



# The 2023 May 20 Queensland Superbolide: Multimodal Observations from Atmospheric Entry to Postdisruption Dust Cloud

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## Abstract

On 2023 May 20, a  $\sim 3.7$  m diameter asteroid entered Earth's atmosphere over northwest Queensland, Australia, at  $27.9 \text{ km s}^{-1}$  and underwent catastrophic fragmentation at  $\sim 29$  km altitude, producing 1 of the 20 most energetic bolide events reported by NASA's Center for Near-Earth Object Studies (CNEOS) since 1988 and the most energetic over Australia ( $\sim 7.1$  kt TNT equivalent). We present a multimodal analysis integrating CNEOS optical data, trajectory determination, infrasound detections at six International Monitoring System stations (up to 8030 km), seismic observations, and Himawari-9 geostationary satellite thermal infrared imagery. Infrasound observations independently confirm a multikiloton source, and the infrasound-derived source altitude ( $30 \pm 5$  km) is consistent with the CNEOS-reported peak brightness altitude. We report the first nighttime detection and mass quantification of a bolide dust cloud from geostationary orbit; the cloud persisted for over 1 hr, yielding a dust mass of 10.9–32.8 metric tons (14%–43% of the preatmospheric mass). With an estimated recurrence interval of  $\sim 1.5$  yr for events of this energy or greater, the Queensland superbolide provides an end-to-end observational benchmark for atmospheric entry models and planetary defense.

*Unified Astronomy Thesaurus concepts:* Asteroids (72); Planetary atmospheres (1244); Planetary science (1255); Impact phenomena (779)

## 1. Introduction

On 2023 May 20, at approximately 21:22 local time (11:22 UTC), a small asteroid entered Earth's atmosphere over northwest Queensland, Australia. Traveling at  $\sim 28 \text{ km s}^{-1}$ , the object underwent catastrophic fragmentation at an altitude of  $\sim 29$  km, producing a brilliant fireball visible from distances exceeding 600 km and accompanied by pronounced sonic booms. US Government (USG) space-based sensors, reported through the National Aeronautics and Space Administration's (NASA) Center for Near-Earth Object Studies (CNEOS), recorded a total radiated energy of  $3.51 \cdot 10^{12}$  J, corresponding to a total impact energy of  $\sim 7.1$  kt of trinitrotoluene (TNT) equivalent ( $1 \text{ kt} = 4.184 \cdot 10^{12}$  J). This places the Queensland bolide among the 20 most energetic events recorded globally by USG sensors since 1988, and the single most energetic event detected over Australia (e.g., I. Clemente et al. 2025;

E. A. Silber & V. Sawal 2025; M. Ronac Giannone & E. A. Silber 2026).

Characterizing such events is central to planetary defense. Because near-Earth objects approximately follow a power-law size-frequency distribution, the integrated impact risk is often dominated by relatively small objects that are frequent enough to matter and can still produce consequential surface effects (P. G. Brown et al. 2013; A. W. Harris & P. W. Chodas 2021). Many such consequences arise from airbursts, where the atmosphere acts as the interaction medium and where the altitude and manner of fragmentation control the efficiency and geometry of energy deposition. Importantly, the physical processes that govern damaging, lower-altitude airbursts (e.g., ablation, radiative emission, shock wave generation, and fragmentation) are the same processes revealed by instrumental observations and modeling of more frequent, higher-altitude airbursts, including superbolides such as the 2023 May 20 event (M. Boslough 2015). When objects enter the atmosphere at hypervelocity, the interaction with ambient atmospheric gases initiates a series of complex phenomena, including ablational mass loss, radiative emissions, intense shock wave generation, and structural fragmentation of the



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impacting body (V. A. Bronshten 1983; Z. Ceplecha et al. 1998; M. Gritsevich & D. Koschny 2011; E. A. Silber et al. 2018). Extraterrestrial objects entering Earth’s atmosphere at velocities ranging from 11.2 to  $\sim 72 \text{ km s}^{-1}$  experience extreme aerodynamic loading, frequently exceeding material binding strength and causing mechanical failure through fragmentation (e.g., Z. Ceplecha et al. 1998; J. M. Trigo-Rodríguez et al. 2021), which dramatically alters energy deposition, shock wave production, and subsequent acoustic and seismic manifestations (e.g., Y. Ishihara et al. 2004; M. Boslough 2015; L. F. Wheeler et al. 2018; S. Arrowsmith et al. 2021; E. A. Silber 2024b). Beyond their relevance to impact hazard assessment, such events also bear on broader questions regarding planetary surface evolution, atmospheric chemistry, and the delivery of organic materials to early Earth (C. Chyba & C. Sagan 1992; P. Jenniskens et al. 2000; E. A. Silber et al. 2018; K. J. Zahnle et al. 2020). The 2013 Chelyabinsk airburst, in which a  $\sim 20 \text{ m}$  asteroid released approximately 440 kt of TNT equivalent energy, demonstrated that even moderate-sized impactors can generate damaging surface effects through shock wave coupling (P. G. Brown et al. 2013; O. P. Popova et al. 2013). Events like the Queensland bolide, though 2 orders of magnitude less energetic than Chelyabinsk, provide critical observational benchmarks for testing and refining the fragmentation and energy deposition models that underpin airburst hazard assessments (e.g., M. Boslough 2015; L. F. Wheeler et al. 2018; E. A. Silber et al. 2025).

Robust characterization of atmospheric entry events requires integrating multiple, independent observational modalities (e.g., P. G. Brown et al. 2023; E. A. Silber 2024a; A. Egal et al. 2025; I. R. Hatty et al. 2026; L. T. Scamfer et al. 2026). Optical sensors, both ground-based and satellite-borne, constrain the trajectory, velocity, fragmentation sequence, and radiative energy output (H. A. R. Devillepoix et al. 2019; H. A. R. Devillepoix et al. 2020; P. Jenniskens et al. 2021; E. A. Silber & V. Sawal 2025). Infrasound arrays detect the low-frequency acoustic waves generated by atmospheric shock waves, independently constraining source energy and altitude through empirical period-yield relations and propagation modeling (T. A. Ens et al. 2012; E. A. Silber 2024b; E. A. Silber et al. 2025). Seismic stations record air-to-ground coupled acoustic arrivals that provide additional constraints on energy deposition and source geometry (C. A. Langston 2004; W. N. Edwards et al. 2009; T. Neidhart et al. 2021; L. T. Scamfer et al. 2026). In recent years, the expansion of global infrasound monitoring networks, particularly the International Monitoring System (IMS) operated by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO PrepCom; P. Campus & D. R. Christie 2009; D. R. Christie & P. Campus 2010; P. Hupe et al. 2022), has substantially advanced the detection and characterization of bolides and other impulsive atmospheric events (e.g., P. G. Brown et al. 2013; C. Pilger et al. 2021; E. K. Sansom et al. 2022; D. C. Bowman et al. 2025; K. Kim 2025; T. C. Wilson et al. 2025; I. R. Hatty et al. 2026; M. Ronac Giannone & E. A. Silber 2026).

The Queensland bolide was observed across a broad range of these modalities, from ground-based sensors to those in geostationary orbit. While the extreme luminosity of the fireball saturated ground-based optical instrumentation, complicating initial photometric analysis, USG space-based sensors captured a detailed brightness profile revealing

multiple fragmentation episodes during atmospheric passage. Infrasound signals were recorded at six IMS stations at distances up to  $\sim 8000 \text{ km}$ , exclusively at stations situated east of the source, revealing a pronounced directional asymmetry driven by prevailing atmospheric wind structure. Seismic instrumentation within Australia detected an acoustic–seismic coupled signal at the nearest station,  $\sim 260 \text{ km}$  from the airburst. Perhaps most notably, thermal infrared imagery from the Japanese Himawari-9 geostationary weather satellite captured the evolution of a lingering dust cloud at the burst altitude, persisting for more than 1 hr after the event. To our knowledge, this represents the first detection and mass quantification of a bolide dust cloud using nighttime thermal infrared observations from geostationary orbit, providing an independent constraint on the disrupted mass of the impacting body through a technique previously applied only to volcanic ash.

