Solar-Terrestrial Physics. 2022. Vol. 8. Iss. 1. P. 62–68. DOI: 10.12737/stp-81202208. © 2022
A.G. Sorokin, V.A. Dobrynin. Published by INFRA-M Academic Publishing House

UDC 534-6
DOI: 10.12737/stp-81202208

Received October 11, 2021
Accepted December 09, 2021

METHOD OF STUDYING INFRASOUND WAVES FROM THUNDERSTORMS

A.G. Sorokin
Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, sor@iszf.irk.ru

V.A. Dobrynin
Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, dobrynin@iszf.irk.ru

Abstract. The paper provides an overview of studies of infrasound signals from thunderstorms over a period of more than 30 years. We deal with several types of infrasound signals from thunderstorms detected at the ISTP SB RAS infrasound station Badary in Buryatia. Special attention is paid to signals arising during the rarefaction phase. A mechanism for generating signals of this type by converting the energy of the electrostatic field into fluctuations in the pressure field was proposed by Dessler in 1973. We propose a method for identifying thunderstorm infrasound signals of various types: 1 — signals from an expanding thermal lightning channel; 2 — signals with an electrostatic generation mechanism. Using infrasound signals recorded earlier at the station in Buryatia as an example, we discuss the validity of the thunderstorm cloud model and assess some parameters of the thunderstorm source of infrasound.

Keywords: atmosphere, thunderstorm, infrasound, lightning channel, dangerous natural phenomena.

INTRODUCTION

About a hundred of lightning discharges occur every second around the world; each releases an energy of ~$1.6 \cdot 10^{16}$ erg. It is therefore understandable that there is great interest in studying such an important phenomenon as atmospheric thunder, whose infrasonic radiation during a thunderstorm consumes a great deal of energy.

Note that the research into infrasonic radiation from thunderstorms has been significantly developed over recent decades due to the advent of the International Monitoring System (IMS), created to ensure the Comprehensive test Ban Treaty (CTBT), which includes a separate infrasonic segment (e.g., [Assink et al ., 2008]). Within the framework of CTBT, it is required to expand the online database of infrasound signals, including those from thunderstorms.

A fairly large number of scientific papers have been devoted to the experimental and theoretical study of thunder. It was initiated in Russia as early as the middle of the 18th century by Mikhail Lomonosov and Georg Rikhman, who first defined the electrical nature of lightning discharges. The nature of acoustic thunder was first explored in detail by Schmidt in 1914, and his main finding was that acoustic thunder exists in both the audible sound and lower infrasonic ranges [Schmidt, 1914]. He pointed to the existence of infrasonic oscilations with an amplitude of ~1 Pa at a frequency of 2 Hz. Some researchers (e.g., [Arabagy, 1952, 1965]) report the presence of the strongest thunderclaps with an amplitude of ~100 Pa with a positive phase of air compression at a frequency of ~0.5 Hz.

CURRENT STATUS OF RESEARCH INTO THE INFRASONIC FIELD OF THUNDERSTORM

Although lightning is one of the best known natural phenomena, it remains poorly understood. The most seemingly simple questions about how lightning is initiated inside thunderclouds and how sound waves then propagate for many tens of kilometers are beginning to clear up only now. According to [Farges, Blanc, 2010], most studies in this direction were started and carried out in 1960–1985 [Uman, 1987; Rakov, Uman, 2003]. These studies generally dealt with the audible region of the frequency range, and only a few examined signals with frequencies below 20 Hz. Such signals usually propagated no further than 20–25 km and had a 2–25 microbar amplitude with a total duration of ~10 s; therefore, they were detected not too far from a source of thunderstorm activity. There is convincing experimental evidence that thunderstorms are active sources of infrasound waves covering a wide height range from the troposphere to the thermosphere [Blanc, 1985; Few, 1995; Drob et al., 2003]. The data points to electrostatic excitation of 0.1–1 Hz infrasound waves from thunderclouds and recently discovered high-frequency infrasound emission, which correlates with lightning-induced transient light events in the mesosphere, called sprites [Liszka, 2004; Farges et al., 2005; Liszka, Hobara, 2006].

Holmes et al. [1971] report the results of the analysis of forty thunderstorm events. The author identifies two main types of infrasonic thunder associated with lightning discharges: a) lightning discharges between clouds (cloud–cloud, CC), with thunder having dominant frequencies from 4 to 30 Hz; b) most frequent cloud-to-ground (CG) lightning discharges with thunder intensity higher and prevailing frequencies above 50 Hz.

Various physical mechanisms have been proposed to explain the causes of sonic and infrasonic thunder. The effect of thunder in the sound range occurs due to the thermal energy release in a lightning channel during a lightning discharge. The infrasound part of thunder can be attributed to the transformation of the electrostatic field of a thundercloud into sound. For instance, in the former case, Few [1982, 1985] associates the expansion of air heated by a lightning discharge with a shock wave transformed into an acoustic N-shaped pressure pulse at a distance of several meters from the channel. This model can explain the frequency spectrum of thunder with a peak around 50 Hz, but not the infrasound low-frequency peak. The fundamentals of the electrostatic model designed to explain the origin of such an infrasound were presented in [Wilson, 1920]. The main point is the appearance of a low pressure zone inside the charged layers located at the base and top of a thundercloud. In the model of a single flat layer with a uniform volume charge density of the same sign, the pressure minimum is in the middle of the layer, where the electric field E vanishes. The pressure decreases by [Wilson, 1920]

$$\Delta p = \varepsilon_0 E_0^2/2 \ \text{N/m}^2, \qquad (1)$$

where E_0 is the electric field on the layer surface (in MKS units), and ε_0 is the permittivity of free space.

