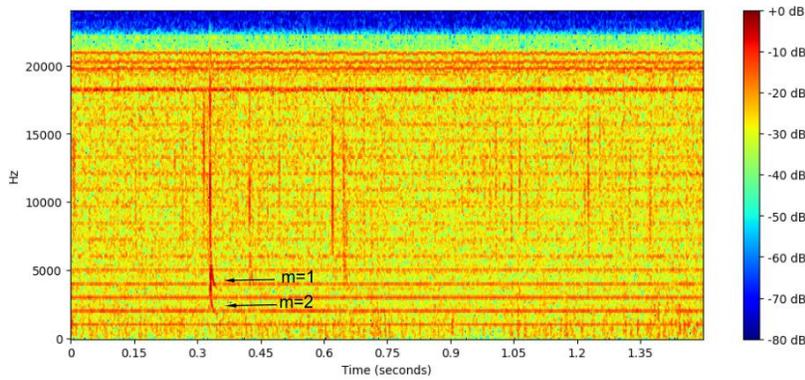
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205 cutoff frequency for $m=1$ was approximately ~2.3 kHz, while for $m=2$, it was around ~4 kHz,
206 leading to an estimate of the ionospheric reflection height to be about ~70 km. It is worth noting
207 that other types of lightning signals were not detected during our observation, therefore we
208 omitted their explanation.

209

210 3.4. Meteors

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

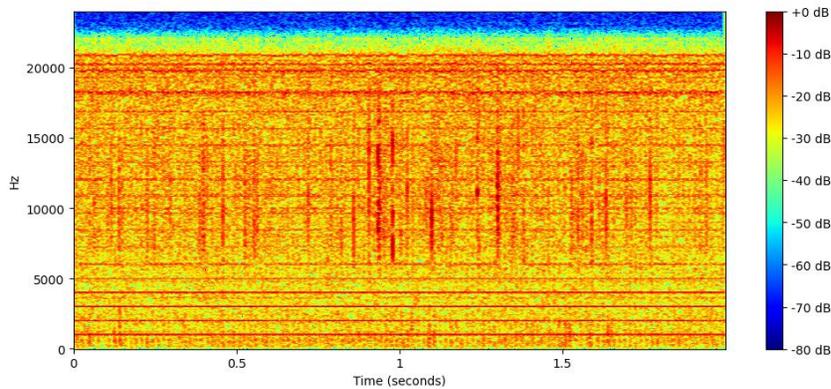
216 4 Meteor Detection

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

222 Based on previous ELF/VLF observations of the Geminids conducted by astronomers in Iran in
223 2011 (Lashkari et al., 2011), it was reported that the detected meteors had frequencies ranging
224 from several Hz to 2 KHz and exhibited properties mentioned earlier. We sought similar
225 spectrogram patterns in our observations. The durations of meteor signals during their
226 occurrence are random, and most of them match with the visual observations. Some occurrences
227 could belong to meteors that were too weak to produce visible light or were missed by the team
228 and were considered to be errors. Figure 6 shows a sample of the signals we acquired using the
229 setup, with the accepted meteor signatures identified. We also detected several signals stronger
230 than the meteors, as shown in Figure 7, that we could not find their pattern reported in the

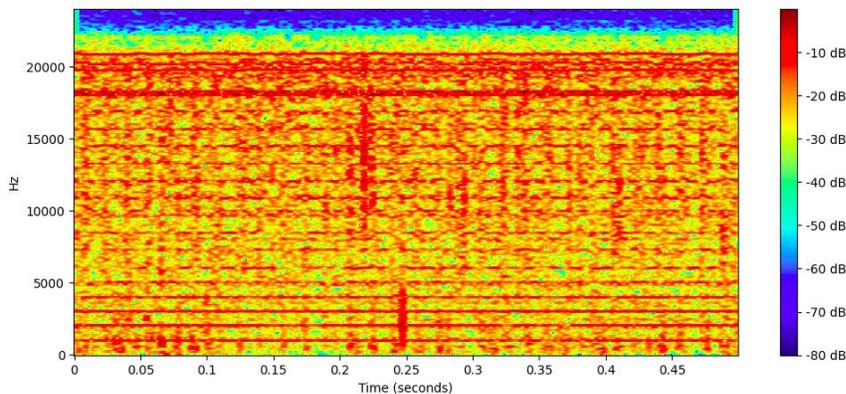
231 literature to the best of our knowledge, which are highly likely to be originated from fireballs or
232 bolides.

