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Infrasound signals of fireballs detected by the Geostationary Lightning Mapper

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ABSTRACT

Context. Fireballs are particularly bright meteors produced by large meteoroids or small asteroids that enter the Earth's atmosphere. These objects, of sizes from some tens of centimetres to a few metres, are difficult to record with typical meteor detection methods. Therefore, their characteristics and fluxes are still not well known. Infrasound signals can travel particularly well through the atmosphere over large distances. Impacting meteoroids and asteroids can produce those signals, as well as space-detectable optical signatures.

Aims. This paper aims to study and compare fireball data from the Geostationary Lightning Mappers (GLMs) on board the two Geostationary Observational Environmental Satellites (GOES-16 and GOES-17) and the data from the infrasound stations of the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty Organisation (Vienna, Austria). The overall goal is a more accurate energy estimation of meteoroids and asteroids as well as a better understanding of both methods.

Methods. The data consist of the brightest 50 events in the GLM database, as identified by recorded peak energy. For 24 of those fireballs, a significant signature could be identified in infrasound data. The data are supplemented by, if available, optical fireball data based on US government sensors on satellites provided by NASA's Center for Near-Earth Object Studies (CNEOS).

Results. The energies as computed from the GLM data range from 3.17×10^7 J up to 1.32×10^{12} J with a mean of 1.65×10^{11} J. The smallest meteoroid recorded by infrasound had an energy of about 1.8×10^9 J, the largest one of about 9.6×10^{13} J, and the mean energy is 5.2×10^{12} J. For 19 events, data were simultaneously available from all three data sources. A comparison between the energy values for the same event as determined from the different data sources indicates that CNEOS tends to give the lowest energy estimations. Analysis of infrasound data results in the largest derived energies.

Conclusions. The energies derived using the three methods often deviate from one another by as much as an order of magnitude. This indicates a potential observational bias and highlights uncertainties in fireball energy estimation. By determining the fireball energy with another independent method, this study can help to better quantify and address this range of uncertainty.

Key words. meteorites, meteoroids – minor planets, asteroids: general – atmospheric effects – instrumentation: detectors – shock waves – methods: observational

1. Introduction

For centuries, people have been fascinated by nightly light phenomena commonly known as shooting stars or meteors. Meteors are caused by small extraterrestrial dust particles, meteoroids, entering the Earth's atmosphere at very high velocities in the range 11.1-73.6 km s⁻¹ (see e.g. Drolshagen et al. 2020). Meteors with an absolute magnitude brighter -4 are called fireballs, and the brightest and rarest of which are sometimes referred to as bolides. The brightness of the phenomena increases with the size and velocity of the impacting meteoroid. Particularly bright bolides are the result of asteroid impacts, extraterrestrial objects with a size of at least one metre (IAU 2017).

Approximately 54 tons of extraterrestrial material impact the Earth's atmosphere on average per day (Drolshagen et al. 2017).

The faint events are frequent and easily observable with the traditional optical meteor networks found all around the globe. Larger asteroids can be detected by ground-based near-Earth object (NEO) surveys. Currently, there is still a lack of observational data and quantitative understanding for impacting objects in the size range above some tens of centimetres. The values for, for example, the impact fluxes given in the few studies focused on this range vary significantly. An overview can be found, for example, in Drolshagen et al. (2017).

Meteor networks are dedicated to continuously monitoring the sky; accordingly, they detect any fireball that takes place in their geographic region and appears under the right circumstances. For example, optical observations highly depend on weather conditions. Therefore, detections of fireballs with optical meteor networks are usually by chance as these events are quite rare and the networks only cover a small portion of the sky at night times. Beyond that, there are some networks

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that are dedicated to observing fireballs. Examples include the originally French Fireball Recovery and InterPlanetary Observation Network (FRIPON; Colas et al. 2014, 2020), the European Fireball Network (EFN; Oberst et al. 1998), the Slovak Video Meteor Network (Toth et al. 2012), the Desert Fireball Network (DFN) in Australia (Howie et al. 2017), the Canadian Automated Meteor Observatory (CAMO; Weryk et al. 2013), and the Spanish Meteor and Fireball Network (SPMN; Trigo-Rodríguez et al. 2004, 2006).

An alternative is detection by satellites, which can cover large areas and are not limited by the cloud cover. Nonetheless, the coverage is not global at any given time but depends on the satellite swath. One global source is NASA's Center for Near-Earth Object Studies (CNEOS) at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. They publish data based on events recorded by US government sensors on bright fireballs on a regular basis (CNEOS 2021). Typically, worldwide events are published if the impact energies exceed about 0.1 kt TNT equivalent (1 kt TNT = 4.184×10^{12} joules; NIST 2016). More recently, even events down to 0.07 kt TNT have been reported regularly. It is noted by CNEOS that data is not kept up to date at all times and some fireballs might not be included. Possibilities for increasing the detection number of fireballs include utilising methodologies that are not conventional for fireball detection and taking advantage of frequency ranges other than the traditional optical and radar range.

Sound waves are longitudinal waves propagating in a medium in the same direction in which the particles oscillate (Pain 1983). These elastic waves are called infrasound when they have frequencies lower than 20 Hz. The lower limit of the infrasound frequency range depends on the effect of gravity on the elastic particle movement, which is influenced by the thickness of the medium. In a gas with a temperature of 20 degrees Celsius and at sea level, the speed of infrasound is 343 m s^{-1} . Some of the factors that influence the propagation of the waves in the medium are the temperature and the wind direction (Le Pichon et al. 2009).

These acoustic signals propagate particularly well over long distances in the atmosphere. A rare, naturally occurring source of these signals are meteoroids and asteroids that penetrate the atmosphere at high speeds. This concept has been demonstrated in numerous publications (Edwards et al. 2010; Silber et al. 2011, 2018; Ens et al. 2012; Hedlin et al. 2012; Brown et al. 2013; Caudron et al. 2016; Ott et al. 2019a, 2020a; Pilger et al. 2015, 2020), proving that infrasound can also be used as a fireball detection method that provides global data.

It is necessary that the entering object is fast and large enough for it to generate measurable infrasound signals; otherwise, the signal is completely attenuated by the atmosphere before it reaches the recording station. In addition, the trajectory of the object should have a reasonably coherent acoustic path to the station. The dominant frequency of the signal also affects the detectability and the ability to reliably calculate the energy from these detections. This is due to the association of lower frequencies with higher initial energies that are less affected by atmospheric absorption. Accordingly, they are more likely to be observed. Furthermore, the more deeply a meteoroid enters the atmosphere, the less its signal is affected by atmospheric absorption. However, the shorter distance has less influence than the fact that the lower frequencies in particular are less attenuated in the upper atmosphere due to the longer mean-free path of the surrounding molecules. Hence, deeply penetrating objects are easier to observe. Nevertheless, even if all the abovementioned criteria are met, it is still possible that the signal of a fireball will not be detected in the station's data if the station itself has

One infrasound data source is the International Monitoring System (IMS) operated by the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO; Vienna, Austria). Its infrasound data are analysed in this study.

Another relatively new source of information on fireballs is a by-product of lightning observations. The Geostationary Lightning Mappers (GLMs) on board the two Geostationary Observational Environmental Satellites (GOES-16 and GOES-17) continuously image the Earth from space. Their data are publicly accessible (NASA 2021) and investigated in this work.

One approach for enhancing our knowledge of fireballs is to collect and combine as much information as possible about bright fireball events from multiple sources. In this study, another independent way of determining energy is identified and investigated. This can help to better quantify this area of uncertainty and determine how to mitigate it.

To illuminate this uncharted area, the main goal of the global near real-time fireball monitoring system NEMO (NEar realtime MOnitoring system) is to supplement standard observations of events with information collected from unconventional sources. NEMO has been in operation at the European Space Agency (ESA) since January 2020 as part of ESA's Space Safety Programme. Based on social media platforms and reports, an alert system was developed to produce fast notifications for events that attract a relative large amount of public attention. A combination of different data sources maximises the scientific information about the detected object via cross-checking, cross-referencing, and cross-validating. More information about NEMO is available in Ott et al. (2020c,a,b) and Drolshagen et al. (2019a,b).

So far, no structured nor comprehensive study that combines the following three data sources with regard to fireball detection has been conducted: the IMS infrasound data, the data recorded by GLM, and CNEOS data.

The main objective of our research is to analyse and compare the methods, especially for the energy estimation of fireball events, and to investigate each method's difficulties and limitations. This paper is focused on the scientific analysis of infrasound data resulting from 50 bright fireballs that were detected with the GLM.

In Sects. 2.1 and 2.2 a brief description of the infrasound data and analysis is given. For the GLM data and data processing, an overview is presented in Sects. 2.3 and 2.4. The study's results are shown in Sect. 3. A discussion and conclusion are given in Sects. 4 and 5, respectively.