After a lightning discharge, the charge disappears, and the low-pressure zone returns to its original state, breaking up into upward and downward rarefaction pulses.

Expression (1) for the rarefaction pulse amplitude in a low-pressure zone inside a flat uniformly charged layer follows directly from Gauss equation (2) and the assumption of static equilibrium — equality between electric force and pressure gradient (3):

$$\nabla \cdot E = \frac{dE}{dz} = \frac{\rho_c}{\varepsilon_0}, \qquad (2)$$

$$\nabla p = \frac{dp}{dz} = \rho_c E, \qquad (3)$$

where p is the air pressure; ρ_c is the charge density. For $\rho_c \neq 0 \, dp/dE = \varepsilon_0 E$ and the spatial pressure variation inside the charged layer

$$\Delta p = p - p_c = \left(E^2 - E_c^2\right)/2,$$

where the index "c" stands for the gas pressure and the electric field strength in the middle of the layer. Since E_c=0, the pressure gradient between the boundary of the charged layer and its middle is determined by Formula (1).

Dessler [1973] confirmed the validity of such an estimate at the microscopic level and brought the idea put forward in [Wilson, 1920] to practical use.

Works on atmospheric infrasound and its relationship with electric fields were started in Holland as early as the 1970s [Holmes et al., 1971]; and in the European Russia two large centers for complex observations were created in the Moscow area (Mikhnevo Observatory) and in the center of the city of Moscow (Geophysical Monitoring Center at the Institute of Geosphere Dynamics RAS) [https://symp.iao.ru/files/symp/aoo/25/ru/abstr_10561.pdf; Adushkin et al., 2020]. An extensive and fruitful work on the morphology of thunderstorms in Western Siberia has been carried out at Tomsk State University, where the intensity and frequency of occurrence of regional thunderstorms were classified [Voznesenskaya et al., 2012].

The papers [Erushchenkov et al., 1976] in SibIZMIR SB RAS (now ISTP SB RAS) and abroad [Balachandran, 1979; Bohannon et al., 1977] were specifically aimed at studying statistical characteristics of infrasonic thunder branch signals to determine the most probable amplitude and waveform of the infrasound signal in the electrostatic generation mechanism of infrasound from a thunderstorm.

In Eastern Siberia, signals from thunderstorms were observed for the first time by Erushchenkov et al. [1976] at Badary station in Buryatia on July 22 and 23, 1975 during visual observation of a thunderstorm. Analysis of the data has identified three characteristic types of infrasonic oscillations from a thunderstorm (Figure 1, *a*–*c*).

The signal waveform of these types [Erushchenkov et al., 1976] fits quite well the model curve (Figure 3, *a*) obtained from the numerical analysis carried out by Pasko [2009].

The signal of the first type is infrasound pulses that begin with the compression phase followed by the rarefaction phase with a duration of ~2 s and an amplitude up to 4 μbar (see Figure 1, *a*). This is a quite often observed infrasound from thunderstorms; the number of such signals is more than 60 %.

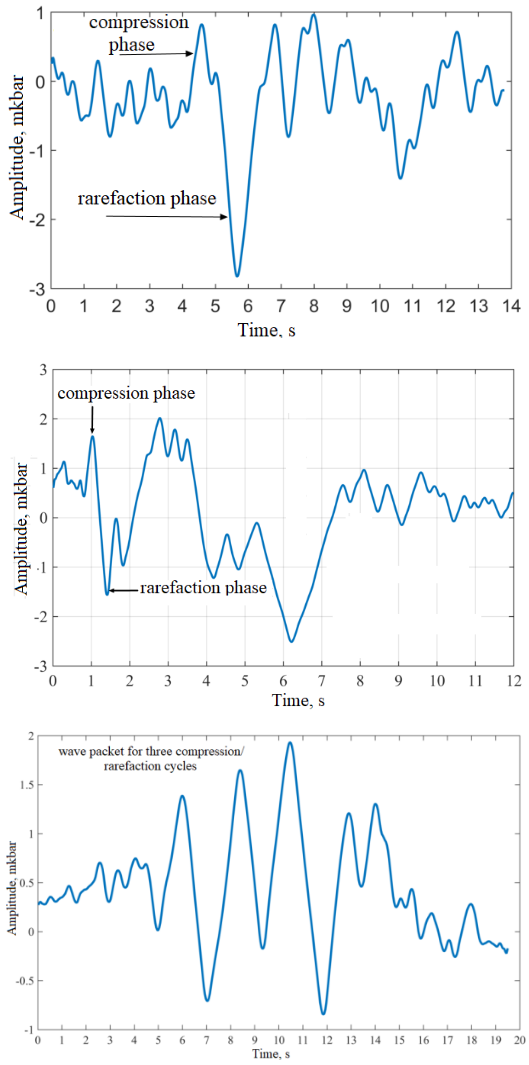

Figure 1. Infrasound from a thunderstorm with the positive arrival phase and the subsequent rarefaction phase (*a*); starting with the compression phase followed by rarefaction phases (*b*); in the form of a train of signals consisting of three compression and rarefaction cycles (*c*)

