

# 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 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  $\geq 40$  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  $\sim 25$  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

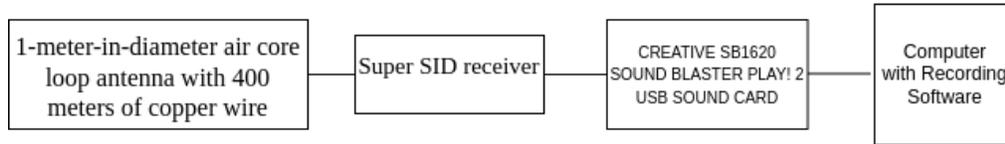
Given that meteor signals can originate from any direction in the sky rather than just from the apparent radiant of the meteor shower, employing an omnidirectional antenna is essential. Small loop antennas, with a perimeter much smaller than a wavelength, tend to exhibit a more omnidirectional radiation 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  $34.76^\circ$   
 145 and a longitude of  $52.17^\circ$ . 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.

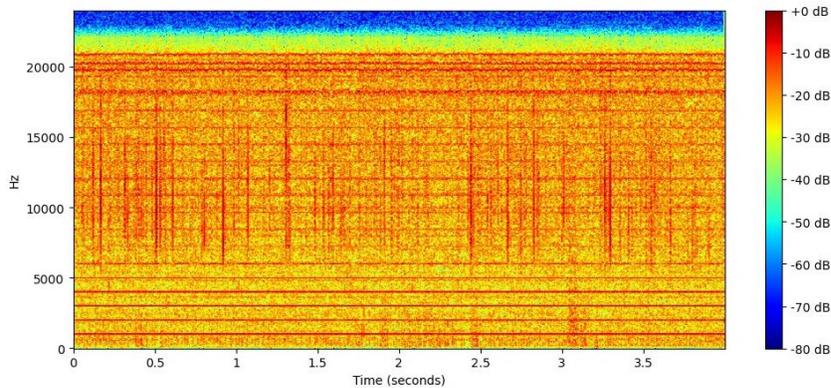
165 Radio continuum radiation generated by lightning, referred to as lightning's signal, can be  
 166 categorized into three distinct types. These categories are known as Sferic, Chorus, and Whistler  
 167 (Volland, 1995). Each type represents a specific pattern in the spectrogram and provides  
 168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

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#### 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.

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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).

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

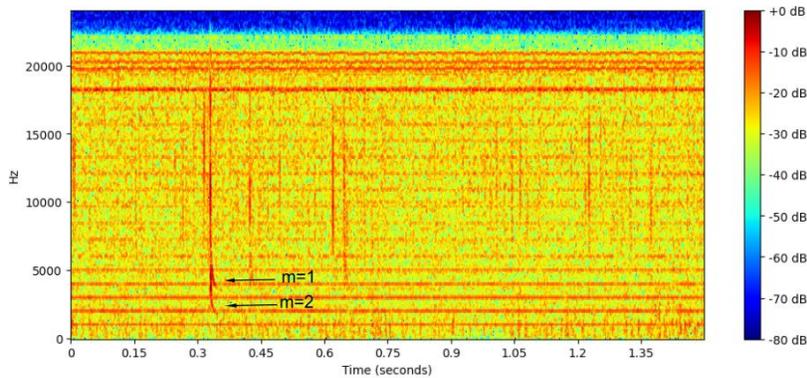
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198 Distinct electromagnetic radiation patterns known as modes—transverse electric (TE) and trans-  
199 verse magnetic (TM)—are propagated within the EIWG. Each mode can have various orders and  
200 propagates only above its corresponding cutoff 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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206 Figure 5: tweeks spectrogram detected by the equipment used in this experiment  
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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)