In this study, we present a comprehensive, multimodal analysis of the 2023 May 20 Queensland superbolide. We integrate space-based optical observations, IMS infrasound detections, seismic recordings, satellite thermal infrared imagery, and numerical simulations to characterize the event’s entry dynamics, energy deposition, acoustic wave propagation, and postdisruption dust cloud evolution. Independent energy estimates derived from infrasound period-yield relations and dust cloud mass measurements are compared with the USG optical energy to assess cross-modal consistency. Infrasound propagation modeling is used to explain the observed directional detection asymmetry and to constrain the acoustic source altitude. We additionally report on dark flight modeling and a ground-based meteorite recovery expedition. These results demonstrate the value of integrating diverse observational platforms, from seismometers to weather satellites, for characterizing superbolides, and provide new observational constraints relevant to atmospheric entry modeling and impact hazard assessment.

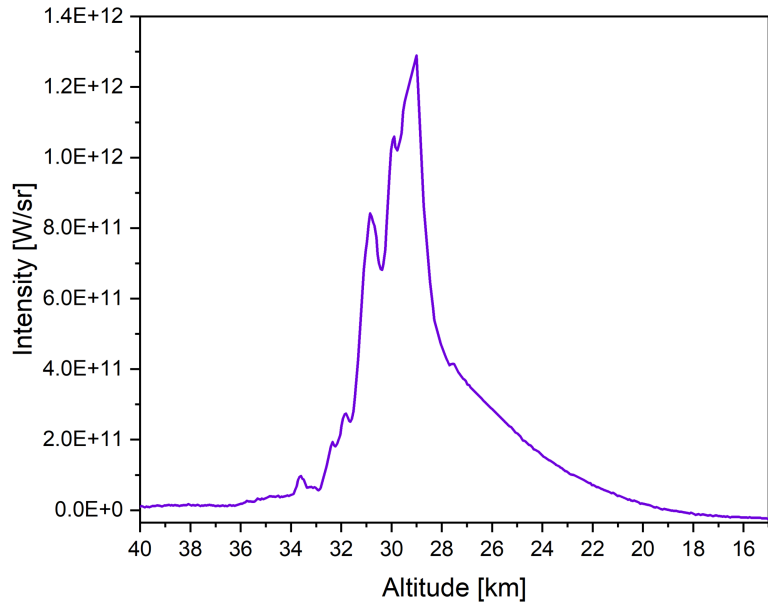
## 2. Spaceborne Optical Records

The fireball was detected by USG space-based sensors, with observational data reported through NASA CNEOS (e.g., E. Peña-Asensio et al. 2022; E. A. Silber & V. Sawal 2025). The bolide reached peak brightness at 11:22:23 UTC at geographic coordinates of approximately  $17.8^\circ \text{S}$  latitude and  $141.9^\circ \text{E}$  longitude, at an altitude of  $29.0 \text{ km}$ . The object entered Earth’s atmosphere at an initial speed of  $27.9 \text{ km s}^{-1}$ . Using the velocity vector components provided by CNEOS ( $v_x = 25.4 \text{ km s}^{-1}$ ,  $v_y = 6.9 \text{ km s}^{-1}$ ,  $v_z = 9.3 \text{ km s}^{-1}$ ), we derived an atmospheric entry angle of  $39.36^\circ$  relative to the local horizontal plane, and an azimuth of  $100.98^\circ$  measured clockwise from geographic north.

The USG sensor data indicate a total radiated energy of  $3.51 \cdot 10^{12}$  joules, corresponding to a total impact energy estimate of  $\sim 7.1 \text{ kt}$  of TNT equivalent. Assuming a bulk density of  $\sim 3000\text{--}3500 \text{ kg m}^{-3}$  (G. S. J. Consolmagno & D. T. Britt 1998), this energy and entry velocity correspond to an estimated preatmospheric diameter of  $\sim 3.5\text{--}3.7 \text{ m}$  and a mass of  $\sim 76$  metric tons.

The optical brightness profile recorded by USG sensors (Figure 1) reveals multiple distinct luminosity peaks, indicative of episodic fragmentation during atmospheric passage. The dominant brightness peak occurred at an altitude of  $\sim 29 \text{ km}$ , corresponding to the main airburst. At least two additional





**Figure 1.** USG derived lightcurve as a function of altitude.

fragmentation episodes are evident at higher altitudes, between  $\sim 30$  and  $33$  km, represented by secondary peaks of lower intensity that indicate progressive structural failure preceding the terminal disruption. A rapid increase in radiative intensity immediately precedes the main airburst at  $29$  km, followed by a sudden decline consistent with extensive fragmentation and rapid mass loss. The slowly decaying tail of the brightness curve is indicative of a lingering high-altitude dust cloud, discussed further in Section 5.

### 3. Observational Constraints

#### 3.1. Witness Reports and Ground-based Optical

The fireball was widely observed by the public and captured by numerous security cameras, dashboard cameras, and smartphones across northwest Queensland. A security camera at Cairns Airport recorded a distinctive green flash followed by a secondary white flash (H. Baker 2023). Video and eyewitness reports confirm that the fireball was visible from distances exceeding  $600$  km, including from the town of Normanton to the west, and a sonic boom was reported by residents near the town of Croydon, approximately  $150$  km east of Normanton, suggesting that the main fragmentation occurred in the vicinity overhead.

The event was recorded by three security cameras close enough to the fireball to perform astrometry (Figure 2, Table 1), of which two (McKinlay and Paddys Green) were suitable for astrometric trajectory determination. All three experienced significant saturation. The main fragmentation event saturated the entire field in the Normanton and Paddy’s Green records. One prominent feature in the optical records after the bright flight phase finished is the presence of a stationary source getting redder until it disappears over the course of a couple of seconds. We interpret this as a large cooling dust cloud left over after the main fragmentation event.

The three videos were astrometrically calibrated using stars with the *SkyFit2* package (D. Vida et al. 2021a). The cameras captured the upper portion of the trajectory above approximately  $80$  km altitude (plane convergence angle of  $\sim 61.5^\circ$ ), but

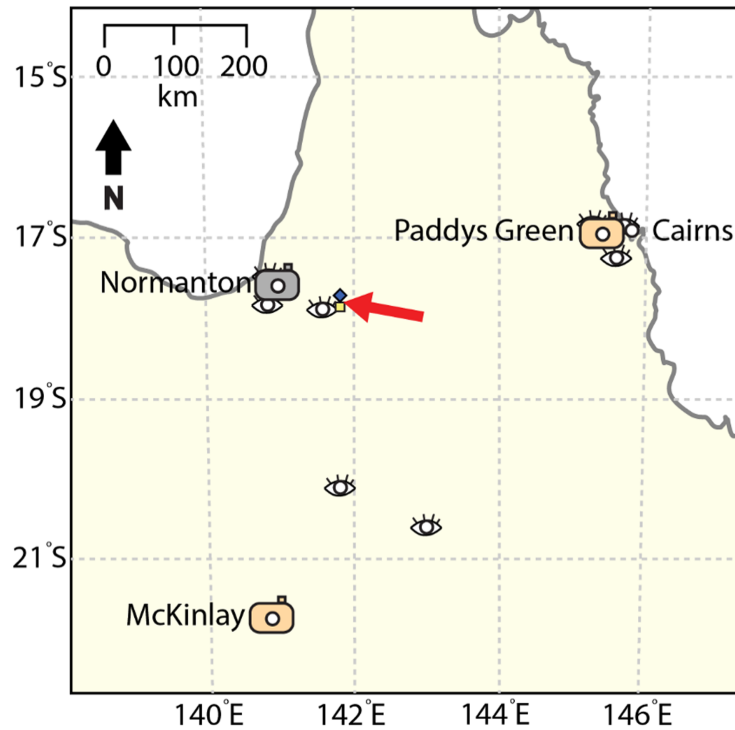
pixel saturation precluded reliable tracking through the lower atmosphere, where the principal energy deposition and fragmentation occurred. Only a single point was able to be measured at the end of the fireball to determine the terminal height. Selected frames from the Paddys Green station are shown in Figure 3. The trajectory begins at  $\sim 127$  km altitude, and the initial velocity measured above  $60$  km altitude is  $\sim 29 \text{ km s}^{-1}$ , consistent with the USG-reported entry speed of  $27.9 \text{ km s}^{-1}$ . The ground-fixed radiant azimuth ( $\sim 99.8^\circ$ ) and elevation ( $\sim 41.5^\circ$ ) are likewise consistent with the USG trajectory geometry. Orbital parameters derived from ground-based camera measurements are shown in Table 2. The resulting heliocentric orbit ( $a \sim 2.4 \text{ au}$ ,  $e \sim 0.82$ ,  $i \sim 2.4^\circ$ ,  $T_j \sim 2.9$ ) is consistent with an Apollo-type asteroid on a Jupiter-family-comet-like orbit. However, the observed entry and fragmentation behavior, including deep atmospheric penetration and catastrophic disruption near  $\sim 29$  km altitude, is more consistent with a relatively competent asteroidal body than with a weak cometary meteoroid.