The signal of the second type is an infrasound signal of an amplitude up to 4.5 μbar which also begins with the compression phase followed by several 2–2.5 s rarefaction phases (see Figure 1, b*)*. Its excitation is associated with the electrostatic mechanism [Dessler, 1973]. There are about 8–10 % of signals of this type.

Infrasound signals of the third type, shown in Figure 1, *c*, are interpreted as wave packets with up to 12 oscillations, a period of ~2.5 s, and an amplitude of less than 3 μbar [Erushchenkov et al., 1976]. The nature of such packets is unclear, but we believe that such a cyclic signal structure can be associated with periodic compression and rarefaction cycles in the charged layer of a thundercloud.

Suggestions have been made that duration of the positive phase (compression) may characterize the rate of growth of an electric charge in the initial stage of a thunderstorm and hence the magnitude of the electric charge in a thundercloud. At the same time, the product of the duration of a negative pulse (rarefaction) and the speed of sound estimates the characteristic thickness of the charge layer at the base of a thundercloud [Dessler, 1973; Pasko, 2009].

Our current task is to develop a method for identifying types of signals from thunderstorms (lightnings) based on existing experience and experimental data.

DESCRIPTION OF THE AREA OF DETECTION OF INFRASOUND FROM THUNDERSTORMS

Active manifestation of thunderstorms in the vicinity of the station Badary in Buryatia and their parameters in this region are closely related to the presence of the extended mountain range of the Eastern Sayan Mountains with a peak height over 3000 m [Filippov, 1974] (Figure 2). Even in relatively hot summers, the Eastern Sayan Mountains have a large reserve of moisture in the form of glaciers lying on the slopes of ridges and stormy mountain rivers flowing through wide valleys. Excess moisture in the atmosphere in summer during evaporation contributes to the intensive formation of clouds in the mountains. Developed cloudiness in its movement to the southeast descends into the Tunka valley (see Figure 2) and, under conditions of the mountainous relief and strong turbulence, acquires the features of a moisture-saturated dark thundercloud with a charge of thunderstorm and rain. Such conditions for the formation and development of thunderclouds are usually observed in the Eastern Sayan Mountains near the watershed and the confluence of the right and left Shumak rivers, as well as the Kitoy River, which are the main sources of atmospheric moisture for the development of thunderstorm activity in the region (see Figure 2).

INTERPRETATION OF INFRASOUND SIGNAL WITH ELECTROSTATIC GENERATION MECHANISM

In the 1960–1980s, a significant amount of work was done on observations of infrasound signals from thunderstorms. These works report on various waveforms of signals recorded in different regions [Bowman, Bedard, 1971; Holmes et al., 1971; Dessler, 1973; Erushchenkov et al., 1976; Bohannon et al., 1977; Balachandran, 1979]. Dessler [1973] presented a new approach to explaining infrasound signals with the rarefaction phase and tried to characterize the state of the thunderstorm atmosphere. Several decades later, Pasko [2009] numerically analyzed the generation of infrasound signals with successive compression and rarefaction phases during a lightning discharge. The author used a linearized system of gas dynamics equations with a number of simplifications and an infrasound signal source model in the form of a layer with uniform distribution of a volume charge whose density was artificially changed in time, simulating the scenario of events. The idea of previous researchers that the charging phase of a gas layer is accompanied by its rapid expansion due to repulsion of like charges, the number of which is growing, was numerically supported. This leads to the formation of an infrasound signal compression pulse. The expansion of the layer implies the formation of a rarefaction region inside it with low gas pressure. After discharge, this region becomes a source of an upward and downward rarefaction pulse. The characteristic form of pressure perturbation in time is shown with explanations in Figure 3, *a*; and the corresponding thunderstorm layer model, in Figure 3, *b*.

Conditions for the applicability of the thundercloud model

The main parameters of the infrasound thunderstorm source model are as follows.

1. Cloud height is ~5 km (height of the middle part of the cloud, including the vertical extent of the cloud). The charge shape — a flat layer several hundred meters high (a_c=400 m) — is consistent with the duration of infrasound pulses, as in other papers [Balachandran, 1979].

2. Location of the recorder is close to the location under a thundercloud.

3. Distribution of the electric charge over the height of a single-layer cloud is symmetrical about the median plane.

4. Peak charge density is 20 nC/m^3.

5. The electric field strength E according to [Wilson, 1920] has only the z component (vertical component). $E_{z\text{-}max}$=4.5·10^5 V/m. The breakdown electric field at a height of 5 km E_b=17·10^5 V/m, this field value at the ground level E_g=31·10^5 V/m [Pasko, 2006].

Output parameters of the model are the results of measurements of infrasound from thunderstorms.