2. Data and methods

2.1. Infrasound data

Acoustic infrasound signals can be produced by various natural or man-made sources, from volcanic eruptions, microbaroms, or fireballs to explosions or rocket launches. These signals below 20 Hz can be measured at large distances from the source after traversing the atmosphere. They manifest as pressure changes that can be recorded by infrasound stations (Hedlin et al. 2012; Edwards et al. 2010).

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Fig. 1. Network of infrasound stations of the IMS as of January 2021. There are 53 certified stations (green circles) and seven stations not yet certified (orange diamonds; five are planned, one is under construction, and one is installed). The data are adapted from CTBTO (2021). The location of station I28 has not yet been determined.

The IMS was created with the aim to identify any nuclear explosion on Earth with an energy larger than 1 kt TNT (National Research Council 2012). It monitors the Earth's surface, underground, underwater, and its atmosphere, using infrasound, seismic, hydroacoustic, and radionuclide technologies. The 60 infrasound stations of the IMS infrasound network will provide worldwide coverage in real time as soon as it is completed. As of January 2021, there are 53 certified stations operated around the world (see Fig. 1). The data are sent to, and distributed by, the International Data Centre (IDC) in Vienna (CTBTO 2021). To identify explosions the IMS infrasound network continuously monitors the atmosphere on a global scale during day time and night time. Consisting of an array of microbarometer sensors with detection capabilities required to be optimised for the frequency range of 0.02-4 Hz, the stations can register the fireball generated pressure changes (Le Pichon et al. 2009).

Although the IMS network was designed to detect nuclear explosions, its infrasound component, among others, can detect a variety of atmospheric or ground-based sources. If these sources generate infrasound, these infrasound waves propagate in the atmosphere. Since infrasound signals undergo little attenuation the propagation distance can extend thousands of kilometres. Infrasound monitoring stations pick up these signatures in their waveforms. This provides a unique data source for fireballs. For details on the mechanisms and dynamics of infrasound generated by meteors, we refer to Silber et al. (2018). From the infrasound signals of fireball events, it is possible to determine the location as well as the energy and thus the approximate mass and size of the related object. If the velocity of the impacting object

is known from another source, the uncertainty of the calculated size can be reduced.

The best-known example of a fireball detected in the infrasound spectrum is the Chelyabinsk bolide. It impacted the atmosphere in February 2013 and was detected by infrasound stations worldwide, including 20 stations of the IMS (Le Pichon et al. 2013; Brown et al. 2013; Pilger et al. 2015). With an extensive survey, Gi & Brown (2017) were able to identify more than 70 additional NEO impacts in infrasound data.

2.2. Infrasound processing and energy estimation

In the following section the data processing of the IMS infrasound data will be briefly introduced. The method is extensively explained in Ott et al. (2019a), for details we refer to their work.

The DASE ToolKit - Graphical Progressive Multi-Channel Correlation (DTK-GPMCC) is a program developed by the French Alternative Energies and Atomic Energy Commission (CEA) in collaboration with the CTBTO. Its basis is a Progressive Multi-Channel Correlation (PMCC) algorithm that is used for the analysis of the recorded waveforms within this work. The algorithm cross-correlates the sensors' data of a station and applies a band-pass filtering. By combination of different channels, a higher signal to noise ratio is achieved. This way, events can be detected in the waveforms and their signal characteristics can be estimated. We refer to Mialle et al. (2018) for further information about the software and data processing.

For each event of the 50 most energetic objects in the GLM database, the time and location of the fireball is known. We

investigate whether these events were also recorded in the IMS infrasound data. Taking into account the time it takes for the acoustic waves to propagate from the location where the fireball happened to the infrasound station, an approximate time of arrival can be calculated by assuming that the wave packets propagate at the speed of sound. The data for the period of +/-2 h around this theoretically calculated value were examined for the IMS stations closest to the fireball, also accounting for potential travel time uncertainties resulting from propagation through different atmospheric layers.

As explained and performed in Ott et al. (2019a) DTK-GPMCC is applied to the data with a configuration of 20 frequency bands logarithmically spaced in the range between 0.02 and 6 Hz and time-window durations in the range of 150 and 30 s. In addition, the expected back azimuth of the incoming signal is used to distinguish between signals from the fireball and other sources. In cases where we can identify a significant signature of the fireball in the station's data, the waveforms of all sensors with qualitatively good data were filtered and stacked. For further investigation, we identify the period at maximum amplitude by using zero crossings around the maximum amplitude of the created beam. For the energy determination, we follow the method proposed by ReVelle (1997). It is a correlation between period and yield of the Air Force Technical Application Centre (AFTAC):

$$\log \frac{E}{2} = 3.34 \cdot \log P - 2.58; \ \frac{E}{2} \le 100 \ \text{kt}, \tag{1}$$

$$\log \frac{E}{2} = 4.14 \cdot \log P - 3.61; \ \frac{E}{2} > 40 \ \text{kt}, \tag{2}$$

with the period at maximum amplitude, P, in seconds and the energy, E, in kt TNT equivalent. The somewhat inconsistent overlap in the energy range of 40 kt TNT equivalent –100 kt TNT equivalent is well known, but not problematic since the largest fireball energy investigated is below 40 kt TNT equivalent and only Eq. (1) is used.

As described in, for example Ott et al. (2019a), Pilger et al. (2020), or Belli et al. (2021), we would like to point out that an energy estimation on the basis of infrasound data is subject to many uncertainties. These are related, among other factors, to the propagation and attenuation of infrasound, but also to the measurement of the wave amplitude taking local turbulence into consideration.

Furthermore, energy computations based on infrasound data originating from objects impacting the Earth's atmosphere are not trivial. Several methods have been proposed in the literature, some focusing on the signal wave period in accordance with ReVelle (1997), others on the amplitude. One alternative method based on the signal's amplitude is for example described by Ens et al. (2012). Nonetheless, the period of the signal is the most commonly used parameter. As noted by, for example, Edwards et al. (2006), the period seems to be the best conserved parameter. During the path of the signal until detection at a station, which can be several thousand kilometres from the source, the period is the parameter that is the most resistant to the environment conditions and changes the least while the signal traverses the atmosphere.

As mentioned before, to calculate a fireball's energy using infrasound data, the waveform's period at maximum amplitude is determined in this study. In combination with Eq. (1) the object's source energy can be calculated. With the formula for the kinetic energy and a velocity value (or estimate) even the mass and size of the impacting meteoroid or asteroid can be estimated as:

$$E_{\rm kin} = \frac{m}{2} \cdot v^2. \tag{3}$$

2.3. GLM data

Satellite-based lightning detectors can record fireball events, as shown by, for example, Jenniskens et al. (2018) or Rumpf et al. (2019). GLM instruments on board the GOES-16 and GOES-17 weather satellites continuously image the Earth from space. They were designed to capture natural lightning activity and are operated by the National Oceanic and Atmospheric Administration (NOAA; GOES-R Data Book 2019). The satellites were placed into operation in geostationary orbit at 35 786 km above the equator. GOES-16 started operation at 75.2° W in December 2017 and GEOS-17 became operational at 137.2° W in February 2019 (GOES-R Data Book 2019; NASA 2021). The overall system is a joint development between the NOAA and NASA (Goodman et al. 2013).

The GLM instruments measure emissions with a narrow 1.1 nm passband. It is centred at 777.4 nm, which corresponds to the OI emission line (neutral atomic oxygen) and is dominant in the lightning spectrum. The sampling rate is 500 frames per second and the charge couple device (CCD) imaging area size is 1372 pixels \times 1300 pixels (GOES-R Data Book 2019). The lightning mappers provide continuous coverage of about half of the Earth in the western hemisphere with a spatial resolution between 8 km and 14 km per pixel. The primary pointing focus is on the land masses of the Americas. Some parts of the Fields Of View (FOVs) of the two lightning mappers overlap, mainly over parts of the United States and the Pacific, allowing for simultaneous observations in those regions (Goodman et al. 2013).

For example, Jenniskens et al. (2018) and Rumpf et al. (2019) show the fireball detection capabilities of the instruments despite the narrow passband. The GLM data are publicly available. They include the location, date, time, and duration of the detected event, notes about the detecting sensor and the measured energy. Fig. 2 shows a map including all fireball detections.

2.4. GLM energy estimation

In the course of this study, the entire GLM fireball database was investigated¹. As of 9 November 2020, it contains 1284 events. The energy curves for the detection time as reported by GLM can be accessed for most detections of the detecting instrument in joules. Only ten events are listed in the database for which no light curve could be analysed. An example of a light curve is presented in Fig. 3. From these values a peak energy was computed. For fireballs that were recorded by both GLM instruments, the mean energy was used. Based on these peak energies the fireballs were sorted and 50 events with the largest peak energies selected. A list of these fireballs can be found in Table A.1.