#### 3.2. Infrasound Observations and Energetics

##### 3.2.1. Infrasound Network and Signal Processing

Infrasound observations of the Queensland superbolide were acquired through the IMS operated by the CTBTO PrepCom (D. R. Christie & P. Campus 2010), a global network of 53 (of a planned 60) infrasound stations designed for illicit explosion monitoring (P. Hupe et al. 2022; H. S. Elbehiri et al. 2025). Each station typically comprises four or more sensors configured to enhance directional resolution and reduce ambient noise through coherent array processing (N. Brachet et al. 2010).

We examined infrasonic data from at least 23 IMS stations at distances up to  $10,000$  km from the event (E. A. Silber 2024a); two stations (I40PG and I52GB) lacked data during the timeframe of interest. Array processing was performed using frequency-wavenumber ( $f$ - $k$ ) analysis implemented in the Cardinal software package (M. Ronac Giannone et al. 2025), which segments infrasonic data in pixelated time-



**Figure 2.** Map of Northern Queensland, showing the location of the three security camera locations that were analyzed, with the two used in trajectory reconstruction shown in orange (trajectory ground track projection is shown by a red arrow). Eyewitness observations as reported to International Meteor Organization (IMO) are shown (with multiple from Cairns and Normanton), along with the CNEOS-reported location (blue diamond) and the location of the meteorite search (yellow square).

**Table 1**  
Summary of Optical Stations Used for Trajectory Reconstruction

| Viewpoint                         | Distance to Fireball (km) | Resolution (pixel) | Pixel Scale (arcmin/pixel) | Framerate (fps) | Station Location Determination Method                |
|-----------------------------------|---------------------------|--------------------|----------------------------|-----------------|------------------------------------------------------|
| Normanton (public leisure center) | ~90                       | 1280 × 720         | 3.8                        | 25              | inferred from parallax of foreground objects         |
| Paddys Green (farm shed)          | ~400                      | 1920 × 1200        | 1.4                        | 30              | reading from RTK GNSS unit tractor parked underneath |
| McKinlay (mine site)              | ~450                      | 2592 × 1944        | 2.3                        | 30              | inferred from parallax of foreground objects         |

**Note.** Precise positions are listed in Appendix A (and the astrometric data products are archived on Zenodo (see [Data Availability](#))).

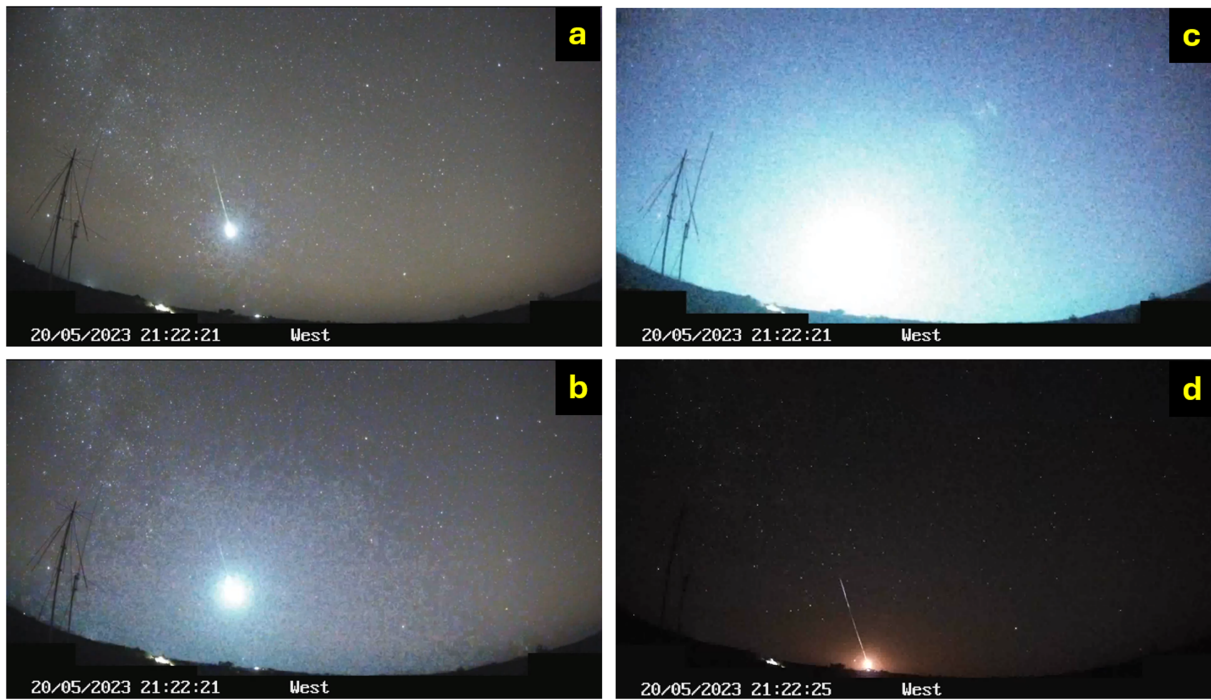
frequency space using frequency bands and temporal windows optimized for signal-to-noise ratio (SNR). Back azimuth, apparent velocity, and semblance were computed for each station to verify association with the bolide event. Signal onset times were identified by aggregating time-frequency pixels into coherent detection families based on consistency in back azimuth, trace velocity, and frequency content. In addition to the IMS network, we examined data from the 32-station Kochi University of Technology (KUT) Infrasound Sensor Network distributed along the southeastern coast of Japan (I. Hamama & M.-Y. Yamamoto 2021; Y. Nishikawa et al. 2024), at distances of ~5700–6800 km from the event. No signals attributable to the Queensland superbolide were identified at any KUT station (Appendix B).

### 3.2.2. Detections and Signal Characterization

Signals from the Queensland superbolide were detected at six IMS infrasound stations at distances from ~831 to ~8029 km (Figure 4). Five of the six detecting stations span from south to north–northeast of the source: I05AU (south, 2799

km), I22FR (east, 2648 km), I39PW (north–northwest, 2930 km), I30JP (north, 5907 km), and I44RU (north–northeast, 8029 km) (Table B1). The sole detection to the west, I07AU (~831 km), exhibited the slowest celerity of all detecting stations ( $0.253 \text{ km s}^{-1}$ ) and a notably weak signal, consistent with upwind propagation. Signal celerities at the remaining five stations ranged from 0.291 to  $0.334 \text{ km s}^{-1}$ . No detections were made at other IMS stations situated to the west despite several being within comparable range, a directional asymmetry attributable to the prevailing stratospheric wind structure favoring eastward propagation at the time of the event. A representative output from the Cardinal-based analysis is shown in Figure 5. This output illustrates the multifrequency beamforming and family-based detection approach implemented in Cardinal, in which consistent time-frequency pixels are grouped to obtain stable estimates of back azimuth, apparent velocity, and signal duration.