1. Type of signal — compression or rarefaction (usual shock-thermal or electrostatic radiation mechanism).

2. By the duration of the compression phase, we estimate the time for charge accumulation to a critical level and the occurence of a discharge (breakdown).

3. By the duration of the rarefaction phase, we estimate the spatial cloud charge size.

4. The amplitude of the negative pressure (rarefaction) is proportional to the square of the amplitude of the electric field strength in the cloud. This method is meant to be used for higher resolution data with simultaneous measurement of electric field strength during a thunderstorm.

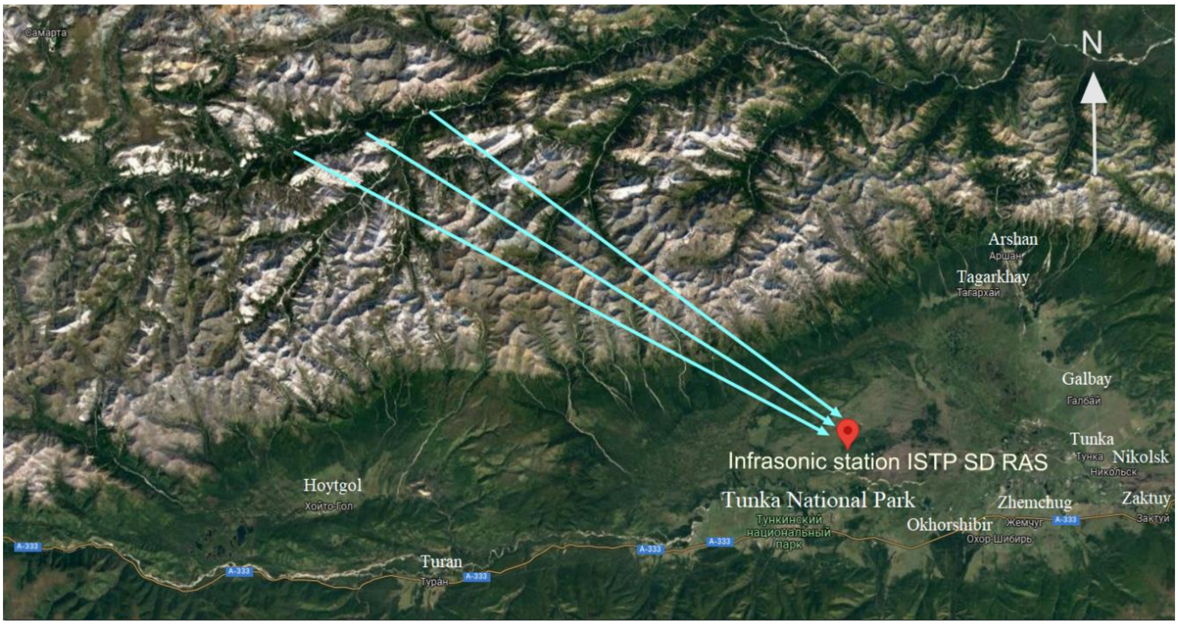

Figure 2. Location of the station in the settlement of Badary in 1975 and the main directions of thunderstorm arrival

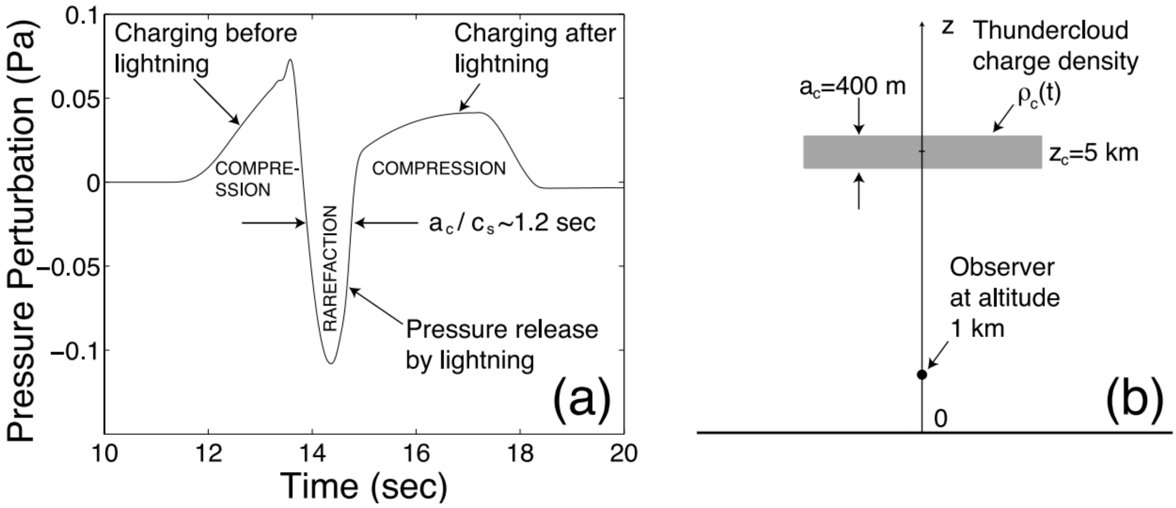

Figure 3. Estimated waveform of an infrasound signal from a thundercloud before and after a lightning discharge (*a*); choice of a thundercloud model [Pasko, 2009] (*b*). Courtesy of John Wiley and Sons and Copyright Clearance Center, License Number 5158670709190, 30 Sep. 2021

METHODOLOGICAL APPROACHES TO INTERPRETING INFRASOUND SIGNALS FROM THUNDERSTORMS

The model proposed by Pasko [2009] and used in this study to explain the infrasound signal structure is one-dimensional. The Z axis is directed vertically, as shown in Figure 3, *b*. The spatially uniform charge density ρ_c is limited inside the layer with a vertical dimension a_c=400 m centered at a height z_c=5 km.