To compare GLM energies to other data, these energies need to be further processed. To convert the energies as given in the GLM database into standard fireball energies, we adapt the method presented by Jenniskens et al. (2018). They conducted an analysis of ten fireballs that were detected by the GLM on board the GOES-16 satellite.

First, to account for missing data points and noise in the data, a Savitzky-Golay filter (SciPy 2021) was applied to the energy

¹ From https://neo-bolide.ndc.nasa.gov/#/

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Fig. 2. Map of all fireball detections in the GLM database, status as of 9 November 2020. The size of the dots correlates with the peak energy of the event in joules in log scale. The grey dots represent the fireball events in the database, including the 50 brightest events that were more closely investigated and only observed by GLM. The yellow dots show only those events that were also found in the infrasound data, and the red ones show the events that were both found by GLM and are in the CNEOS database. The green dots represent events that were detected by all three methods.



Fig. 3. Absolute magnitude light curve calculated from the GLM-reported lightning energy over the time in ms after the initial recording. The presented event is a fireball recorded on 17 September 2018, first observed at 01:08:01:112 UT by the GLM onboard the GOES-16 satellite. The dots show individual observation points and the solid line an interpolation of the data.

curve data. The preliminary event energies are found by integrating the curve. As described by Jenniskens et al. (2018) the resulting energies have to be corrected taking into account that the energy was emitted in all directions as well as the contribution of the passband of GLM. To do so, we used the following formula:

$$E = \sum E \cdot \frac{4 \cdot R^2}{r^2} \cdot c, \tag{4}$$

with the interpolated, integrated energy, $\sum E$, the distance of the satellite from the event, *R*, the radius of the effective aperture of the lightning sensor, r = 0.0558 m, and the correction factor for the passband $c = 1.018 \times 10^3$. For details we refer to Jenniskens et al. (2018). To compute the exact value of *R* of each event, the coordinates of the fireball and of the satellite reported in the GOES-R data were used. The results are listed in Col. 9 of Table A.1, representing the total radiated energy of the event *E*.

It is possible to compute the absolute magnitude of a fireball from the GLM data. The absolute magnitude of a meteor indicates its brightness if it had appeared above an observer on the Earth's surface at the zenith at an altitude of 100 km. To calculate the absolute magnitude, mag, the following equation was used (Jenniskens 2021, priv. comm.):

mag =
$$-2.5 \cdot \log\left(\frac{E}{4 \cdot \pi \cdot R_{\text{zenith}}^2 \cdot \Delta \lambda \cdot F}\right)$$
, (5)

with $R_{\text{zenith}} = 100$ km, the effective width of the visual passband of the sensor for the eye $\Delta \lambda \approx 380$ nm, and the standard irradiance *F* at 548 nm: $F = 3.67 \times 10^{-11}$ W m⁻² nm⁻¹ (Jenniskens 2006, 2021, priv. comm.; Jenniskens et al. 2018).

3. Results

Table A.1 lists the 50 investigated fireballs. As mentioned before, the events were chosen based on the recorded peak energies in the GLM database. The presented information about the date, time, and location of the detection are given as reported in the GLM database. For all of these 50 events, a correlation with an



Fig. 4. Infrasound signal received at station I20EC (located on the Galapagos Islands, Ecuador) at about 3137 km from the recorded event on 22 June 2019 between 22:04:10 and 02:04:10 UT, processed with PMCC. *Top:* PMCC result is shown for the entire investigated time range; the colours indicate wave directions (back azimuths). *Middle:* part of the signal associated with the fireball event. The fireball was identified from about 00:12 UT until 00:34 UT. The derived back azimuth of the recorded infrasound signal is colour-coded as well, together with its apparent velocity for the analysed frequency bands. *Bottom:* the filtered (based on the signal's frequency range) and stacked beam of the station is depicted for the same time interval.

event listed in the CNEOS database was checked². 32 events on our list can also be found in the CNEOS fireball data. The energy as given in the CNEOS database is also listed in Table A.1 as well as information about the fireball's altitude and velocity, if available. This section summarises the findings and contributions made.

3.1. Infrasound detections

The infrasound data are analysed as described in Sect. 2.2. For 24 of the 50 GLM events, we identified a significant infrasound signature of the recorded fireball. An example of an infrasound signal processed with PMCC is presented in Fig. 4 for the event of 22 June 2019. According to the infrasound energies detected, this is the second largest event of our database. The coordinates listed in the GLM data show that the event occurred over the Caribbean. We would like to mention that this event is particularly noteworthy because it was not only recorded with many different detection methods, but also with ground-based telescopes before it entered the Earth's atmosphere, an extremely rare occurrence. The asteroid in question is 2019 MO (Ott & Drolshagen 2019c). The data were extracted from the waveform recorded at station I20EC (located on the Galapagos Islands, Ecuador) at a distance of about 3137 km from the event.

For the data processing, in addition to the calculated energy, the velocity information provided by CNEOS is used, if available. Alternatively, a velocity of 15 km s⁻¹ is assumed. This value is based on studies investigating the velocity distribution of NEOs. A number of studies found the maximum of the distribution around 15 km s⁻¹ (see e.g. Chesley & Spahr 2004, Greenstreet et al. 2012, or Drolshagen et al. 2020). For the size computation we utilise a default density of 3000 kg m⁻³. This value was chosen as compromise between two common density assumptions. In the review published in Gritsevich & Koschny

4000 kg m⁻³ if no further information about the object is available and a value of 3500 kg m⁻³ was suggested. Additionally, following Levin (1956) this value is a common assumption. Alternatively, the European Cooperation for Space Standardisation (ECSS) supposes a meteoroid density of 2500 kg m⁻³ for impact risk assessments for satellites (ECSS 2008). Obviously, these assumed values introduce uncertainties that should be kept in mind. The results are listed in the appendix. Table B.1 gives a gen-

(2011) the meteoroid density was estimated to be between 1000-

eral overview of the analysed fireballs recorded with infrasound including mean values and standard deviations. Additional information is given in Table B.2. It lists for each fireball the distance to the station, the identified signal's start and end time, the computed celerity and type of arrival, the recorded median back azimuth, the recorded maximum amplitude, the frequency range in which the fireball's signature was found, the derived period at maximum amplitude and the derived source energy. If the event was detected with more than one station, the determined single-station values are listed individually.

The 24 GLM events that were also detected by the IMS infrasound system show a large variance in energies and hence, masses and sizes. The energies can be visually compared in Fig. 5. The mean energy is 5.2×10^{12} J, the mean size of the recorded objects is 1.7 m diameter, and the mean mass is 45 t. The smallest event that could be detected has an energy of about 1.8×10^9 J, a size of approximately 0.2 m, and a mass of circa 16 kg. It is the meteoroid that entered the Earth's atmosphere on 13 September 2018. On 21 August 2020, the largest recorded asteroid with an estimated energy of about 9.6×10^{13} J was detected. We derived a mass of around 850 t corresponding to a diameter of circa 8.2 m for this event.

3.2. Energy comparison

For all 50 fireballs that were recorded by GLM and investigated in this work, the energies were computed from

² https://cneos.jpl.nasa.gov/fireballs/, accessed: 27 January 2021.



Fig. 5. Event energies determined with the infrasound data (IS, blue circles), the lightning mapper data (GLM, orange squares), and the values of the CNEOS data (CNEOS, green triangles). They are plotted against the event date. All energies are shown in log scale and joules.

the lightning sensors' data as described in Sect. 2.4. The results are presented in Col. 9 of Table A.1. The derived energy values range from 3.17×10^7 J (circa 7.6×10^{-6} kt TNT equivalent) up to 1.32×10^{12} J (circa 0.32 kt TNT equivalent). The mean is 1.65×10^{11} J (circa 0.040 kt TNT equivalent). The determined values for the absolute magnitude of the fireball derived from the GLM data are presented in the last column of the table. They range from about -10.6 mag up to -22.2 mag, the computed mean value is -19.1 mag. The energy value determined from the infrasound data is given in Col. 10 of the table. The energy reported in the CNEOS database, if available, is listed in Col. 11 of Table A.1. For 19 of the 24 events for which we identified a clear infrasonic signature of the fireball, an energy value is available in the CNEOS database. From all investigated GLM events with the highest peak energies, 32 are also represented in the CNEOS database.

Considering only the 24 events that were recorded by GLM and infrasound, the derived GLM energies range from 1.54×10^{10} J (circa 0.0037 kt TNT equivalent) up to 1.32×10^{12} J (circa 0.32 kt TNT equivalent). The mean is 2.03×10^{11} J (circa 0.049 kt TNT equivalent). Hence, the event with the largest energy of our 50 events was found in the infrasound data, as expected. The one with the lowest energy is not present in the infrasound data. In Table A.1 there is no other strong or obvious correlation between the computed GLM energies and the probability that the event is detectable by infrasound. The same is valid for CNEOS detections. The energies determined by the three different methods can be visually compared in Fig. 5.