Dominant signal periods at each detecting array were measured from beamformed waveforms, where beamforming coherently sums array element recordings based on computed



**Figure 3.** Ground-based optical observations of the Queensland superbolide. Selected frames from the Paddys Green station showing the evolution of the event. Frame (a) displays the initial entry. Frames (b) and (c) illustrate the rapid increase in luminosity, leading to severe sensor saturation for  $\sim 3$  s around the brightest part. Frame (d) shows the final stages of the trajectory on which the terminal height was constrained.

**Table 2**

Orbital Parameters Determined from Ground-based Camera Measurements

| Symbol   | Parameter                               | Value      | Uncertainty               |
|----------|-----------------------------------------|------------|---------------------------|
| $e$      | Eccentricity                            | 0.817740   | $\pm 4.25 \times 10^{-4}$ |
| $a$      | Semimajor axis (au)                     | 2.442921   | $\pm 9.18 \times 10^{-3}$ |
| $q$      | Perihelion distance (au)                | 0.445246   | $\pm 8.28 \times 10^{-4}$ |
| $i$      | Inclination ( $^\circ$ )                | 2.223803   | $\pm 7.45 \times 10^{-2}$ |
| $\Omega$ | Longitude of ascending node( $^\circ$ ) | 58.971216  | $\pm 2.45 \times 10^{-3}$ |
| $\omega$ | Argument of perihelion ( $^\circ$ )     | 284.083221 | $\pm 0.124$               |
| $m$      | Mean anomaly ( $^\circ$ )               | 348.446493 | $\pm 7.01 \times 10^{-2}$ |

arrival delays to reduce local noise and provide a representative waveform. The dominant acoustic period at maximum amplitude was determined by measuring the duration between successive zero-crossings surrounding the peak amplitude (D. O. ReVelle 1997; T. A. Ens et al. 2012; E. A. Silber 2024a). Full array processing results, including measured signal periods are provided in Appendix B (Table B2).

### 3.2.3. Propagation Modeling and Source Altitude

To investigate the propagation characteristics of infrasonic signals and to constrain the acoustic source altitude, we conducted ray-tracing and propagation modeling using InfraGA (P. Blom 2014) and NCPAProp (R. M. Waxler et al. 2017). The bolide’s peak brightness location ( $17.8^\circ\text{S}$ ,  $141.9^\circ\text{E}$ ) was defined as the source, and range-dependent atmospheric specifications from the Ground-to-Space (G2S) repository (D. P. Drob et al. 2003; C. H. Hetzer 2024) provided vertical profiles of temperature, winds, density, and pressure, spatially interpolated along great-circle paths to each IMS station. Range-dependent ray-tracing was conducted for source altitudes from 20 to 50 km in 5 km increments, with launch angles from  $-89^\circ$  to  $+89^\circ$  in  $5^\circ$  steps along great-circle

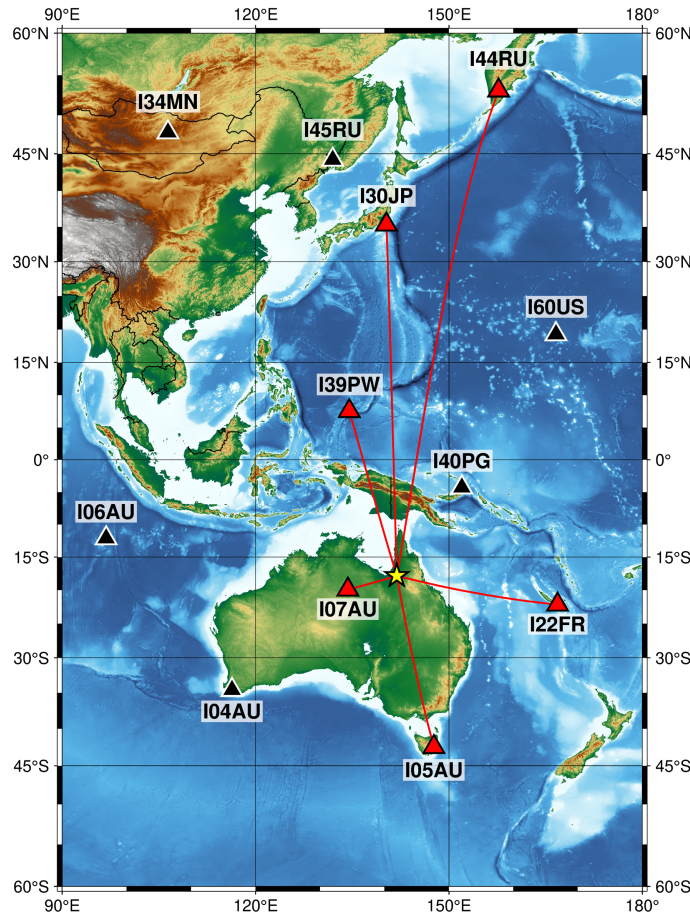
azimuths to each station (E. A. Silber 2024b). Ray paths passing near each station were retained as candidate arrivals (Appendix B). NCPAProp simulations complemented the InfraGA analysis by quantifying atmospheric transmission losses and further characterizing the directional propagation asymmetry.

Modeling results confirmed that the observed detection pattern is seasonally driven: prevailing atmospheric winds at the time of the event strongly favored eastward infrasonic propagation, inhibiting westward transmission (D. P. Drob et al. 2010; J. Park et al. 2016). The weak, low-celerity signal at I07AU is consistent with this interpretation, as upwind propagation at short range remains possible but attenuated. The infrasonic source altitude was determined by comparing InfraGA-modeled acoustic travel times with observed arrival times at each IMS station individually, following the methodology of E. A. Silber (2024b), E. A. Silber et al. (2011), and T. C. Wilson et al. (2025). Source altitude was examined across all six detecting stations, but the final constraint was derived from the closest stations at distances up to 5000 km (E. A. Silber et al. 2011), where propagation effects introduce the least uncertainty. For each hypothetical source altitude, candidate arrivals whose closest approach was consistent with the observed travel times were selected, and the best-fit altitude was identified as that providing the smallest travel-time residuals. The analysis yielded consistent constraints across all six detecting stations, converging on a source altitude band of  $30 \pm 5$  km, in agreement with the USG-reported peak brightness altitude of 29 km.

### 3.2.4. Infrasonic Energy Estimate

The source energy of the Queensland superbolide was estimated independently from infrasound observations using empirical period-yield relations of the form  $\log(E) = A \log(\tau) + B$ ,





**Figure 4.** Contextual map showing the event (star) and the six IMS stations, which detected the fireball (red triangles). Other nearby IMS stations that did not have any detections are also shown (black triangles).

where  $E$  is the source energy in kilotons of TNT equivalent and  $\tau$  is the dominant infrasound signal period in seconds. The measured dominant infrasound periods exhibit appreciable station-to-station variability, as expected for a multistation bolide detection with different propagation paths, waveform morphologies, and signal-to-noise conditions (e.g., T. A. Ens et al. 2012; N. Gi & P. Brown 2017). We therefore use the all-station averaged dominant period,  $\tau = 6.7 \pm 2.4$  s.

Applying the averaged-period relation of E. A. Silber et al. (2025) gives 9.7 kt, while the averaged-period relation of N. Gi & P. Brown (2017) gives 9.0 kt. These recent bolide-calibrated averaged-period relations therefore place the infrasound-based energy estimate at  $\sim 9$ –10 kt. The altitude-partitioned relation of E. A. Silber et al. (2025) for sources below 30 km gives an intermediate estimate of  $\sim 8.5$  kt, consistent with the expectation that deep, high-density energy deposition can couple efficiently to the acoustic field. The infrasound-based estimates independently confirm that the Queensland superbolide was a multikiloton airburst and are consistent with the CNEOS radiometric energy of  $\sim 7.1$  kt. We retain the CNEOS value as the preferred absolute energy estimate because it is derived from direct space-based radiometric observations of the fireball. The physical interpretation of the infrasound-based estimates is discussed in Section 6.2.