The selected vertical extent of the layer corresponds to typical values of several hundred meters, as in previous publications, to match and explain the duration of the experimentally observed infrasound pulses.

Figure 3, *a* presents one of the results of model calculations of the formation of an infrasound pulse during a lightning discharge [Pasko, 2009]. Along the Y axis is the pressure perturbation in Pascals; along the X axis is the time. Starting from about the 12th second of the current time, there is an increase in the compression pulse associated with an increase in the charge in the layer (see the diagram Δ of charge removal in a cloud layer during a lightning discharge (Δ=50 %) in Figure 2) [Pasko, 2009]. The shift in time between the action of the charge and the infrasound rarefaction pulse is due to wave propagation to a remote infrasound receiver.

Interpretation of infrasound signal No. 1 on July 22, 1975

Infrasound signal No. 1 was recorded at the station Badary in the Tunka Region of Buryatia on July 22, 1975 and was a single pulse with a negative pressure rarefaction phase (Figure 4, *a*). It can be seen that the pulse is not complicated by interference from multiple thunderclaps — such single pulses make up no more than 10 % of all signals detected and occur most often at the very beginning of a thunderstorm. To interpret the phenomenon, a thundercloud is best represented as a simple single-layer charged layer, as in Figure 4, *b*, where H is the height of the charge layer; a_c is the thickness of the charged layer; Δt is the period of formation of an infrasound pulse in the charged layer; c_s is the speed of sound; M1–M3 are microbarometers of the infrasound station. The measured characteristics of infrasound signal No. 1 and the estimated thundercloud parameters for this case are listed in Table 1.

A lightning discharge removes most of the charge of the thundercloud layer, and the rarefaction region remains in the center of the charged layer of the cloud. The subsequent pressure rebalancing is accompanied by the occurence of infrasound pulses of negative polarity moving upward and downward from the layer. The duration of the rarefaction pulse is determined by the time interval it takes for the rarefaction region in the charged layer to disappear. This time is $\Delta t = \frac{a_c}{c_s} = 1.2$ s, where a_c is the thickness of the charged layer of a thundercloud, equal to 400 m; $c_s \sim 330$ m/s is the speed of sound. In our case, from the analysis of infrasound signals of two types recorded at the station Badary from thunderstorms in the Tunka Region of Buryatia in July 1975, it is possible to estimate the thickness of charged layers a_{c_1} and; and, if there is a double infrasound signal, from the relation $a_{c_{1,2}} = \Delta t_{1,2} c_s$, where $\Delta t_{1,2}$ are the time scales of infrasound pulses 1 and 2 with the electrostatic generation mechanism (Figure 5, *a*, *b*).

Thus, the estimated characteristics of infrasound signals can be used to assess characteristics of a charged layer of a thundercloud, as well as values of the electric field from the charged layer that generates infrasound signals. Let us present some estimates of the parameters of the charged thunderstorm layer based on the measured infrasound parameters.

Interpretation of the waveform of an infrasound double signal on July 23, 1975

Infrasound signal No. 2 was recorded at the ISTP SB RAS station Badary on July 23, 1975 and was a pulse with a double repeating structure with a clear negative pressure rarefaction phase (Figure 5, *a*). Notice that the pulse is almost uncomplicated by interference from multiple thunderclaps; it can only be noted that the incomplete remainder of the first rarefaction pulse is superimposed on the beginning of the second rarefaction pulse approximately at the 15th second.

A thundercloud in this case can be represented as two charged layers located at close height levels H_1 and H_2, as shown in Figure 5, *b*, where H_1 and H_2 are the heights of the layer of charges Q_1 and Q_2; a_{c1} and a_{c2} are thicknesses of the charged layers; Δt_1 and Δt_2 are periods of the formation of infrasound pulses in the charged layers a_{c1} and a_{c2} respectively; M1–M3 are microbarometers of the infrasound station. The measured characteristics of infrasound signals 1 and 2 and the estimated parameters of thunderclouds for this case are listed in Table 2.

DISCUSSION AND CONCLUSION

The assumption that a lightning discharge should be preceded by a significant increase in the charge in a thundercloud is natural and quite justified. Charge accumulation is also thought to be associated with the formation of an initial compression pulse [Pasko, 2009]. Charge removal from a thundercloud during discharge generates a rarefaction pulse of duration a_c/c_s, which depends on the thickness a_c of the charge layer and the speed of sound c_s in the layer [Dessler, 1973]. Extension of the process of charging a thundercloud after lightning leads to a subsequent cycle of compression/rarefaction pulses. Note that the waveform shown in Figure 3, *a* is confirmed by many experimental results (e.g., [Erushchenkov et al., 1976; Balachandran, 1979; Few, 1985]).