The figure shows the energies obtained by the different detection and analysis methods and highlights the differences. The CNEOS data tend to yield a lower energy as compared to the other two methods. CNEOS data of 10 of the 19 events that were recorded with all three methods are the lowest of the estimations. The results we obtain from the infrasound data seem to estimate higher energies. In fact, they are the highest for 13 of the 19 events. Additionally, the infrasound energies of the five events detected only with infrasound and by GLM are larger than the corresponding GLM energies. As this sample consists of five events only it is not sure whether this is a systematic behaviour. Overall, the different energies of an event often have a discrepancy of about an order of magnitude among themselves. This emphasises the inherent uncertainties of the results.

4. Discussion

Only a limited number of studies have so far examined meteoroids and asteroids in a size range of a few tens of centimetres to a few tens of metres. Due to the limited numbers of recordings of these intermediate sized objects in traditional meteor observations, statistically significant numbers have not been investigated. Yet, these meteoroids or asteroids regularly impact the Earth's atmosphere and they form the connection between harmless meteoroids and potentially hazardous larger asteroids. Our work proposes an approach to solve this problem.

There are only a few technologies capable of observing the fireballs connected to these objects. We focus on: (1) the GLM instruments on board the GOES-16 and GOES-17 satellites, (2) fireballs detected via infrasound travelling through the atmosphere in infrasound data from CTBTO's IMS, which monitors the entire Earth, and (3) the US government sensors on satellites that provide data on a global scale for the fireball and bolide database from NASA's CNEOS at JPL.

We do not identify a clear correlation between the energy computed relying on the GLM data and the detection probability by infrasound or by CNEOS. For the events that were detected by both the GLM sensors and the IMS infrasound system there is a large difference of the determined energies.

If one compares the energy values that were determined from all three data sources analysed for the same event, the results often vary by about an order of magnitude. The CNEOS data tend to yield the lowest energies and the results derived from infrasound data are the largest. This highlights the inaccuracies and uncertainties of the different detection methods and points towards some over- or underestimation of calculated energies depending on the utilised method and data.

In this context, we would like to emphasise again the ambiguities in our assumptions and analyses, especially for the derived sizes and masses. They are based on energy values that are affected by uncertainties, and velocity values are only known for nine of the 24 events. For all others, a value of 15 km s⁻¹ was assumed, which can strongly influence the result, as is evident in Eq. (3). The velocities in the CNEOS database are not free of errors either. Drolshagen et al. (2020) mention that a common velocity error assumed for the CNEOS data is about $1-2 \text{ km s}^{-1}$, Brown et al. (2016) estimated the uncertainty to be in the order of 0.1–0.2 km s⁻¹, and Devillepoix et al. (2019) found for two of ten studied events velocity deviations from independent observations of up to 28%. Furthermore, to calculate the diameter of the impacting object, a spherical shape and a density of 3000 kg m⁻³ have been assumed. The density values used in the literature vary greatly, as discussed for example in Drolshagen et al. (2021). Therefore, our results need to be interpreted with caution.

Our data do not show a significant correlation between the total energy of a fireball measured by GLM and its detection probability by the IMS infrasound stations. We acknowledge that even at 50 investigated events, the size of the dataset studied is still slightly limited. With more data, several new aspects and correlations could appear, which is an interesting aspect for future work. We would also like to mention that we do not see any correlation between the reported GLM peak energy and the infrasound detection probability. A large peak energy could be associated with a single large explosion and can be registered particularly well with the infrasound sensors, but it is not automatically linked to a larger object (i.e. a larger total fireball energy). Such outbursts or fragmentations could affect the detection probability. Unfavourable infrasound detection conditions can also be a limiting factor. These would be related to numerous factors such as wind direction and turbulence in the atmosphere, as well as background noise interfering with the signal detection and reducing the signal to noise ratio.

The evaluation of fireball signals from infrasound data has only, thus far, been assessed to a very limited extent and is a relatively new field of current research. Accordingly, the infrasound-based results are naturally associated with quite large uncertainties. Furthermore, it has been theorised that different stations might record signals from different portions of the trail. For example, Silber et al. (2011) attributed a large difference in signal period for the closest stations to measuring samples of varying parts of the trajectory and the terminal burst. However, they note that the exact origin is still quite unclear. Hence, especially for the events whose signature we only identified at a single station, the results are relatively inaccurate. By averaging the identified periods from several stations, the results can be improved in most cases. As it can be seen in Table B.1, 14 of our 24 recorded events were detected by one IMS infrasound

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station only. For a detailed discussion of the uncertainties of the evaluation of fireball signals from infrasound data and possible reasons, we refer again to Ott et al. (2019a), Pilger et al. (2020), or Belli et al. (2021).

The 24 fireballs investigated in this study were anywhere from circa 200 km to about 4700 km away from the recording station (on average about 2218 ± 1140 km). Since the utilised dataset is confined to the Americas and the bordering oceans, the possible infrasound stations that could record an analysable fireball are limited and fixed in geometry. This is coupled with the restricted characteristics the fireball must have to be recorded, thus it is important to note that the average distance might be largely biased by the geographical location and altitude of entry. However, the minimal and maximal distance are important parameters to determine the sensitivity of the method and put this study into a perspective. Even though the distance must be coupled with the event energy to deduct its importance on observability, a maximum distance of 4676 km shows how sensitive the system is, which should lead to a significant increase in fireball numbers detected in the coming years. In this study, the minimum distance of 200 km shows that the sampling number is large enough to make meaningful assumptions based on the obtained results. Noteworthy, the latest IMS infrasound station, which is centrally located in the observation area of the GLM instruments (I25FR, Guadeloupe), has only been certified since 25 November 2020. It has therefore not yet contributed to this study, but could make a major contribution to future investigations.

Based on the source-station distances, one can conclude that the propagation of most measured signals is stratospheric. The alternatives, tropospheric or thermospheric arrivals, are unlikely since most sources are far from the detecting station with a mean source-station distance over 2000 km. Neither tropospheric nor thermospheric propagation is normally able to transport enough signal energy to be detected over such long ranges. Tropospheric propagation is especially unlikely given the high altitude of the sources. The radiated energy would have to travel to the near surface and encounter a very stable tropospheric channel in the lowest atmospheric layers, mere kilometres above the surface. Even in this unlikely event, the topography and turbulence make the transport very unstable and the signal usually dissipates before it reaches a station. Therefore, it can be argued that tropospheric arrivals for signals over 1000 km from the source are improbable (Drob et al. 2003).

A closer look at the arrivals from the closest fireball observation of only 200 km distance shows that it is possible that a tropospheric arrival was observed. However, the observation could not be definitively associated with a propagation type. It is quite possible that this detection is a direct arrival. This is supported by the fact that a distance of about 200 km is probably too short for indirect (stratospheric) wave guidance. However, the celerity is quite high. Nonetheless, it could also be another specific reflection, of which there are many possibilities.

Regarding thermospheric propagation: an arrival from the thermosphere is possible if the stratospheric conduction conditions are unfavourable but a signal is recorded, nonetheless. The closer the station, the better this propagation will be, as thermospheric attenuation will remove most of the signal content, at least the higher frequency components. For strong sources, some low frequency signal energy from thermospheric propagation paths may turn up with late arrival times, sometimes as a separate signal group in addition to a dominant stratospheric detection. A further indicator for the propagation type is the observed frequency range: If there is signal energy around/above 1 Hz, the signal is most likely the result of stratospheric propagation (Blom et al. 2018). As can be seen in Table B.2, all but two events have frequency ranges above 1 Hz.

To reinforce this assessment, the celerity for each detection of each station for all events was calculated to serve as an additional control parameter. These values were evaluated by dividing the fireball distance by the travel time and are presented in Table B.2. For example, according to Negraru et al. (2010), the following celerities should be linked to certain ducting layers: In most cases 'boundary layer arrivals' can be found for celerities over 330 m s⁻¹. The reflection usually occurs at 1 km. Higher reflections for heights up to 20 km are associated with tropospheric arrivals. The travel times of those arrivals usually range between 310 and 330 m s⁻¹. Stratospheric arrivals are reflections at heights from 20 to 50 km and have celerities of 280–320 m s⁻¹. Celerities in the range of 180–300 m s⁻¹ are found for thermospheric arrivals (Negraru et al. 2010).