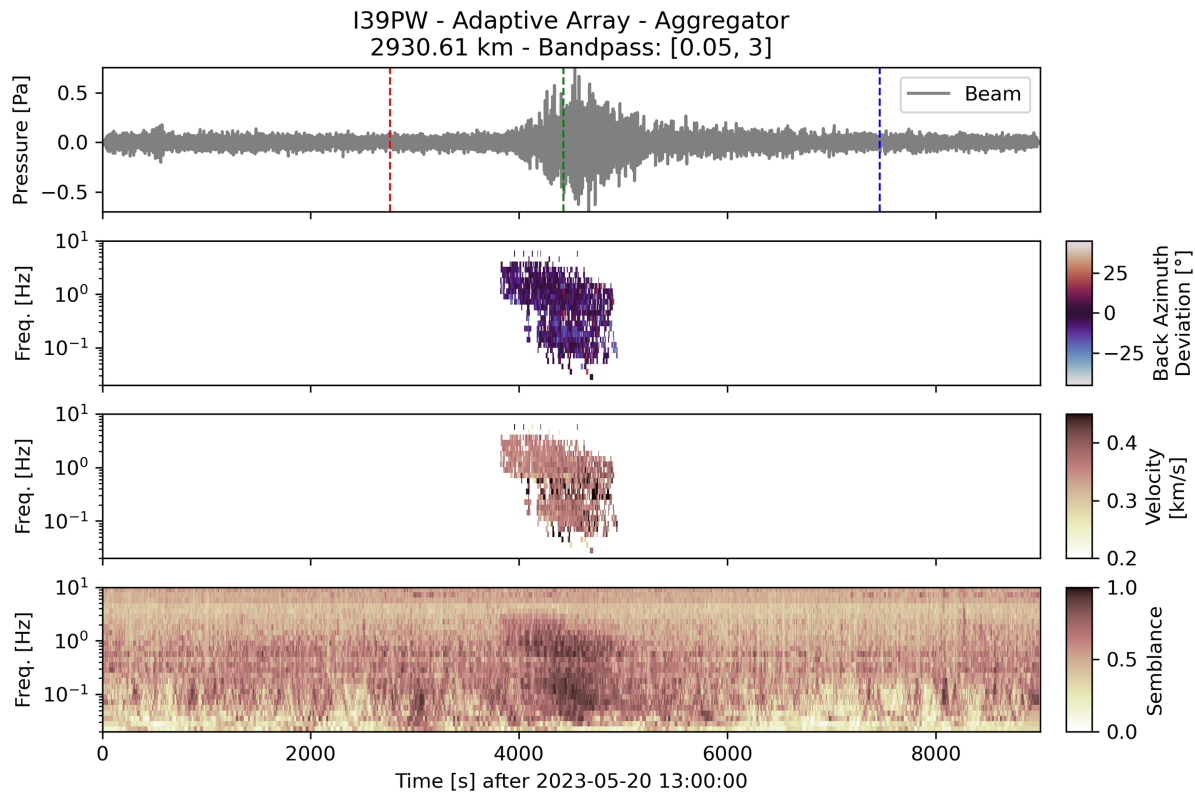
The infrasound observations also provide a source altitude constraint of  $30 \pm 5$  km, consistent with the CNEOS peak brightness altitude of 29 km.

### 3.3. Seismic Observations

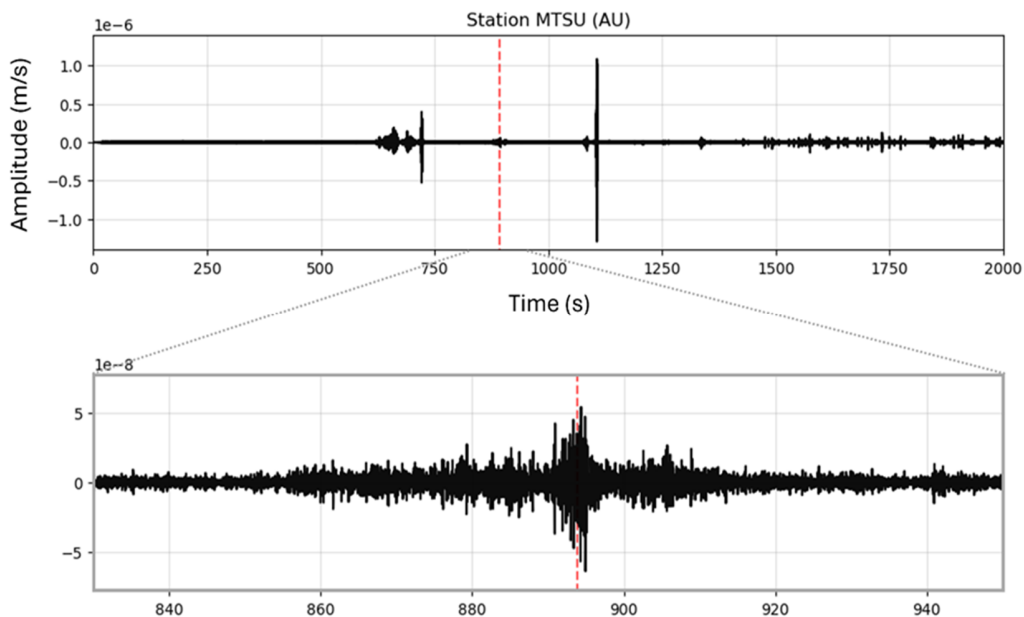
In the region of the Queensland superbolide entry, only five seismic stations from the Australian National Seismograph Network (ANSN, AU network; Geoscience Australia 2021) were located within a 500 km radius of the fireball. The closest station, MTSU, is situated approximately 260 km from the event’s peak brightness location. As the Queensland fireball was a highly energetic event, we investigated the potential for seismic detection of an air-to-ground coupled acoustic arrival.

To model the expected air-to-ground coupling, we assumed shock wave emission from the location of peak brightness at an estimated altitude of 30 km and employed the ray-tracing package *infraGA* (P. Blom 2014) to simulate all possible signal propagation paths within 500 km from the source. Ray-tracing used atmospheric profiles obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) reanalysis (H. Hersbach et al. 2018, 2020). Rays were sampled every  $0.5^\circ$  from vertical to horizontal, directed toward the MTSU seismic station (azimuth  $98.9^\circ$ ) and toward azimuths between  $92^\circ$  and  $104^\circ$  in steps of  $0.5^\circ$  (Figure B4, Appendix B).

The ray-tracing results show an arrival reaching the ground at a location approximately 1.9 km from the MTSU station ( $-18.15^\circ\text{S}$ ,  $144.32^\circ\text{E}$ ), with a corresponding travel time of 893.85 seconds from the peak brightness time. Based on this prediction, the seismic signal recorded at MTSU was examined for evidence of an arrival at this expected time.