The well-known paper [Dessler, 1973] considers two cases of the formation of a charged layer in a thundercloud preparing for a lightning discharge.

1. The simplest case of charge distribution in a cloud is a flat horizontal disk of radius r and thickness $d \ll r$. In this case, the charge drain causes rarefaction pulses to be emitted predominantly along the flat-disk axis so that this signal can be observed above the cloud or directly below it.

2. Another type of the spatial charge distribution can be a cylindrical form, when the length of a cylinder is much greater than its radius. In general, the cylinder axis can be tilted at an angle to the ground. In this case, a significant part of infrasound is emitted across the axis of the cylinder.

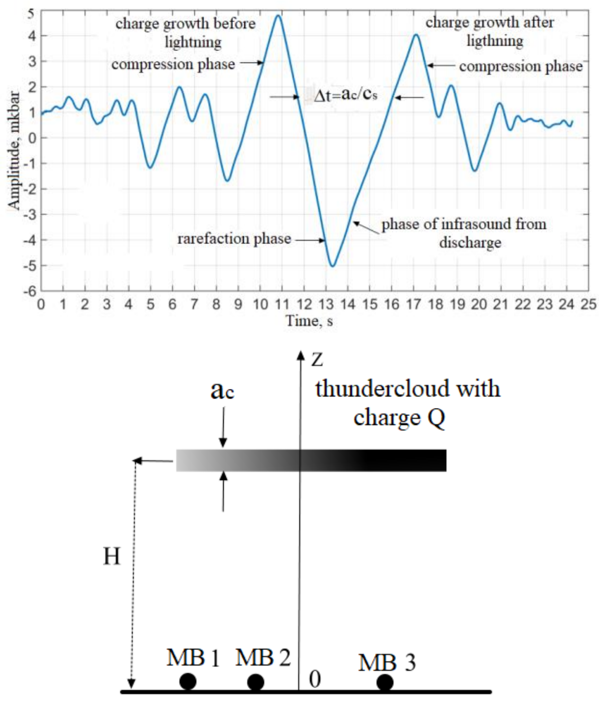

Figure 4. Interpretation of a single infrasound signal from a thunderstorm at the station Badary on July 22, 1975 (*a*); a thundercloud model for this signal (*b*)

Table 1

Characteristics of an infrasound signal and a charged layer of a thundercloud on July 22, 1975

Double signal amplitude, Pa	Duration of the compression phase, s	Duration of the rarefaction phase *Δt*, s	Thickness of a charged layer, m	Electric field strength in the layer, V/m	Charge accumulation time, s	Spatial charge scale, m
1.0	2.4	3.0	≈990	$3.3 \cdot 10^5$	2.4	≈990

Table 2

Characteristics of the first and second infrasound signals and the charged layer of a thundercloud on July 23, 1975

Double signal amplitude, Pa	Duration of the compression phase, s	Duration of the rarefaction phase	Thickness of the charged layer	Electric field strength in the layer, V/m	Charge accumulation time, s	Spatial charge scale, m
0.6	~0.7	Δt_1~2.0 c	a_{c1}~660 м	$\sim 2.6 \cdot 10^5$	~0.7	~660
0.7	1.4	Δt_2,~2.5 s	a_{c2} ~825 m	$2.8 \cdot 10^5$	1.4	~825

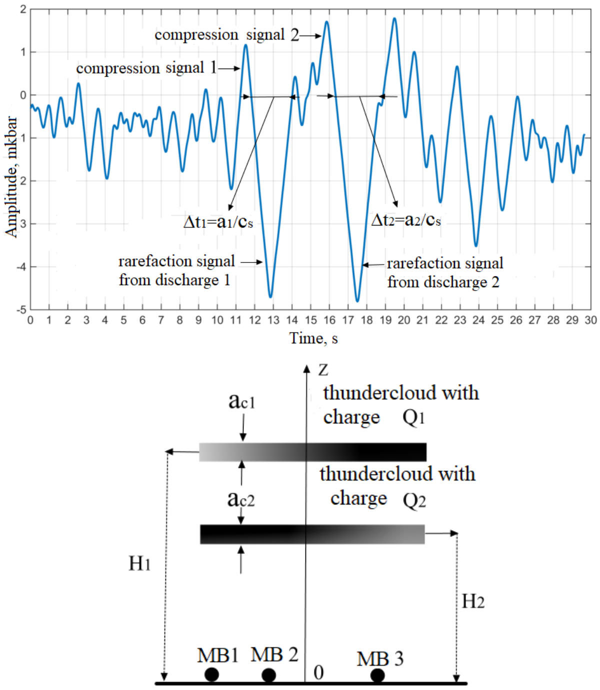

Figure 5. Interpretation of the waveform of a double infrasound signal at the station Badary on July 23, 1975 (*a*); a thundercloud model for this signal (*b*)

The estimate of the spatial distribution of a charge in the layer of a thunderstorm cloud, its waveform and scale, as well as the assessment of the magnitude of the electric field strength in the cloud depend on consideration of features of the directional pattern of infrasound from thunderstorms. This is a difficult problem that is supposed to be solved as data on infrasound signals from thunderstorms with a high time resolution is accumulated at the new infrasound station at the ISTP SB RAS Geophysical Observatory, located near the village of Tory in Buryatia.