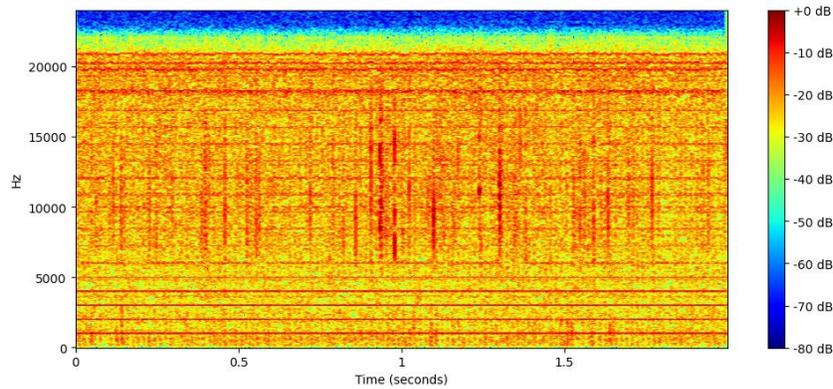
## 222 4 Meteor Detection

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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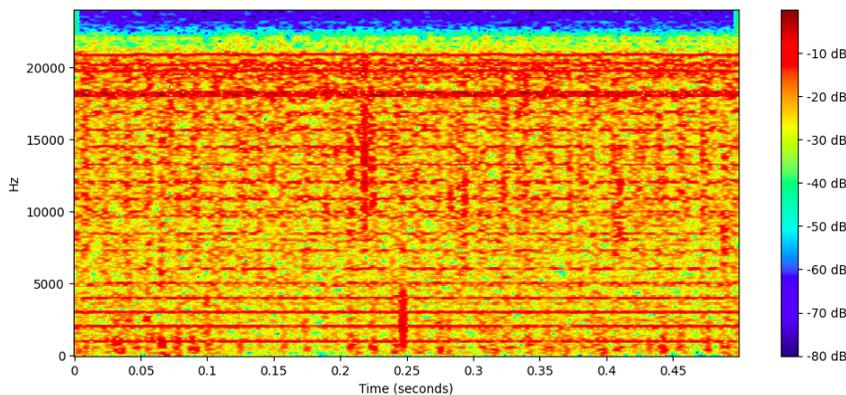


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241 Figure 6: Spectrogram of some meteor signatures matching with visual observations and  
 242 previous studies

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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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### **Key Points:**

20

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

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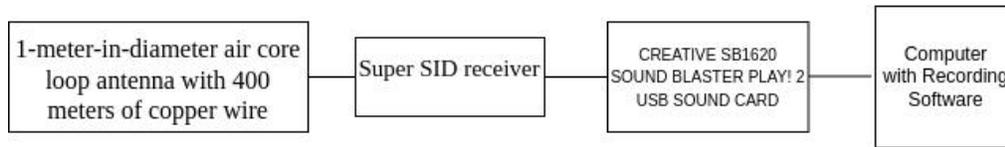
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Figure 1: The Super SID receiver used in this experiment

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.



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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137 The observation was conducted in a remote location in Semnan, Iran, with a latitude of  $34.76^\circ$   
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### 145 3 Distinguishing Meteor Signals in Spectrogram Amidst Unwanted Radiations

146

147 The ELF and VLF frequency bands containing meteor signals often experience high levels of  
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 151 ELF/VLF radiations, with hundreds of pulses occurring in a single second at high speeds (Rust,  
 152 1988). This phenomenon, coupled with the Earth-ionospheric waveguide (EIWG) that reflects  
 153 these electromagnetic waves at altitudes ranging from 50 to 150 kilometers, can result in the  
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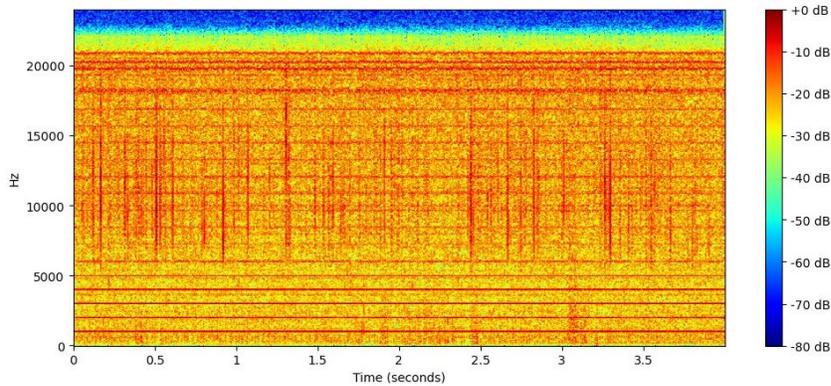
158 Radio continuum radiation generated by lightning, referred to as lightning's signal, can be  
 159 categorized into three distinct types. These categories are known as Sferic, Chorus, and Whistler  
 160 (Volland, 1995). Each type represents a specific pattern in the spectrogram and provides  
 161 valuable insights into the nature and behavior of these electromagnetic phenomena.