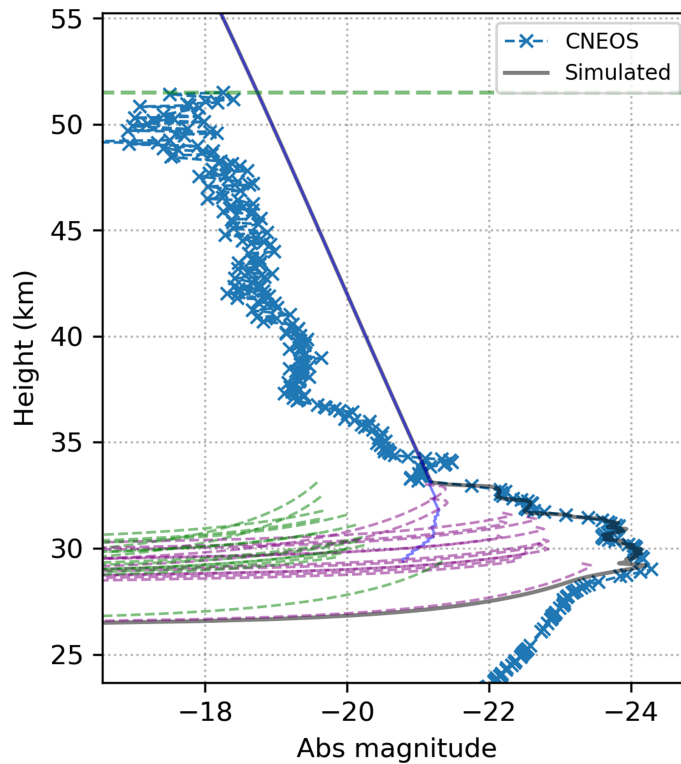
**Figure 5.** Cardinal output for station I39PW. The panels provide an analysis of the signal’s characteristics over time. The vertical dashed lines (red, green, and blue) represent theoretical or predicted arrival windows based on different atmospheric propagation waveguides. Panels from top to bottom represent timeseries (the bandpass-filtered—0.05–3 Hz—waveform, showing a high-amplitude arrival between 4000 and 5000 s); back azimuth deviation (the consistency of the signal’s arrival direction; the focused cluster indicates a coherent point source); trace velocity; and semblance (a correlation metric where higher values—darker regions—identify the arrival of a coherent, nonrandom signal).



**Figure 6.** Vertical component of the seismic signal recorded at MTSU station (AU network). The trace is bandpass filtered between 5 and 15 Hz. The red dashed line indicates the theoretical shock wave arrival time predicted by infraGA ray-tracing simulations. The reference time (0 s) corresponds to 11:22 UTC, the estimated peak brightness time.

The vertical component of the seismic record, bandpass filtered between 5 and 15 Hz, reveals a feature consistent with the predicted acoustic arrival (Figure 6). The timing agreement between the infraGA-predicted arrival and the observed

seismic feature provides independent support for the CNEOS-reported source altitude and confirms that the  $\sim 7$ –8 kt airburst at 29 km produced a detectable air-to-ground coupled signal at 260 km range.



**Figure 7.** Modeled light curve of the Queensland superbolide. The CNEOS-observed absolute magnitude profile (blue crosses) is compared with the simulated composite light curve (gray solid line). Dashed curves show the contributions of individual fragments and debris clouds. The diagonal blue line indicates the prefragmentation single-body trajectory. The horizontal dashed green line marks the altitude of the light-curve start.

## 4. Entry and Energy Deposition Modeling

### 4.1. Light-curve Modeling

To further constrain the fragmentation sequence, we modeled the CNEOS light curve using the J. Borovička et al. (2013) semiempirical fragmentation model as implemented by D. Vida et al. (2023a). The deceleration was not modeled as the initial part of the trajectory before the fireball saturated the sensors did not show any deceleration, and the single observed terminal point did not provide sufficient constraint on the dynamics. Because the ground-based optical record is limited to altitudes above the saturation threshold, the primary trajectory, energy deposition, and fragmentation constraints for this event are derived from USG space-based sensor data and infrasound observations. The model reproduces the observed brightness profile as a function of altitude, capturing the progressive brightening from  $\sim 50$  km through the main flare at  $\sim 29$  km (Figure 7). The initial part of the light curve has not been matched by the ablation model, a common occurrence with bright events due to suspected preheating of the body (P. Spurný et al. 2020; A. Egal et al. 2025). A total preatmospheric mass of 150 t was recovered from the modeling, translating to a diameter of  $\sim 4.6$  m for an assumed bulk density of  $3000 \text{ kg m}^{-3}$ , or  $\sim 4.3$  m for  $3500 \text{ kg m}^{-3}$  (G. S. J. Consolmagno & D. T. Britt 1998). This model-dependent size range is compatible with a few-meter stony impactor; the observed deep penetration is instead constrained by the low terminal disruption altitude and modeled fragmentation sequence. Individual fragment and debris cloud contributions (dashed curves) illustrate how successive breakup episodes combine to produce the composite light curve, showing that the total brightness was dominated by light

produced by released gram-sized grains. The fireball experienced a gradual loss of about 70% of its mass into fragments between the heights of 33–29.5 km, followed by a catastrophic loss of the remaining mass in a single fragmentation around 29.4 km. As the deceleration could not be accurately modeled, the dynamic pressure at fragmentation ( $P_{\text{dyn}} = \rho_{\text{atm}} v^2$ ) is dependent on the model velocity. The model indicates that the main fragmentations at 33 km began at pressures of around 10 MPa, while the catastrophic fragmentation occurred at a pressure of  $\sim 15$  MPa. These pressures are indicative of a strong rocky composition, and the high pressures were reached due to the high entry velocity of almost  $30 \text{ km s}^{-1}$ , compared to usually slower entries at below  $20 \text{ km s}^{-1}$  for most other meteorite-dropping fireballs. This late terminal fragmentation at high dynamic pressures and the catastrophic break up with concentrated energy deposition deep in the atmosphere qualifies this object as a member of the recently recognized more dangerous impactor class, together with Novo Mesto and 2023 CX1 (D. Vida et al. 2023b; A. Egal et al. 2025). The modeled light curve dropped off sharply following catastrophic fragmentation due to the cessation of direct ablation-related light production. However, the CNEOS light curve integrates all visible light produced by the fireball, including the extremely bright persistent train, which dominates the total light after the terminal fragmentation (as visible in Figure 3(d)). This chemistry-driven process is not captured by the model and is thus ignored (D. Vida et al. 2021b).

### 4.2. Fragment–Cloud Model (FCM) Simulations

To constrain the preatmospheric properties of the impactor and reproduce the observed energy deposition profile, we applied the Fragment–Cloud Model (FCM; L. F. Wheeler



et al. 2017), a semianalytical approach that models asteroid entry, fragmentation, and ablation by treating the breakup as a combination of discrete fragments and expanding debris clouds. The FCM captures progressive, strength-controlled fragmentation through user-defined structural groups, each characterized by a mass fraction, strength, number of discrete pieces, and a cloud mass fraction that governs the proportion of mass shed into the debris cloud upon breakup.

Simulations were initialized using the USG-reported entry parameters ( $v = 27.9 \text{ km s}^{-1}$ , entry angle =  $39.36^\circ$ ; Section 2) and a bulk density of  $2875 \text{ kg m}^{-3}$ , with an exponential atmospheric model. The meteoroid was modeled with four structural groups spanning a range of fragment strengths from  $\sim 15$  to  $\sim 45 \text{ MPa}$ . We explored initial radii from 1.3 m (diameter 2.6 m) to 2.0 m (diameter 4.0 m) across multiple trials, iteratively adjusting the structural group parameters to match the normalized energy deposition curve derived from the USG light curve.

The FCM simulations successfully reproduced the principal flare features observed in the USG energy deposition profile, including the altitude and relative magnitude of the main fragmentation episodes. However, the model does not capture the postdisruption dust cloud observed in satellite imagery, as the FCM does not simulate the late-stage thermodynamic evolution of disrupted material at the terminal altitude. We note that the FCM solution is not unique: the large number of adjustable parameters (structural group strengths, mass fractions, cloud mass fractions, and dispersion coefficients) permits a range of configurations that produce comparable fits to the observed energy deposition curve. With this caveat, the best-fit solution yielded a preatmospheric diameter of approximately 2.6 m, with additional trials exploring diameters up to 4 m also producing reasonable fits. The larger FCM trial diameters (3.6–4.0 m) are consistent with the  $\sim 3.7 \text{ m}$  estimate derived from the USG total impact energy, while the best-fit 2.6 m solution may reflect the simplified treatment of ablation and the parameterization of fragment cloud evolution in the FCM. Therefore, these estimates indicate that the preatmospheric size is best regarded as meter-scale, approximately 3–4 m, with the spread reflecting differences among radiometric, semiempirical fragmentation, and FCM assumptions rather than a unique size solution.