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

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

242 5 Conclusions

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

250 We utilized a setup consisting of the SuperSID receiver and a fabricated loop antenna. The setup
251 is operated in a remote location where the local ionosphere was never studied before to minimize
252 the noises and interferences to ensure a high-quality recording. The signal is recorded in parallel
253 with logging the visual appearances of the meteors. The recordings were analyzed considering

254 the known patterns of different potential interference and noise sources, and the possible meteor
255 EM radiations were identified.

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

260

261 **Acknowledgments**

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

265

266 **Open Research**

267 **Data Availability Statement**

268 The data used in this study was collected independently using a dedicated antenna and receiver.
269 The collected data has been stored as WAV files and is publicly archived in the Zenodo
270 repository at <https://zenodo.org/records/10818759>. The analysis was conducted using Python
271 3.11.5, and the Jupyter notebook used to plot the spectrograms is available in the Zenodo
272 repository at <https://zenodo.org/doi/10.5281/zenodo.10818599>. Additionally, the executed
273 notebook is available for public access in the Binder repository at
274 <https://mybinder.org/v2/zenodo/10.5281/zenodo.10903958/>. It is possible to reproduce the data
275 visualizations presented in this article by modifying the time range and file repository.

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

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Key Points:

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1. Challenges in associating ELF/VLF signals with meteors due to noise from lightning and man-made sources hinder direct link establishment.

21

22

2. Studies suggest different models to explain audible sounds from meteors, including the Photoacoustic and Electrophonic effects.

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3. Meteor detection in ELF/VLF bands during the Geminids meteor shower involved analyzing spectrograms to correlate radio with visual.

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26

27 **Abstract**

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

38 **Plain Language Summary**

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

45 **1 Introduction**

46 When observing bright meteors, it has been reported that a sound is heard, which is believed to
47 be produced by the meteors themselves (Halley, 1714) and Blagdon (1784) did the first scientific
48 study on this phenomenon. However, considering that light travels faster than sound, this
49 phenomenon seems strange. Based on the Electrophonic effect, meteors generate EM waves that
50 can be converted into audible sounds by metal objects near observers (Keay, 1980). Many
51 researchers, such as Keay (1980), and Beech et al. (1995), have extensively studied the
52 relationship between meteors and EM signals, particularly in the ELF/VLF range, aiming to
53 connect these signals with observable meteor events. Keay (1991) established criteria for
54 perceiving electrophonic sound, suggesting a minimum fireball brightness and duration needed
55 for these EM signals to be heard. Beech et al. (1995), Garaj et al. (1999), and Price and Blum
56 (2000) recorded ELF/VLF signals related to meteor events, attempting to correlate these signals
57 with visual records but faced challenges in clear association due to various factors such as
58 equipment limitations and timing issues. Studies encountered difficulties distinguishing genuine
59 meteor-related ELF/VLF signals from the prevalent background ELF/VLF noise caused by
60 lightning and man-made sources like naval transmissions and power line harmonic radiation.

61 Price and Blum (2000) reported detecting ELF/VLF signals alongside fireballs during the 1999
62 Leonid meteor storm. However, they faced challenges in definitively associating these ELF/VLF
63 signals with specific fireball occurrences due to timing discrepancies in their optical records.
64 They noted that the general occurrence of ELF/VLF signals was more prevalent during the peak

65 of the meteor storm. Additionally, they argued that the ELF/VLF signals they detected peaked at
66 a frequency distinct from those typically associated with lightning, suggesting an alternate source,
67 possibly fainter meteors. Despite these observations, they could not establish a direct link
68 between the recorded ELF/VLF signals and individual fireball events.