The celerities and inferred associated propagation layers of all events can be found in the Table B.2. Of the 43 arrivals observed in this study, 32 have celerities between 280 and 320 m s⁻¹, consistent with stratospheric arrivals. The two arrivals classified as tropospheric have celerities of 320 and 322 m s⁻¹, respectively, which is in the uncertainty range of our measurement. Hence, both are most likely stratospheric arrivals, too. For eight events the computed rather slow celerities point towards thermospheric arrivals. The derived mean celerity value is 289 m s⁻¹. The celerity values determined reinforce the estimation of stratospheric propagation for most arrivals.

The low number of fireball signals detected by more than one station hinders the statistical analysis of uncertainties for this work. Hence, a larger dataset should be considered for future examinations and is expected to yield meaningful options for both error and data determination.

The detection of fireballs with lightning sensors is still a relatively young field of research. To our knowledge, GLM fireball data have not yet been systematically and comprehensively analysed and the relevant literature is limited. Statements about the accuracy of the results or the applied formulas are therefore difficult to make. However, it is immediately clear from Fig. 3 that the reported lightning energies show strong fluctuations in the light curve. Such a behaviour will certainly influence the final result and requires further investigation.

We would like to mention that work is currently underway at NASA's Ames Research Center to quantify the distortions and uncertainties in the GLM data from fireballs. The instruments were designed to detect and process lightning signals. An important distinction is that lightning signals are assumed to be impulsive not only during the initial onboard processing but also during further calculations on the downloaded data. Signals from fireballs, however, are not impulsive on timescales applicable to lightning. As a result, the fireball energies provided in the database are less accurate. The NASA's Ames Research Center team is currently working on improving the calibration and on estimating the uncertainties in the GLM fireball data (Dotson 2021, priv. comm.).

The accuracy of the fireball data presented in the CNEOS database is also not well known.

5. Conclusion

In this work fireballs detected with the GLM instruments were analysed. The 50 events with the largest peak energies in the GLM database were investigated in detail, and the fireball energies were computed. For these events, the data recorded at the IMS infrasound stations were examined, and for 24 of the fireballs a significant signature could be identified in the waveform data. From these signals, we were able to determine the object's source energy as well as estimate the mass and size of the impacting object. If available, the energy values as published in the CNEOS database were also compared.

The energies as computed from the GLM data are in the range between 3.17×10^7 J and 1.32×10^{12} J with a mean of 1.65×10^{11} J. No correlation between the energy that we computed based on the GLM data and the detection probability by infrasound or by CNEOS was found. A comparison between the energy values that were determined based on the different data sources indicates that the energies given in the CNEOS database are usually on the low side, while the infrasound data results tend to be larger.

The analysis of a large dataset of events as seen by infrasound and by lightning sensors presented in this study improves the understanding of signals from fireballs for both methods. Based on both data sources, reliable and accurate quantitative estimates of impact time, location, and, especially, impact energy are possible, and thus infrasound and lightning sensors provide a global and continuous observation method for large fireballs. This can help fill the knowledge gap that exists for the meteoroid and asteroid population in the intermediate size range of some tens of centimetres to a few metres. We recommend a more detailed study into this subject once a longer time frame can be analysed. Data of a larger time span would contain an increased number of larger events, which are rare and thus infrequently observed. Analysis of the corresponding data could lead to more accurate infrasound results as larger objects would be more likely to be recorded by multiple stations. Our results are a good first step and show the potential of such analyses. Despite these uncertainties, it is remarkable that three different methods are in principle able to provide information on fireballs on a global scale. For the present sample of 19 fireballs captured by all three methods, the derived energies differ by about a factor of ten. That might appear large but is still rather encouraging in view of the experimental status of the analysis methods. A few well-characterised benchmark cases could greatly improve the situation. Such cases could be objects that are discovered in space before they hit the Earth. Objects of only a few metres in size can be detected by current survey telescopes under favourable conditions. The impact velocity, time, and location will be known quite precisely for these objects. Under lucky circumstances, additional information on the mass could be obtained by, for example, infrared measurements of the object's albedo and size or by recovered meteorite fragments. If this information is available, the impact energy will be known and the different sensors and detection methods might be calibrated.

It is interesting to note that the space-based GLM lightning sensors recorded almost 1300 fireball events over a period of about three years. In this study, we only investigated the 50 largest events – sorted by their peak energy – in more detail. However, we found that a high peak energy does not necessarily correspond to a large total fireball energy. We determined the energies for all 1274 fireballs in the database with available data (as described in Sect. 2.4) to investigate if the analysis procedure of the lightning data is valid for smaller events. We found that the smallest detected energies are of the order of 10^7 J. For a velocity of 15 km s⁻¹, a spherical shape, and a density of 3000 kg m⁻³, this would correspond to objects of only around 0.05 m in size. For the three events with the smallest GLM energies, we determined energies of 9.64×10^6 J, 1.77×10^7 J, and 2.02×10^7 J. Surprisingly, the smallest energy of the subset investigated in this study $(3.17 \times 10^7$ J) is only slightly larger than of those three smallest events in the entire database. It is the ninth smallest event in terms of total energy in the complete database. The event with the largest fireball energy investigated in this study $(1.32 \times 10^{12}$ J) also has the third largest peak energy of all the events in the database. Hence, this study covers almost the complete range of sizes of the fireballs that were detected with the GLM sensors. Additional lightning sensors will be deployed and will soon provide worldwide coverage. This will be a new source of data for bright fireballs, with the whole of the Earth's surface as the target area.

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References

- Belli, G., Pace, E., & Marchetti, E. 2021, Geophys. J. Int., 225, 3
- Blom, P. S., Dannemann, F. K., & Marcillo, O. E. 2018, Geophys. J. Int., 215, 240
- Borovička, J., & Charvát, Z. 2009, A&A, 504, 2
- Brachet N., Brown D., Le Bras R., et al. 2010, Infrasound Monitoring for Atmospheric Studies, eds. A., Le Pichon, E., Blanc, & A. Hauchecorne (Dordrecht: Springer)
- Brown, P., Spalding, R. E., ReVelle, D. O., Tagliaferri, E., & Worden, S. P. 2002, Nature, 420, 294
- Brown, P. G., Edwards, W. N., ReVelle, D. O., & Spurny, P. 2007, J. Atmos. Sol. Terres. Phys., 69, 600
- Brown, P., Assink, J., Astiz, L., et al. 2013, Nature, 503, 238
- Brown, P., Wiegert, P., Clark, D., & Tagliaferri, E. 2016, Icarus, 266, 96
- Caudron, C., Taisne, B., Perttu, A., et al. 2016, Geosci. Lett., 3, 26
- Chesley, S. R., & Spahr, T. B. 2004, Mitigation of Hazardous Comets and Asteroids, eds. M. J. S. Belton, T. H. Morgan, N. H. Samarasinha, D. K. Yeomans (Cambridge: Cambridge University Press), 22
- CNEOS 2021, Fireballs [online], available at: https://cneos.jpl.nasa. gov/fireballs/ [Accessed: 27 Jan. 2021] (NASA)
- Colas, F., Zanda, B., Bouley, S., et al. 2014, Proc. of the International Meteor Conference, Giron, France, 18-21 September 2014, 34
- Colas, F., Zanda, B., Bouley, S., et al. 2020, A&A, 644, A53
- CTBTO 2021, CTBTO preparatory commission [online], available at: https: //www.ctbto.org/map/#mode=ims [Accessed: 27 Jan. 2021]
- Devillepoix, H. A. R., Bland, P. A., et al. 2019, MNRAS, 483, 5166
- Drob, D. P., Picone, J. M., & Garce's, M. 2003, J. Geophys. Res., 108, 4680
- Drolshagen, G., Koschny, D., Drolshagen, S., Kretschmer, J., & Poppe, B. 2017, PSS, 143, 21
- Drolshagen, E., Ott, T., Koschny, K., Drolshagen, G., & Poppe, B. 2019a, Proc. of the International Meteor Conference, Petnica, Serbia, 21 September 2017, 38
- Drolshagen, E., Ott, T., Koschny, K., et al. 2019b, Proc. of 1st NEO and Debris Detection Conference, Darmstadt, Germany 22 24 January 2019
- Drolshagen, E., Ott, T., Koschny, K., et al. 2020, PSS, 184, 104869
- Drolshagen, E., Ott, T., Drolshagen G., et al. 2021 A&A, 650, A159
- ECSS 2008, European Cooperation for Space Standardization, Space Engineering, Space Environment, ECSS-E-ST-10-04C
- Edwards, W. N. 2010, Infrasound Monitoring for Atmospheric Studies (Springer: The Netherlands)
- Edwards, W. N., Brown, P. G., & ReVelle, D. O. 2006, J. Atmos. Sol. Terr. Phys., 68, 1136
- Ens, T. A., Brown, P. G., Edwards, W. N., & Silber, E. 2012, J. Atmos. Sol. Terr. Phys., 80, 208