162

#### 163 3.1. Sferics

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

171



172  
173 Figure 4: Sferics spectrogram (random vertical orange sharp lines) detected by the equipment  
174 used in this experiment

175  
176 **3.1.2. Tweaks**

177  
178 A specific type of atmospheric phenomenon, tweaks, involves the refraction of certain Sferics  
179 through various ionosphere layers. This process provides valuable information about  
180 the 'ionosphere's electron density, reflection height, and the distances traveled by the reflected  
181 wave (Hiroyo et al., 2003). Spectrogram patterns of these refracted Sferics can be used to analyze  
182 these properties. The cutoff frequency of the EIWG, around 1.8 kHz (Budden, 1961), causes  
183 noticeable dispersion in these waves. Reflection by the lower ionosphere renders them valuable  
184 for studying altitudes below 100 km.

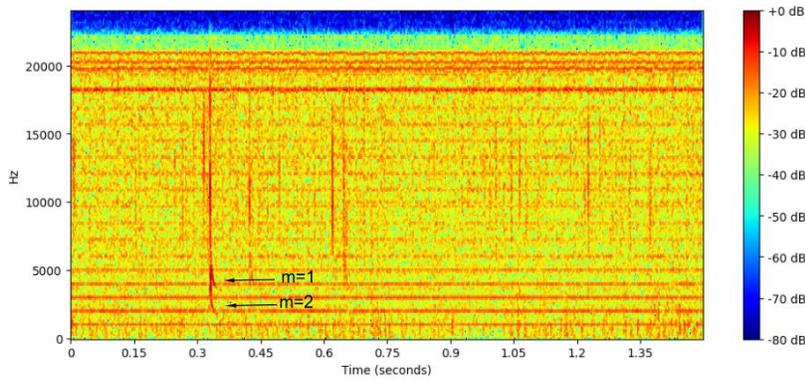
185 The strong dispersion near the 'EIWG's cutoff frequency is revealed by tweak atmospherics. The  
186 cutoff frequency,  $f_c$ , can be obtained from the spectrogram of tweaks, allowing for the estimation  
187 of the local EIWG height  $h$  using (1), where  $c = 299792458$  m/s is the velocity of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

189 
$$f_c = c/2h \quad (1)$$

190  
191 Distinct electromagnetic radiation patterns known as modes—transverse electric (TE) and  
192 transverse magnetic (TM)—are propagated within the EIWG. Each mode can have various  
193 orders and propagates only above its corresponding cutoff frequency to satisfy the boundary  
194 conditions of the waveguide. The cutoff frequency of the  $m$ th mode is represented by: (Budden,  
195 1961)

196 
$$f_{cm} = mc/2h \quad (2)$$

197  
198



199  
200 Figure 5: tweeks spectrogram detected by the equipment used in this experiment  
201

202 Approximately ~6000 sferics and ~491 tweeks were recorded during our observation. Among the  
203 tweeks, instances were observed with  $m=1$  and  $m=2$  propagation modes, with 80% of  
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)