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

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

83 Our study analyzes 'meteors' direct ELF/VLF emissions during the peak of the Geminids meteor
84 shower 2017, known for its elevated ZHR (Zenithal Hourly Rate), which is usually about 100
85 meteors per hour. Our methodology involves identifying the meteor's frequency-time diagram
86 (spectrogram) amidst other recognized local and natural noises in these frequency bands. By
87 comparing visual meteor observations and radio-based detections, an attempt is made to identify
88 specific spectrogram patterns related to meteors. Section 2 provides a detailed description of the
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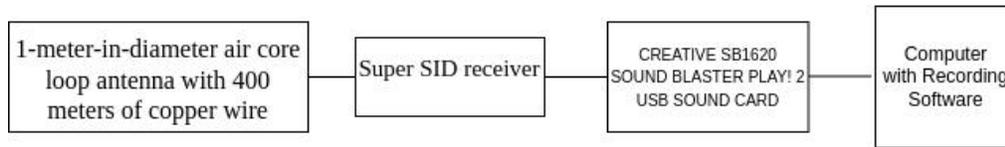
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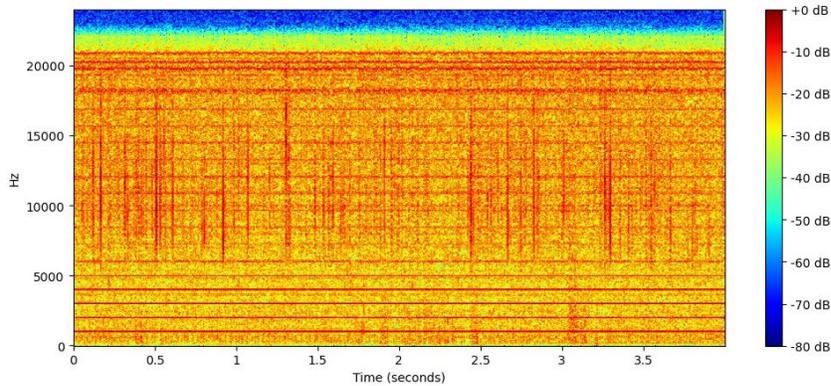
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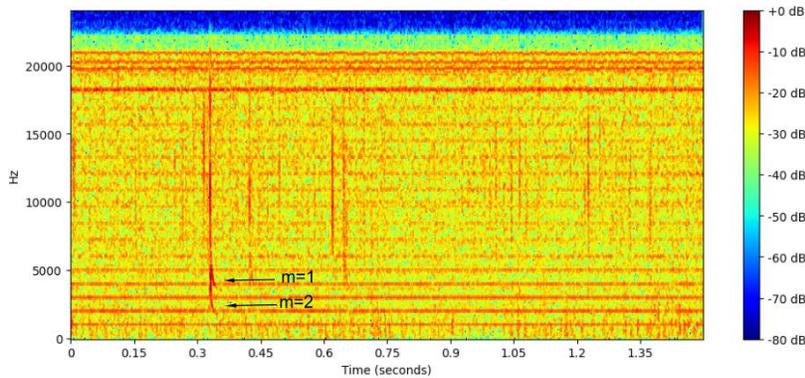
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204 occurrences attributed to $m=1$ and 20% to $m=2$; no higher modes were detected. The average
205 cutoff frequency for $m=1$ was approximately ~2.3 kHz, while for $m=2$, it was around ~4 kHz,
206 leading to an estimate of the ionospheric reflection height to be about ~70 km. It is worth noting
207 that other types of lightning signals were not detected during our observation, therefore we
208 omitted their explanation.