- Garces, M. A. 2013, InfraMatics, 2, 2
- Gi, N., & Brown, P. 2017, PSS, 143, 169
- GOES-R Data Book 2019, Greenbelt, Maryland: NASA Goddard Space Flight Center
- Goodman, S. J., Blakeslee, R. J., Koshak, W. J., et al. 2013, Atmos. Res., 125, 34 Greenstreet, S., Ngo, H., & Gladman, B. 2012, Icarus, 217, 355
- Gritsevich, M., & Koschny, D. 2011, Icarus, 212, 2, 877
- Hankey, M., & Perlerin, V. 2014, Proc. of the International Meteor Conference, Giron, France, 18-21 September 2014, 160
- Hedlin, M. A. H., Walker, K., Drob, D. P., & de Groot-Hedlin, C. D. 2012, Ann. Rev. Earth Planet. Sci., 40, 327
- Howie, M., Paxman, J., Bland, P. A., et al. 2017, Exp. Astron., 43, 237
- IAU 2017, Commission F1 of the International Astronomical Union (IAU)
- Jenniskens P. 2006, Meteor Showers and their Parent Comets (Cambridge, UK: Cambridge University Press), 790
- Jenniskens, P., Albers, J., Tillier, C. E., et al. 2018, Meteor. Planet. Sci., 53, 2445
- Kofler, R., Drolshagen, G., Drube, L., et al. 2018, Acta Astron., 156, 409
- Le Pichon, A., Blanc, E., & Hauchecorne, A. 2009, Infrasound Monitoring for Atmospheric Studies (The Netherlands: Springer)
- Le Pichon, A., Ceranna, L., Pilger, C., et al. 2013, Geophys. Res. Lett., 40, 3732
- Levin, B. Yu. 1956, Physical Theory of Meteors and MeteorMatter in the Solar System (Moscow: USSR Academy of Sciences)
- Marty, J., Ponceau, D., & Dalaudier, F. 2010, Geophys. Res. Lett., 37, L19802
- Mialle, P., Brown, D., & Arora, N. 2018, in Infrasound Monitoring for Atmospheric Studies 2 (New York: Springer)
- NASA 2021, Bolide Detections from Geostationary Lightning Mapper [online], available at: https://neo-bolide.ndc.nasa.gov/#/ [Accessed: 27 Jan. 2021]
- National Research Council 2012, The Comprehensive Nuclear Test Ban Treaty: Technical Issues for the United States (Washington, DC: The National Academies Press)
- Negraru, P. T., Golden, P., & Herrin, E. T. 2010, Seismol. Res. Lett., 81, 4, 615
- NIST 2016, National Institute of Standards and Technology, Guide for the Use of the International System of Units (SI) [online], Availabe at: https://www.nist.gov/physical-measurement-laboratory/ nist-guide-si-appendix-b8 [Accessed: 19 Feb. 2018]
- Northon, O. R., & Chitwood, L. A. 2008, Field Guide to Meteors and Meteorites (London: Springer Verlag)
- Oberst J., Molau, S., Heinlein, D., et al. 1998, Meteor. Planet. Sci., 33, 49
- Ott, T., & Drolshagen, E. 2019, Fireball over the Caribbean (South of Puerto Rico) detected before it entered! [online] available at: https://www.imo.net/fireball-over-the-caribbean-detectedbefore-it-entered// [accessed: 10 April 2021]
- Ott, T., Drolshagen, E., Koschny, D., et al. 2019, Planet. Space Sci., 179, 104715
- Ott, T., Drolshagen, E., Koschny, D., et al. 2020a, Acta Astron., 177, 172
- Ott, T., Drolshagen, E., Koschny, D., et al. 2020b, Proc. of the IMC 2019, Bollmannsruh, Germany, 11
- Ott, T., Drolshagen, E., Koschny, D., et al. 2020c, Proc. of the International Meteor Conference, 53, Pezinok-Modra, Slovakia, 30 August - 2 September 2018, 53
- Pain, H. J. 1983, The Physics of Vibrations and Waves (Great Britain: Wiley)
- Pilger, C., Ceranna, L., Ross, J. O., et al. 2015, Geophys. Res. Lett., 42, 2523
- Pilger, C., Gaebler, P., Hupe, P., Ott, T., & Drolshagen, E. 2020, Atmosphere, 11, 83
- ReVelle, D. O. 1997, in Annals of the New York Academy of Sciences Near-Earth Objects – The United Nations International Conference, New York Academy of Sciences
- Rumpf, C. M., Longenbaugh, R. S., Henze, C. E., et al. 2019, Sensors, 19, 1008
- Schunová-Lilly, E., Jedicke, R., Verešb, P., Denneau, L., & Wainscoat, R. J. 2017, Icarus, 284, 114
- SciPy 2021, [online] "scipy.signal.savgol_filter" available at: https://docs. scipy.org/doc/scipy/reference/generated/scipy.signal.
- savgol_filter.html [accessed: 09. Mar 2021] Silber, E. A., Le Pichon, A., & Brown, P. G. 2011, Geophys. Res. Lett., 38,
- L12201 Silber, E. A., Boslough, M., Hocking, W. K., Gritsevich, M., & Whitakerg, R.
- W. 2018, Adv. Space Res., 62(3), 489
- Toth, J., Kornos, L., Piffl, R., et al. 2012, Proc. of the International Meteor Conference, 30th IMC, Sibiu, Romania, 2011, 82
- Trigo-Rodríguez, J.M., & Llorca, J. 2006, MNRAS, 372, 655
- Trigo-Rodríguez, J. M., Castro-Tirado, A., Llorca, J., et al. 2004, Earth Moon Planets, 95, 553
- Trilling, D. E., Valdes, F., Allen, L., et al. 2017, AJ, 154, 170
- Weryk, R. J., Campbell-Brown, M. D., Wiegert, P. A., et al. 2013, Icarus, 225, 1