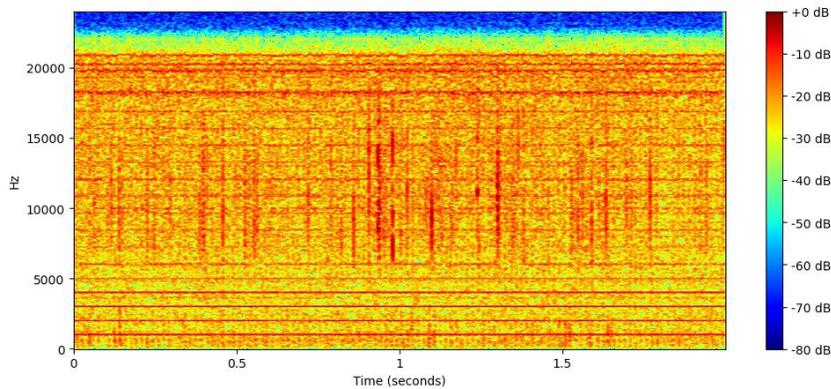
### 216 4 Meteor Detection

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

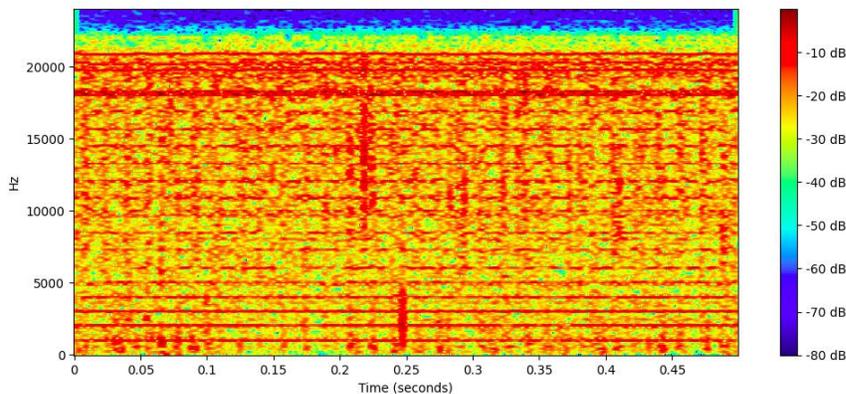
231 literature to the best of our knowledge, which are highly likely to be originated from fireballs or  
232 bolides.

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

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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

## 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.

276

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

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[Samane.aghelasand@gmail.com](mailto:Samane.aghelasand@gmail.com))

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### **Key Points:**

20

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.

23

24

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

25

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,  
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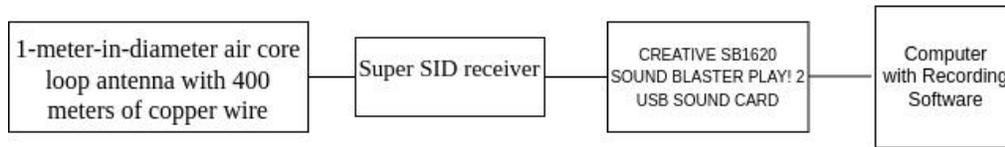
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Figure 1: The Super SID receiver used in this experiment

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### 145 3 Distinguishing Meteor Signals in Spectrogram Amidst Unwanted Radiations

146

147 The ELF and VLF frequency bands containing meteor signals often experience high levels of  
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 156 between signals originating from meteors and those from other sources, such as lightning, to  
 157 identify and study the signals produced by meteors accurately.

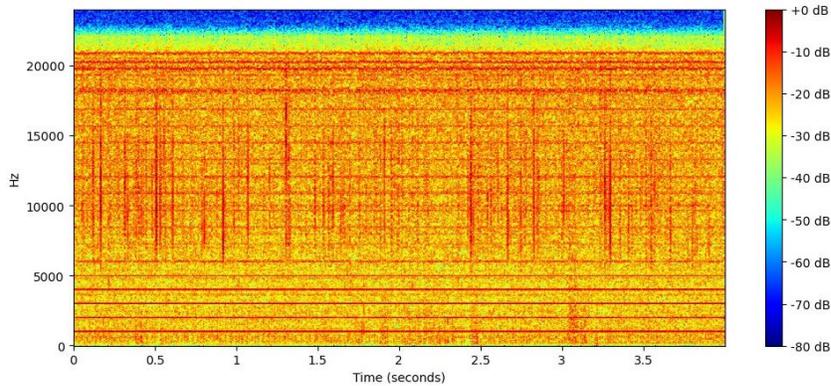
158 Radio continuum radiation generated by lightning, referred to as lightning's signal, can be  
 159 categorized into three distinct types. These categories are known as Sferic, Chorus, and Whistler  
 160 (Volland, 1995). Each type represents a specific pattern in the spectrogram and provides  
 161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

162

#### 163 3.1. Sferics

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

171



172  
173 Figure 4: Sferics spectrogram (random vertical orange sharp lines) detected by the equipment  
174 used in this experiment

175  
176 **3.1.2. Tweaks**

177  
178 A specific type of atmospheric phenomenon, tweaks, involves the refraction of certain Sferics  
179 through various ionosphere layers. This process provides valuable information about  
180 the 'ionosphere's electron density, reflection height, and the distances traveled by the reflected  
181 wave (Hiroyo et al., 2003). Spectrogram patterns of these refracted Sferics can be used to analyze  
182 these properties. The cutoff frequency of the EIWG, around 1.8 kHz (Budden, 1961), causes  
183 noticeable dispersion in these waves. Reflection by the lower ionosphere renders them valuable  
184 for studying altitudes below 100 km.