Emphasizing the complexity of this problem, we can plot the distribution of azimuths and zenith angles (vertical angles of arrival) against a series of thunderstorms recorded by Erushchenkov A.I [Erushchenkov et al., 1976] at the station Badary in July 1975 (Figure 6).

The distribution of azimuths and vertical angles of arrival of infrasound signals with a negative phase was calculated from measurements of the delay times of rarefaction pulses between various infrasonic microphones located at the vertices of a spatial triangle with legs of 250 m. Numbers near the points and triangles in Figure 6 correspond to the numbers of wave packets (more than 40) detected at the station over this period. We can see that the infrasound sources of thunderstorm 1 (July 22, 1975) were located to the north and northeast of the station, whereas thunderstorm 2 (July 23, 1975) was mainly to the southwest of the station. Also noteworthy is that the zenith angles of arrival of radiation do not fit Dessler's prediction about concentration of radiation near zero zenith angles (practically no arrival with an angle of incidence of 0°). At the same time, it was shown in [Erushchenkov et al., 1976], as in [Balachandran, 1979], that pressure amplitude variations at two of three remote infrasonic microphones for these signals differed 2–3 times. This suggests a narrow directivity of infrasonic radiation.

At the same time, the difference between true shapes of thunderstorm layers may be significant since incoming infrasound pulses occur in a fairly wide range of zenith angles.

In conclusion, we should note shortcomings and prospects for the development of this work.

1. The flat thunderstorm layer model adopted in this work ignores the multilayer structure and interference of signals during repeated lightning discharges, but at the same time it is quite simple and allows us to explain the occurence of a low-frequency infrasound signal with the rarefaction phase.

2. The infrasonic measurement network is not dense enough to estimate angular infrasound signal spectra and requires to be expanded.

3. The spatial distribution of a charge in a cloud and its type are determined very approximately.

In addition, it is important to keep in mind the following.

1. Infrasound pulses from thunderstorms are impulsive rather than harmonic, and the wavelet analysis should be used to estimate their duration.

2. Slope of the charged layer of a thundercloud distorts the duration of the rarefaction pulse due to propagation along the layer, so it is necessary to estimate the zenith angles of infrasound arrival from thunderstorm sources.

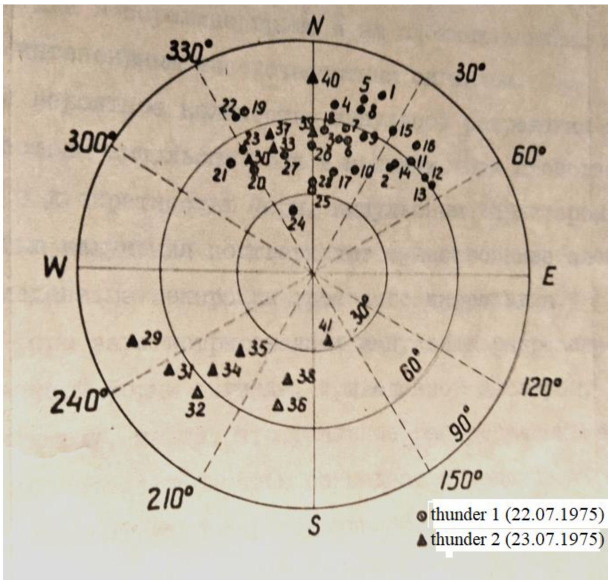

Figure 6. Location of sources of infrasound rarefaction pulses in azimuth — zenith angle (AΨ) coordinates during July 22–23, 1975 thunderstorms at the station Badary [Erushchenkov et al., 1976]

We thank the referees for the favorable attitude to our work and for the helpful comments that contribute to improving the quality of the paper. We are also grateful to A.M. Uralov for his attention to the work and for valuable advice during its discussion.

The work was financially supported by Project No. 0278-2021-0004 "Geophysical Monitoring and Complex Observations of Earth's Atmosphere and Near-Earth Space for Research in Solar-Terrestrial Physics".

REFERENCES

Adushkin V.V., Rybnov Yu.S., Spivak A.A. *Infrasound in the Atmosphere*. M.: Torus Press, 2020, 319 p. (In Russian).

Arabagy V.I. On some characteristics of thunderstorm. *Doklady AN SSSR* [Reports of AS USSR]. 1952, vol. 82, no. 3, pp. 377–378. (In Russian).

Arabagy V.I. *The spectrum of thunder*. The nature, 1965, no. 7, pp. 74–75. (In Russian).

Assink J.D., Evers L.G., Holleman I., Paulssen H. Characteristics of infrasound from lightning. *Geophys. Res. Lett*. 2008, vol. 35, L15802. DOI: 10.1029/2008GL034193.