209
210 **3.4. Meteors**

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

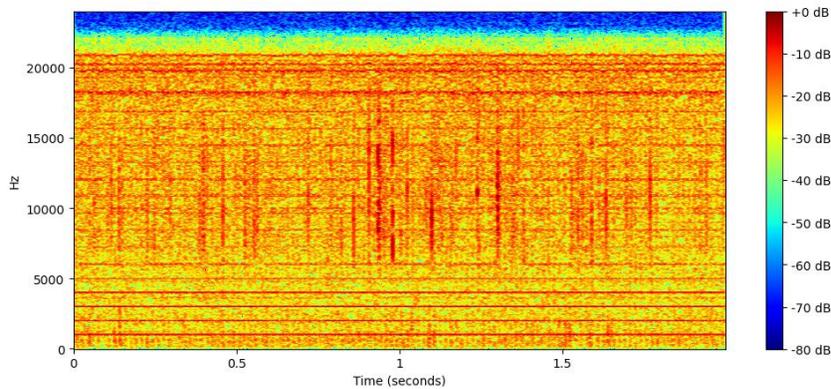
216 **4 Meteor Detection**

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

222 Based on previous ELF/VLF observations of the Geminids conducted by astronomers in Iran in
223 2011 (Lashkari et al., 2011), it was reported that the detected meteors had frequencies ranging
224 from several Hz to 2 KHz and exhibited properties mentioned earlier. We sought similar
225 spectrogram patterns in our observations. The durations of meteor signals during their
226 occurrence are random, and most of them match with the visual observations. Some occurrences
227 could belong to meteors that were too weak to produce visible light or were missed by the team
228 and were considered to be errors. Figure 6 shows a sample of the signals we acquired using the
229 setup, with the accepted meteor signatures identified. We also detected several signals stronger
230 than the meteors, as shown in Figure 7, that we could not find their pattern reported in the

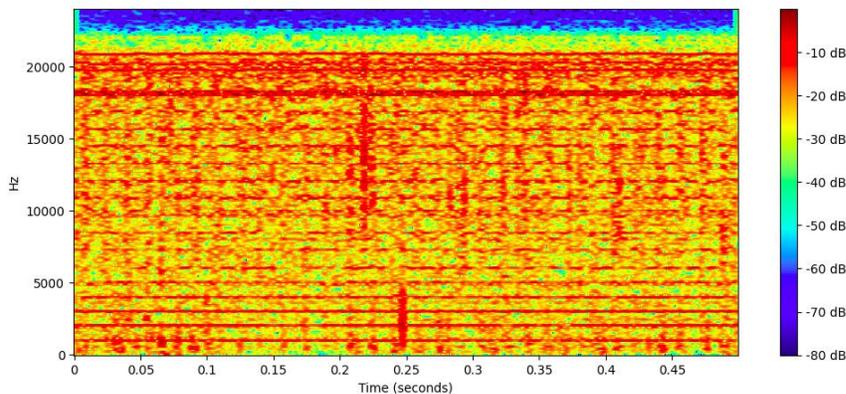
231 literature to the best of our knowledge, which are highly likely to be originated from fireballs or
232 bolides.

233
234



235
236 Figure 6: Spectrogram of some meteor signatures matching with visual observations and
237 previous studies

238
239



240
241 Figure 7: Spectrogram of signatures likely related to fireballs or bolides

242 5 Conclusions

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

250 We utilized a setup consisting of the SuperSID receiver and a fabricated loop antenna. The setup
251 is operated in a remote location where the local ionosphere was never studied before to minimize
252 the noises and interferences to ensure a high-quality recording. The signal is recorded in parallel
253 with logging the visual appearances of the meteors. The recordings were analyzed considering

254 the known patterns of different potential interference and noise sources, and the possible meteor
255 EM radiations were identified.

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

260

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264 Prof. Morris Cohen for their invaluable assistance and support throughout this project.

265

266 **Open Research**

267 **Data Availability Statement**

268 The data used in this study was collected independently using a dedicated antenna and receiver.
269 The collected data has been stored as WAV files and is publicly archived in the Zenodo
270 repository at <https://zenodo.org/records/10818759>. The analysis was conducted using Python
271 3.11.5, and the Jupyter notebook used to plot the spectrograms is available in the Zenodo
272 repository at <https://zenodo.org/doi/10.5281/zenodo.10818599>. Additionally, the executed
273 notebook is available for public access in the Binder repository at
274 <https://mybinder.org/v2/zenodo/10.5281/zenodo.10903958/>. It is possible to reproduce the data
275 visualizations presented in this article by modifying the time range and file repository.

276

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