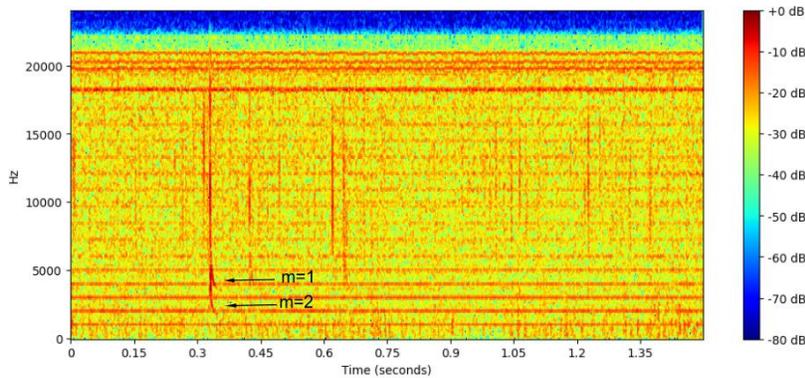
185 The strong dispersion near the 'EIWG's cutoff frequency is revealed by tweak atmospherics. The  
186 cutoff frequency,  $f_c$ , can be obtained from the spectrogram of tweaks, allowing for the estimation  
187 of the local EIWG height  $h$  using (1), where  $c = 299792458$  m/s is the velocity of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

$$189 \quad f_c = c/2h \quad (1)$$

190  
191 Distinct electromagnetic radiation patterns known as modes—transverse electric (TE) and  
192 transverse magnetic (TM)—are propagated within the EIWG. Each mode can have various  
193 orders and propagates only above its corresponding cutoff frequency to satisfy the boundary  
194 conditions of the waveguide. The cutoff frequency of the  $m$ th mode is represented by: (Budden,  
195 1961)

$$196 \quad f_{cm} = mc/2h \quad (2)$$

197  
198



199  
200 Figure 5: tweeks spectrogram detected by the equipment used in this experiment  
201

202 Approximately ~6000 sferics and ~491 tweeks were recorded during our observation. Among the  
203 tweeks, instances were observed with  $m=1$  and  $m=2$  propagation modes, with 80% of  
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)

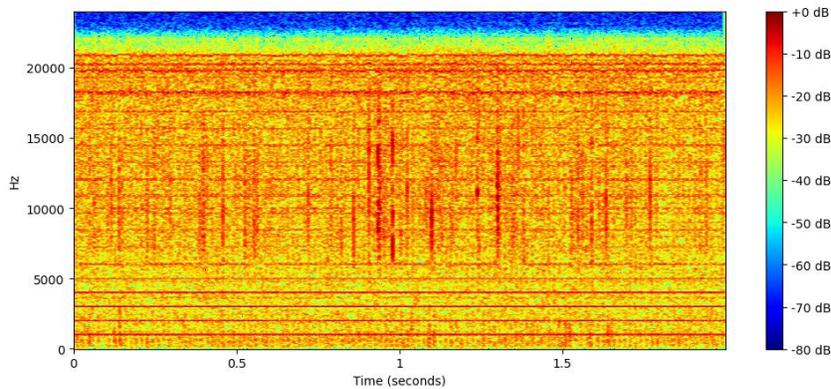
216 **4 Meteor Detection**

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

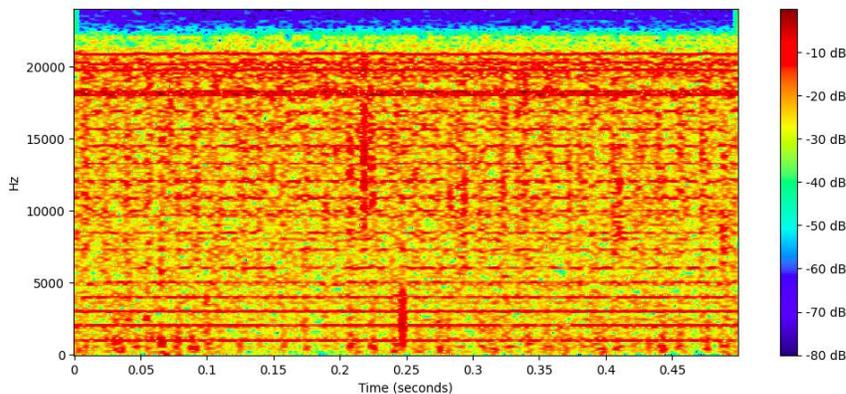
231 literature to the best of our knowledge, which are highly likely to be originated from fireballs or  
232 bolides.

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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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.

276

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