Balachandran N.K. Infrasonic signals from thunder. *J. Geophys. Res*. 1979, vol. 84, no. C4, pp. 1735–1745.

Blanc E. Observations in the upper atmosphere of infrasonic waves from natural or artificial sources: A summary. *Ann. Geophys*. 1985, vol. 3, pp. 673–688.

Bohannon J.L., Few A.A., Dessler A.J. Detection of infrasonic pulses from thunderclouds. *Geophys. Res. Lett*. 1977, vol. 4, no. 1, pp. 49–51.

Bowman H.S., Bedard A.J. Observations of infrasound and subsonic disturbances related to severe weather. *Geophys. J.* 1971, vol. 26, iss. 1-4, pp. 215–242. DOI: 10.1111/j.1365-246X.1971.tb03396.x.

Dessler A.J. Infrasonic thunder. *J. Geophys. Res*. 1973, vol. 78, no. 12, pp. 1889–1896.

Drob D.P., Picone J.M., Garces M. Global morphology of infrasound propagation. *J. Geophys. Res*. 2003, vol. 108, no. D21, p. 4680. DOI: 10.1029/2002JD003307.

Erushchenkov A.I., Filippov A. Kh., Makukhin V.L. Infrasound waves from lightning discharge. *Issledovaniya po geomagnetizmu, aeronomii i fizike Solntsa* [Res. on Geomagnetism, Aeronomy and Solar Physics] 1976, iss. 38, pp. 73–78. (In Russian).

Farges T., Blanc E., le Pichon A., Neubert T., Allin T.H. Identification of infrasound produced by sprites during the Sprite2003 campaign. *Geophys. Res. Lett*. 2005, vol. 32, L01813. DOI: 10.1029/ 2004GL021212.

Farges T., Blanc E. Characteristics of infrasound from lightning and sprites near thunderstorm areas. *J. Geophys. Res.* 2010. Vol. 115, A00E31. DOI: 10.1029/2009JA014700.

Few A.A. Acoustic radiations from lightning. *Handbook of Atmospherics*. CRC Press, Inc., Boca Raton, Fla., 1982, vol. 2, pp. 257–289.

Few A.A. The production of lightning-associated infrasonic acoustic sources in thunderclouds. *J. Geophys. Res*. 1985, vol. 90, no. D4, 6175–6180. DOI: 10.1029/JD090ID04P06175.

Few A.A. Acoustic radiations from lightning. *Handbook of Atmospheric Electrodynamics*. CRC Press, Boca Raton, Fla. 1995, vol. 2, pp. 1–31.

Filippov A.C. *Thunderstorms of Eastern Siberia*. Hidrometeoisdat, 1974. 75 p. (In Russian).

Holmes C.R., Brook M., Krehbiel P., McCrory R. On the power spectrum and mechanism of thunder. *J. Geophys. Res*. 1971, vol. 76, no. 9, pp. 2106–2115.

Liszka L. On the possible infrasound generation by sprites. *J. Low Frequency Noise Vibration and Active Control*. 2004, vol. 23, no. 2, pp. 85–93.

Liszka L., Hobara Y. Sprite-attributed infrasonic chirps — Their detection, occurrence and properties between 1994 and 2004. *J. Atmos. Solar-Terr. Phys*. 2006, vol. 68, pp. 1179–1188.

Pasko V.P. Theoretical modeling of sprites and jets. *Sprites, Elves and Intense Lightning Discharges*. NATO Science Ser. II: Mathematics, Physics and Chemistry. 2006, vol. 225.

Pasko V.P. Mechanism of infrasonic pulses from thunderclouds. *J. Geophys. Res*. 2009, vol. 114, D08205. DOI: 10.1029/ 2008JD011145.

Rakov V.A., Uman M.A. *Lightning, Physics and Effects*. Cambridge Univ. Press, New York, 2003. 687 p.

Schmidt W. Uber den Donner – Meteorol. Z, 1914, Bd. 31, H. 10, 487–489.

Uman M.A. *The Lightning Discharge*. Academic, London, 1987, 377 p.

Voznesenskaya K.V., Kolesnik A.G., Soloviev A.V. Infrasound signals from lightning discharges. *Izvestiay High Scool, Physics*. 2012, vol. 55, no. 7. (In Russian).

Wilson C.T.R. Investigations on Lightning Discharges and on the Electric Field of Thunderstorms. *Philosophical Transactions of the Royal Society of London***.** *Series A.* 1921, vol. 221. DOI: 10.1098/RSTA.

URL: https://symp.iao.ru/files/symp/aoo/25/ru/abstr_ 10561.pdf (accessed February 24, 2022).

Original Russian version: A.G. Sorokin, V.A. Dobrynin, published in Solnechno-zemnaya fizika. 2022. Vol. 8. Iss. 1. P. 62–69. DOI: 10.12737/szf-81202208. © 2022 INFRA-M Academic Publishing House (Nauchno-Izdatelskii Tsentr INFRA-M)

How to cite this article

Sorokin A.G., Dobrynin V.A. Method of studying infrasound waves from thunderstorms. *Solar-Terrestrial Physics*. 2022. Vol. 8. Iss. 1. P. 62–68. DOI: 10.12737/stp-81202208.