Appendix A: Investigated fireballs - 50 brightest measured by peak brightness

Date	Time	lat in deg	lon in deg	altitude in km	velocity in km/s	Detecting satel- lite(s)	GLM - peak energy in J	GLM Energy in J	Infrasound Energy in J	CNEOS Energy in J	Absolute Magni- tude
2017-07-	22:01:34	24.84	-118.6		15.0*	GLM-16	5.04E-13	7.51E+10	9.20E+11	5.80E+10	-19.1
2017-09-	05:11:25	50.06	-117.09	36	14.7	GLM-16	4.23E-13	1.34E+11	1.88E+12	3.80E+10	-19.7
2017-10-	12:51:48	-19.04	-64.09		15.0*	GLM-16	2.81E-13	4.55E+10	5.44E+10	3.00E+10	-18.5
2017-12-	12:47:29	14.56	-48.93	38	15.0*	GLM-16	8.76E-13	1.26E+11		1.1E+11	-19.6
29 2018-02-	02:15:18	-16.03	-58.7		15.0*	GLM-16	3.51E-13	4.10E+10	9.62E+11	3.90E+10	-18.4
12 2018-03-	14:08:24	-43.6	-40.59		15.0*	GLM-16	4.02E-12	9.04E+11			-21.8
2018-05-	02:27:12	31.95	-59.36		15.0*	GLM-16,	2.33E-13	2.89E+10		7.3E+10	-18.0
08 2018-09-	00:51:20	42.73	-49.97		15.0*	GLM-17 GLM-16	2.67E-13	7.35E+10	1.84E+09	4.20E+10	-19.1
13 2018-09-	01:08:01	-6.86	-27.64		15.0*	GLM-16	1.37E-12	3.48E+11	1.46E+12	1.50E+11	-20.7
17 2018-09-	19:01:30	-22.08	-17.39		15.0*	GLM-16	3.05E-13	3.71E+10			-18.3
26 2018-10-	00:27:01	-40.07	-30.78	31.5	14.7	GLM-16	1.00E-12	3.29E+11		3.8E+10	-20.7
05 2018-11-	08:02:44	42.37	-51.16		15.0*	GLM-16	1.23E-12	2.35E+11		2E+10	-20.3
15 2018-11-	21:48:23	47.72	-173.34	32.5	19.1	GLM-17	1.65E-12	7.40E+11	8.62E+11	2.20E+11	-21.6
17 2019-02-	18:17:09	22.44	-83.8	23.7	16.3	GLM-16,	2.93E-12	5.04E+11	2.22E+10	5.79E+11	-21.1
01 2019-04-	11:06:18	43.79	-164.87		15.0*	GLM-17 GLM-17	7.20E-13	2.01E+11	5.19E+11		-20.1
22 2019-05-	15:35:45	28.59	-88.36	26.5	15.0*	GLM-16,	5.66E-13	3.49E+10	1.30E+11	2.20E+10	-18.2
04 2019-05-	15:16:00	47	10.76	32.6	15.0*	GLM-17 GLM-16	7.02E-13	1.81E+11	3.01E+10	9.50E+10	-20.0
22 2019-06-	21:25:45	14.91	-65.78	25	14.9	GLM-16	2.88E-12	1.32E+12	1.04E+13	2.95E+12	-22.2
22 2019-06-	16:52:47	21.5	-130.68	59	42.3	GLM-16,	2.88E-13	8.83E+10		3.2E+10	-19.3
30 2019-07-	20:42:56	44.93	-147.57	30.6	16.1	GLM-17 GLM-17	1.08E-12	2.37E+11	1.30E+12	2.55E+11	-20.3
23 2019-08-	04:36:41	-32.72	-22.04		15.0*	GLM-16	5.07E-13	7.10E+10			-19.0
06 2019-08-	17:07:27	-47.06	-68 68		15.0*	GLM-16	2.55E-13	2.58E+10	2.80E+11		-17.9
22	12:02:53	21.96	-131 24	30.8	13.4	GLM-10, GLM-17 GLM-16	5 19F-13	2.55E±11	21002111	4E+10	-20.4
24	02:34:57	25.18	131.24	30.6	17.2	GLM-10, GLM-17 GLM-16	7.34E 13	8 15E+10	2.64E±11	5 90E+10	10.2
12	12.20.22	22.10	-47.57	28	17.2	CLM-16	2.05E 12	0.15E+10	2.04E+11	1.00E+11	-19.2
2019-09- 14 2010-00	12:39:32	-58.92	-52.91	38	15.9	GLM-10	5.95E-15	1.01E+11		1.09E+11	-20.0
2019-09- 27	13:35:44	25.8	-28.84		15.0*	GLM-16	0.79E-13	1.32E+11	1 (05 13	3.4E+10	-19.7
2019-09-	11:08:37	52.86	-38.3		15.0*	GLM-16	3.74E-13	2.56E+10	4.60E+12		-17.9
2019-10- 24	09:51:16	22.28	-18.45		15.0*	GLM-16	4.64E-13	3.94E+10			-18.4
2019-11- 05	11:24:49	-10.73	-143.31	38	27.4	GLM-17	3.84E-13	1.38E+11	8.37E+10	1.10E+11	-19.7
2019-11- 07	10:03:14	53.09	-38.06		15.0*	GLM-16	2.67E-13	5.24E+10			-18.7
2019-11- 15	18:02:10	4.02	171.02		15.0*	GLM-17	5.95E-13	6.35E+10			-18.9
2019-11- 28	20:30:52	35.94	-31.09	35	13	GLM-16	2.74E-13	8.83E+10	2.59E+10	2.70E+10	-19.3
2019-12- 03	06:46:26	5.85	-51.66	61.5	15.0*	GLM-16	1.24E-12	3.93E+08		4.2E+10	-13.4
2020-01- 15	06:31:39	-23.89	-125.68	31.5	15.0*	GLM-16, GLM-17	2.82E-13	1.54E+10	1.67E+11	1.96E+11	-17.4
2020-01- 24	11:13:30	28.17	-35.37	32	21.2	GLM-16	4.02E-13	5.73E+10	9.20E+10	2.60E+10	-18.8
2020-01-	01:34:12	-28.24	-22.32		15.0*	GLM-16	4.26E-13	7.62E+10			-19.1
2020-02-	10:07:03	-43.87	-93.79		15.0*	GLM-16, GLM-17	2.95E-13	1.87E+10			-17.6
2020-03- 23	16:51:50	-24.49	-67.85	25	15.0*	GLM-16	2.74E-13	6.01E+10	8.79E+11	1.33E+11	-18.8

Table A.1: Fireballs analysed in this study.

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2020-04-	09:31:16	-15.47	-24.31		15.0*	GLM-16	3.09E-13	3.17E+07			-10.6
2020-05-	09:37:51	7.27	-43.36	52.5	15.0*	GLM-16	2.55E-13	4.82E+10		4.1E+10	-18.6
2020-05- 12	23:22:55	16.08	173.48		15.0*	GLM-17	1.78E-12	2.42E+11	7.53E+11	8.30E+10	-20.4
2020-05- 17	03:57:49	34.94	-17.32		15.0*	GLM-16	1.24E-12	2.27E+11			-20.3
2020-06- 01	16:27:30	16.59	-115.89	15.0*	GLM-16, GLM-17	2.30E-13	4.16E+10			-18.4	
2020-06-	04:54:37	25.47	-17.7		15.0*	GLM-16	5.06E-13	7.14E+10			-19.0
2020-07- 24	18:36:12	-15.39	-127.21		15.0*	GLM-16, GLM-17	2.81E-13	4.80E+10	2.3E+12		-18.6
2020-08- 02	16:36:24	-35.29	-33.76	38	11.1	GLM-16	5.54E-13	2.08E+11		7.4E+10	-20.2
2020-08- 21	13:41:11	33.33	-167.08		15.0*	GLM-17	2.65E-13	1.49E+11	9.61E+13		-19.8
2020-10- 21	06:38:49	-29.94	-94.02	39	15.0*	GLM-16, GLM-17	4.18E-13	5.12E+10		2.7E+10	-18.7
2020-10- 22	17:39:32	22.11	-134.11	40	17.6	GLM-16, GLM-17	2.46E-13	9.56E+10		4.4E+10	-19.3
2020-10- 24	13:25:18	-13.23	-64.41		15.0*	GLM-16	3.44E-13	1.62E+10			-17.4

Notes. Listed are the 50 events in the GLM database with the largest recorded peak energies for the investigated 39 months period from 31 July 2017 - 21 October 2020 sorted by date. The listed information about the date, time, and location of the detection are given as reported in the GLM database. The information about altitude and velocity is extracted from the CNEOS database, if available. Otherwise, 15 km s^{-1} is assumed as a default velocity. These cases are marked by an asterisk. Listed as well are the satellite that detected the event and the fireball energy and the absolute magnitude value based on the reported GLM lightning energy (in joules) computed as described in Sect. 2.4. If available, the energy computed from the IMS infrasound data in joules (derived as explained in Sect. 2.2) and the energy reported in the CNEOS database are listed as well.

Appendix B: Investigated fireballs - 24 detected with the IMS infrasound stations

Table B.1: Results and characteristics of the infrasound analysis of 24 fireballs for which a significant signature could be identified in the IMS infrasound data.

Date	Time	number of de- tecting stations	Period in s	Best esti- mate energy	Best estimate energy in Joule	Size in m	Mass in kg
		0		in kt TNT	8,		
				equivalent			
2017-07-31	22:01:34	1	3.1	2.2E-01	9.2E+11	1.7*	8178*
2017-09-05	5:11:25	3	3.8 ± 1.8	4.5E-01	1.9E+12	2.2	17585
2017-10-09	12:51:48	2	1.3 ± 0.1	1.3E-02	5.4E+10	0.7*	480*
2018-02-12	2:15:18	2	3.1 ± 1.1	2.3E-01	9.6E+11	1.8*	8533*
2018-09-13	0:51:20	2	0.5 ± 0.1	4.4E-04	1.8E+09	0.2*	16*
2018-09-17	1:08:01	6	3.5 ± 1.8	3.5E-01	1.5E+12	2.0*	13333*
2018-11-17	21:48:23	1	3.0	2.1E-01	8.6E+11	1.4	4715
2019-02-01	18:17:09	2	1.0 ± 0.6	5.3E-03	2.2E+10	0.5	166
2019-04-22	11:06:18	2	2.6 ± 1.5	1.2E-01	5.2E+11	1.4*	4622*
2019-05-04	15:35:45	1	1.7	3.1E-02	1.3E+11	0.9*	1156*
2019-05-22	15:16:00	1	1.1	7.2E-03	3.0E+10	0.6*	267*
2019-06-22	21:25:45	3	6.3 ± 2.5	2.5E+00	1.0E+13	3.9	90086
2019-07-23	20:42:56	1	3.4	3.1E-01	1.3E+12	1.9	10030
2019-08-22	17:07:27	1	2.2	6.8E-02	2.8E+11	1.2*	2489*
2019-09-12	2:34:57	1	2.1	6.3E-02	2.6E+11	1.0	1758
2019-09-30	11:08:37	1	5.0	1.1E+00	4.6E+12	3.0*	40889*
2019-11-05	11:24:49	1	1.5	2.0E-02	8.4E+10	0.5	224
2019-11-28	20:30:52	1	1.1	6.2E-03	2.6E+10	0.6	308
2020-01-15	06:31:39	3	1.8 ± 1.4	4.0E-02	1.7E+11	1.0*	1511*
2020-01-24	11:13:30	1	1.6	2.3E-02	9.2E+10	0.6	409
2020-03-23	16:51:50	4	3.0 ± 1.5	2.1E-01	8.8E+11	1.7*	7822*
2020-05-12	23:22:55	1	2.9	1.8E-01	7.5E+11	1.6*	6667*
2020-07-24	18:36:12	1	4.0	5.4E-01	2.3E+12	2.4*	20444*
2020-08-21	13:41:11	1	12.0	2.3E+01	9.6E+13	8.2*	853333*

Notes. Listed are the date and energy as computed from the GLM data, followed by the number of the IMS infrasound stations in whose data we found a signal of the fireball, the extracted period at maximum amplitude and the computed energy in kt TNT equivalent and joules. The determined size and mass of the corresponding impacting meteoroid or asteroid are also given. These values are computed using the velocity information provided by CNEOS, if available. If not, a velocity of 15 km/s is assumed. These cases are marked by an asterisk; see Table A.1. Additionally, for the size, a spherical shape and a density of 3000 kg/m³ are assumed.