#### 4.3. Hydrocode Modeling

Three-dimensional hydrocode modeling of superbolides is challenging, especially when aimed at determining effects at significant distance from the epicenter of the burst. For the 2023 May 20 event, the altitude of maximum energy deposition was  $\sim 29 \text{ km}$  and the nearest seismic station was  $\sim 260 \text{ km}$  downrange from the main burst. The minimum dimension of the computational domain along the track is therefore about 300 km, but a full-physics simulation would require that the  $\sim 2 \text{ m}$  diameter asteroid be resolved as it traverses the atmosphere and breaks up. Current computing capabilities cannot resolve the effects of such a small object over a 3D domain that is 4 or 5 orders of magnitude larger in every dimension, but fortunately this is not necessary. This enormous difference in scale does make simulations difficult even when using methods that ignore the details of the entry physics and directly insert a distributed source function.

Our approach is based on methods developed for understanding the impacts of Comet Shoemaker-Levy 9 (SL9) on

Jupiter in 1994, summarized by D. A. Crawford et al. (1995). That simulation pushed the limits of high-performance computing at the time, even though the ratio of the fragment size (assumed to be 1–3 km) was only about 3 orders of magnitude smaller than the 3D computational domain. To deal with the enormous scale difference, the simulation was run in two phases. The entry, deformation, and breakup of the fragments were modeled as a 2D axisymmetric problem in a stratified atmosphere with a stretched scale to account for the oblique entry angle. These 2D results were rotated and mapped onto the 3D mesh at much lower resolution, to model the penetration and ejection of the ballistic plume.

The SL9 simulations were run prior to the impact event itself, in an attempt to test predictions to guide the observational campaign and as a means of validation (M. B. Boslough et al. 1994). This method was simplified for modeling airbursts in Earth’s atmosphere using semianalytical models to generate energy deposition functions that could be directly inserted into a 3D mesh to model the Tunguska event (M. B. E. Boslough & D. A. Crawford 1997) and into a 2D mesh to model bolides smaller than 1 m in diameter (M. B. E. Boslough & G. R. Gladstone 1997). In both cases, these simulations suggested that even bolides of the scale of the 2023 May 20 event can generate some of the phenomena that were observed for the SL9 impacts, including ballistic plumes.

Another method of energy insertion was used to model the Chelyabinsk event, made possible by the large quantity of observational data. This enabled modelers to use the light curve as a proxy for energy deposition as a function of time and position along the path, which could be inserted into the 3D mesh over an extremely large computational domain to initialize a 3D simulation. This yielded phenomena in reasonable resemblance to the observed debris cloud, including the bifurcation into contrarotating vortices (D. A. Kring & M. Boslough 2014). Because the USG light curve is also known for the 2023 May 20 event, we have used the same means of energy insertion that was used for Chelyabinsk.

### 5. Postdisruption Mass Fate

Following the catastrophic disruption of the Queensland superbolide at  $\sim 29 \text{ km}$  altitude, the impactor mass was partitioned among three fates: fine-grained particulate material suspended as a high-altitude dust cloud, potential macroscopic fragments entering ballistic dark flight, and ablated vapor. This section presents observations and modeling that constrain the first two of these pathways.

#### 5.1. Dust Cloud Infrared Observations

##### 5.1.1. Detection

After a multiton asteroid explodes in Earth’s atmosphere, the material left behind comes in two forms: possible meteorites that fall to the ground within minutes of the event and a dust cloud that persists in the atmosphere. After the dust cloud cools rapidly in the seconds following its release, it can be observed optically for minutes to days, until it is advected by the winds, settles gravitationally, or is lost against the background (J. Borovička et al. 2020). If the cloud is sunlit, it is visible from visible to infrared wavelengths (A. R. Klekociuk et al. 2005). When the event occurs at night, as with the 2023 Queensland superbolide, the cloud can be

detected when it masks background thermal radiation at long-wave infrared wavelengths.

We identified the dust cloud from the Queensland superbolide in thermal infrared images taken by the Japanese Himawari-9 weather satellite in geostationary orbit (Appendix C). The Advanced Himawari Imager (AHI) captures 16 bands from visible to thermal infrared of the full visible Earth disk once every 10 minutes. At infrared wavelengths, the AHI provides  $2 \text{ km pixel}^{-1}$  ground resolution at nadir.

The cloud is visible from the first scan after the bolide ( $\sim 5$  minutes postevent) in bands 11–16 ( $8.6\text{--}13.3 \mu\text{m}$ ), and persists for over 1 hr in certain bands, notably band 13, centered on  $10.4 \mu\text{m}$ . To isolate and measure the cloud’s signature, we modeled the cooling rate of the ground’s natural thermal radiation linearly, enabling measurement of the temperature anomaly caused by the cloud as an absorption spectrum.

### 5.1.2. Cloud Position and Motion

Using reprojection and parallax correction methods described in Appendix C, and accounting for a  $\sim 1.8 \text{ km}$  displacement of the cloud due to winds (assuming an average  $6 \text{ m s}^{-1}$  from the east–southeast), we estimate the cloud originated at  $-17.830, 141.907$ . This position is approximately  $3 \text{ km}$  north of the extrapolated optical trajectory.

Over the  $\sim 1 \text{ hr}$  following the bolide, the dust cloud drifts in directions ranging from west to northwest ( $270^\circ\text{--}320^\circ$  headings), indicating that the cloud was subjected to winds from azimuths of approximately  $90^\circ\text{--}140^\circ$ . At  $29 \text{ km}$  altitude (location of the airburst), atmospheric models indicate winds from azimuth  $70^\circ\text{--}120^\circ$  at speeds of  $5\text{--}7 \text{ m s}^{-1}$ , so the observed cloud drift extending to northwest bearings is partially at odds with the wind model at  $24\text{--}31 \text{ km}$  altitude. It is possible that some dust was deposited at higher altitudes where the southeast wind component is stronger. It is unlikely that the observations are explained by the cloud losing significant altitude, as the wind was effectively null between  $20$  and  $23 \text{ km}$ , and below  $20 \text{ km}$  the westerly jet stream dominates. The most likely explanation is that the reanalysis wind models are not perfectly accurate for this altitude range and region. Despite the slight directional inconsistency, the speed of the cloud is consistent with the  $5\text{--}7 \text{ m s}^{-1}$  model wind speed.

### 5.1.3. Dust Mass Estimate

At the first appearance of the cloud ( $\sim 2023\text{-}05\text{-}20\text{T}11:27:00$ ), in the  $10.4 \mu\text{m}$  band, we measure a total dust mass of  $10.9\text{--}32.8$  metric tons. This range is driven entirely by the assumed mass absorption coefficients for meteoritic dust ( $100\text{--}300 \text{ cm}^2 \text{ g}^{-1}$ ). Laboratory mid-infrared measurements of chondritic powders show that mass absorption coefficients near the  $10 \mu\text{m}$  silicate feature depend on both composition and grain-size distribution, with grain size exerting a strong control on the total opacity (G. A. Batalla-Falcon et al. 2025). Because the particle-size distribution of the Queensland dust cloud is not independently constrained, the retrieved mass should be interpreted as conditional on the assumed absorption coefficient range.

For a bolide that underwent catastrophic disruption at  $29 \text{ km}$  altitude, it is reasonable to assume that most of the impactor mass would have been deposited in the dust cloud. The

measured dust mass corresponds to  $14\%\text{--}43\%$  of the preatmospheric asteroid mass of  $\sim 76$  metric tons implied by the USG total impact energy at  $27.9 \text{ km s}^{-1}$  entry velocity. This is a physically reasonable fraction, indicating that our method and assumptions for processing the dust cloud infrared signature are likely sound.