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Table B.2: Details of the infrasound analysis of 24 fireballs for which a significant signature could be identified in the IMS infrasound data.

Date	Time	detecting stations	fireball- station dis- tance in km	frequency range in Hz	signal's start time in UT	signal's end time in UT	celerity	arrival	median back az- imuth in degree	maximum amplitude in Pa	Period in s	Best es- timate energy in kt TNT equivalent
2017-07-31	22:01:34	I57US	994	0.26 - 4.51	22:58:54	23:01:00	284	stratospheric	199	2.3	3.1	2.2E-01
		I56US	200	0.15 - 6	05:19:00	05:23:06	346		8.5	447.11	2	5.3E-02
2017-09-05	5:11:25	I10CA	1501	0.2 - 4.51	06:32:41	06:40:20	294	stratospheric	274	0.07	3.85	4.7E-01
		I57US	1828	0.11 - 3.39	06:50:45	07:09:03	281	stratospheric	3.5	1.71	5.55	1.6E+00
2017-10-09	12.51.49	I08BO	559	0.2 - 6	13:19:28	13:24:40	308	stratospheric	122	0.30	1.35	1.4E-02
	12.31.46	I41PY	1067	0.2 - 3.55	13:51:56	13:56:20	285	stratospheric	317.9	0.14	1.25	1.1E-02
2018-02-12	2.15.18	I08BO	1043	0.04 - 6	03:06:24	03:12:18	322	tropospheric	90.4	0.14	2.35	9.1E-02
2010-02-12	2.13.10	I09BR	1145	0.063 - 2.55	03:31:11	03:39:11	239	thermospheric	266.2	0.079	3.85	4.7E-01
2018-09-13	0.51.20	I42PT	1892	1.44 - 6	02:30:06	02:30:39	318	stratospheric	297.4	2.14	0.4	2.5E-04
2010-09-15	0.51.20	I18DK	3970	0.61 - 6	04:41:21	04:43:24	286	stratospheric	157.3	0.05	0.55	7.1E-04
		I50GB	1469	0.82 - 4.51	02:31:31	02:34:58	287	stratospheric	278.4	0.092	1.2	9.7E-03
		I09BR	2425	0.26 - 1.44	03:25:08	03:29:38	290	stratospheric	66.7	0.022	3.2	2.6E-01
2018-09-17	1:08:01	I11CV	2495	0.11 - 2.55	03:30:04	03:36:01	287	stratospheric	190.7	1.025	6.7	1.4E-01
		I17CI	2940	0.08 - 1.92	03:54:32	04:01:29	288	stratospheric	240.1	0.033	3.1	3.0E+00
		I49GB	3690	0.26 - 4.51	04:29:27	04:38:54	298	stratospheric	331.8	46.81	2.85	2.3E-01
		108BO	4562	0.11 - 2.55	05:25:57	05:30:12	292	stratospheric	81.6	0.062	4.05	1.7E-01
2018-11-17	21:48:23	153US	2443	0.047 - 6	00:01:17	00:11:05	295	stratospheric	226.7	320.86	3	2.1E-01
2019-02-01	18:17:09	I5IGB	2180	0.46 - 1.44	20:07:19	20:13:52	320	tropospheric	243.8	28.96	1.45	1.8E-02
		HOCA	3261	1.08 - 4.51	21:54:17	21:55:02	250	thermospheric	2 166.1	0.02	0.55	7.1E-04
2019-04-22	11:06:18	15908	2811	0.46 - 6	13:35:03	13:45:15	305	stratospheric	345.8	0.19	1.5	2.0E-02
2010 05 04	15 35 45	144RU	2915	0.11 - 6	13:39:49	14:03:04	294	stratospheric	98.7	26.34	3.65	4.0E-01
2019-05-04	15:35:45	HOCA	2485	0.35 - 1.92	18:00:53	18:03:29	283	stratospheric	157.5	0.093	1.7	3.1E-02
2019-05-22	15:16:00	109BR	3167	0.46 - 6	18:17:25	18:18:40	290	stratospheric	31.4	0.018	1.1	7.2E-03
2010 06 22	21.25.45	151GB	1936	0.2 - 2.55	23:16:28	23:20:37	286	stratospheric	187.9	161.48	3.55	3.6E-01
2019-06-22	21:25:45	120EC	3137	0.02 - 6	00:12:01	00:33:19	296	stratospheric	54.5	0.17	7.2	3.8E+00
2010 07 02	20 12 56	108BO	3455	0.05 - 3.39	00:40:21	00:47:42	290	stratospheric	2.8	0.18	8.2	5.9E+00
2019-07-23	20:42:56	15308	2223	0.083 - 2.55	22:42:25	22:55:31	294	stratospheric	182.5	/8.16	3.4	3.1E-01
2019-08-22	1/:0/:2/	102AR	842	0.11 - 6	1/:55:35	18:00:17	2/8	thermospheric	2 5.7	0.57	2.15	6.8E-02
2019-09-12	2:34:57	ISIGB	1849	0.26 - 6	04:11:09	04:18:36	308	stratospheric	113.4	20.67	2.1	6.3E-02
2019-09-30	11:08:37	13/NO	3393	0.083 - 4.51	14:24:17	14:28:08	286	stratospheric	267.9	0.12	4.95	1.1E+00
2019-11-05	11:24:49	121FR	402	0.2 - 6	11:45:26	11:48:23	303	stratospheric	241.2	2.22	1.5	2.0E-02
2019-11-28	20:30:52	142P1	436	0.26 - 6	20:56:17	21:00:11	266	thermospheric	219	128.34	1.05	6.2E-03
2020 01 15	06 21 20	121FR	2267	0.11 - 6	08:32:26	08:42:05	301	stratospheric	140.9	0.96	3.15	2.4E-01
2020-01-15	06:31:39	124FR	2547	0.047 - 6	08:46:29	09:01:44	298	stratospheric	108.9	0.26	1.95	4.9E-02
2020 01 24	11.12.20	120EC	40/0	1.44 - 0	11:43:20	11:44:05	250	thermospheric	200.2	0.49	0.4	2.5E-04
2020-01-24	11:15:50	142P1	1381	0.35 - 6	12:23:24	12:41:00	292	stratospheric	209.2	92.48	1.55	2.3E-02
2020-03-23		108BO	918	0.11 - 4.51	1/:41:49	1/:4/:40	289	stratospheric	1//	0.29	5.2	1.5E+00
	16:51:50	109DK	2291	0.55 - 1.08	19:11:20	19:10:08	209	atrataanhania	254.0	0.02	2.7	1.3E-01 5.2E-02
		102AK	4155	0.40 - 1.92	20.02.29	20.05.05	290	stratospheric	90.7	0.05	$\frac{2}{2}15$	5.5E-02 6.8E-02
2020 05 12	23.22.55	158110	1637	0.2 2 20	00.52.07	00.57.10	295	stratospheric	210.1	0.051	2.15	1.8E 01
2020-03-12	18.36.12	130US	1583	0.2 - 5.59	20:25:20	20.26.32	290	thermospheric	217.1	0.23	4.9	5.4E.01
2020-07-24	10.30.12	1211'K	1000	0.2 - 0.01	15.27.19	15:45:42	240	thormoonhari	202.0	0.082	12.2	2.4E-01
2020-08-21	15:41:11	13903	1004	0.054 - 0.15	13:37:18	13:43:42	201	mermospherio	525	0.022	12.3	2.3E+01

Notes. Listed are the dates, followed by the names of the IMS infrasound stations in whose data we found a signal of the fireball. For each detecting station, the distance to the station, the identified signal's start and end time, the computed celerity and type of arrival, the recorded median back azimuth, the recorded maximum amplitude, the frequency range in which the fireball's signature was found, the derived period at maximum amplitude, and the derived source energy in kt TNT equivalent are presented.