### 5.2. Dark Flight Modeling

Following catastrophic disruption, any surviving macroscopic fragments would decelerate rapidly and enter a ballistic dark flight phase governed by gravity and atmospheric drag. To evaluate the potential meteorite fall zone, we modeled atmospheric conditions with the Weather Research and Forecasting (WRF) tool (W. C. Skamarock et al. 2019) using global snapshot data from the National Centers for Environmental Prediction (NCEP 2000). We then performed dark flight simulations using the trajectory parameters from the optical reference solution (Section 2) as the initial state vector, using the propagation code of M. C. Towner et al. (2022).

Fragment masses were sampled across a range spanning gram-scale to kilogram-scale. The fireball direction being almost directly contrary to the subtropical jet stream (max  $30 \text{ m s}^{-1}$  at  $8\text{--}12 \text{ km}$  altitude, the dominant wind in the column), any putative surviving meteorites would have made a U-turn compared to their bright flight direction. This means that gram-sized material from the main fragmentation point would have been blown back uprange by  $\sim 7 \text{ km}$ . The resulting fall zone is a  $\sim 20 \text{ km}$  long elongated strip oriented approximately along the trajectory azimuth ( $\sim 101^\circ$ ). This fall-zone estimate should be interpreted as a search-guidance calculation rather than a unique meteorite-survival solution. Fragment masses were prescribed rather than inferred from the observed fragmentation sequence, and the saturated lower-atmosphere optical record prevents an independent constraint on terminal velocity or fragment production. Methods that explicitly include fragmentation and variable fragment properties (e.g., J. Moilanen et al. 2021) could further refine the strewn field, but such modeling is not warranted by the available observations. The predicted strip is therefore conditioned on the assumed terminal masses, release altitude, drag behavior, and wind field (H. Devillepoix & M. Cupák 2026).

Australian weather radars have successfully been able to observe meteoritic debris on at least one occasion (H. Devillepoix et al. 2022; S. Anderson et al. 2023), at relatively close range ( $\sim 90 \text{ km}$ ). For this event, unfortunately, no such radar was closer than  $300 \text{ km}$  from the event. We nevertheless examined Level 1 radar data from the Bureau of Meteorology stations at Mornington Island, Greenvale, and Mount Isa (J. Soderholm et al. 2019) for potential returns. No radar return was registered within  $40 \text{ km}$  of the main fragmentation event.

### 5.3. Meteorite Search and Recovery Attempt

A four-person team (S.A., K.R.B., H.B., and H.A.T.) was dispatched to search for meteorite fragments within the bounds of the fall site near Blackbull (Figure 4) for 7 days between the 19th and the 26th of June 2023, taking one day to rest midweek due to high temperatures at the fall site. The vast majority of the searching area was covered with  $20 \text{ cm-}$  to  $100 \text{ cm-}$  tall grass that obscured most of the ground from eye level (Figure C3, Appendix C). The density of trees in the area,

along with obscuration of the ground by grasses and other vegetation prevented the team from driving more than a few meters off the dirt roads that crossed through the fall site. This limited walking searches to less than 50 m from the dirt road for safety, in the event of an emergency medical evacuation. Although some cleared areas were searched more easily, no meteorites were recovered from the fall site. Four, millimeter-sized, black fragments were collected as a contingency, but these were proven to be charcoal by further analysis via scanning electron microscopy (SEM). The nonrecovery is consistent with the expectation that high-altitude catastrophic disruptions rarely produce recoverable meteorites (H. A. R. Devillepoix et al. 2019), particularly when the predicted fragments are small and the search terrain is heavily vegetated and remote.

## 6. Discussion

### 6.1. Comparative Context

The Queensland superbolide, at  $\sim 7\text{--}8$  kt TNT equivalent, ranks among the 20 most energetic events in the USG sensor record since 1988 and is the most energetic event recorded over Australia. For comparative context, it is nearly 2 orders of magnitude less energetic than the 2013 Chelyabinsk airburst ( $\sim 440$  kt; P. G. Brown et al. 2013; O. P. Popova et al. 2013). As with many well-documented bolide events (e.g., Chelyabinsk (P. G. Brown et al. 2013), Bering Sea (S. Arrowsmith et al. 2021), Indonesia (E. A. Silber et al. 2011), and Tajikistan (E. A. Silber 2024b)), the Queensland superbolide underwent catastrophic fragmentation during atmospheric passage, producing a dominant airburst and associated shock wave.

Few events in this energy range have been simultaneously characterized by USG space-based optical sensors, a global infrasound network extending to 8000 km, seismic detection, geostationary satellite thermal infrared imagery, modeling, and a dedicated meteorite search effort. This multimodal dataset makes the Queensland superbolide a valuable calibration event for testing observational methods and theoretical models across a wide range of modalities.

A useful comparison can also be made with several well-documented meteorite-producing airbursts involving meter-scale asteroids. One of the most notable cases is asteroid 2008 TC<sub>3</sub>, a  $\sim 4$  m object that was discovered prior to impact and produced the Almahata Sitta meteorite fall in Sudan (P. Jenniskens et al. 2009; P. Jenniskens et al. 2022). Although the preatmospheric size of 2008 TC<sub>3</sub> is comparable to the estimated  $\sim 3\text{--}4$  m diameter of the Queensland impactor, the total impact energy was substantially lower (on the order of  $\sim 1$  kt), and the atmospheric disruption occurred through progressive fragmentation rather than a single catastrophic airburst. This fragmentation behavior allowed numerous macroscopic fragments to survive atmospheric passage and reach the ground.

Similarly, the small asteroid 2018 LA, which produced the Motopi Pan meteorite fall in Botswana, had an estimated diameter of approximately 2–3 m and generated a multikiloton airburst followed by meteorite recovery (P. Jenniskens et al. 2021). These cases demonstrate that objects in the meter-size regime can produce recoverable meteorites when fragmentation occurs in a sufficiently gradual manner or at lower dynamic pressures. In contrast, the Queensland superbolide appears to have undergone catastrophic disruption near  $\sim 29$  km altitude, producing a dominant airburst and extensive

dust generation. Such high-altitude catastrophic fragmentation significantly reduces the probability that macroscopic fragments survive to the ground. At the same time, the absence of recovered meteorites may also reflect the challenging search environment, including rugged terrain, dense vegetation, and limited accessibility within the predicted strewn field, all of which likely reduced the probability of successful recovery.

Recent observations of the predicted impactor 2023 CX1 provide another instructive comparison. That object, significantly smaller ( $\sim 0.7$  m diameter), nevertheless underwent catastrophic fragmentation during atmospheric entry, producing a spherical shock wave and demonstrating that even small asteroids can experience explosive disruption depending on their internal structure and entry conditions (A. Egal et al. 2025). These examples illustrate the wide range of fragmentation behaviors exhibited by meter-scale asteroids and highlight the importance of detailed observational constraints for understanding how meteoroid structure and entry dynamics control energy deposition and meteorite survival.

The Queensland superbolide is notable for the low altitude of its principal fragmentation and terminal disruption. The dominant energy-deposition episode occurred near 29 km altitude, after the object had penetrated into a comparatively dense atmosphere for a meter-scale impactor entering at  $27.9\text{ km s}^{-1}$ . This behavior suggests that the body retained substantial structural coherence through much of its atmospheric flight before undergoing catastrophic breakup over a restricted altitude interval.

The low disruption altitude does not uniquely determine intrinsic material strength, because fragmentation depends on entry speed, entry angle, shape, ablation history, internal flaws, macroporosity, rotation state, and the distribution of preexisting fractures. However, the observed late disruption is consistent with relatively high effective structural integrity compared with weak, highly fractured, or highly porous bodies that fragment progressively at higher altitudes. The semiempirical light-curve model gives dynamic pressures of order 10–15 MPa for the major fragmentation and terminal breakup, but because the deceleration history is not directly constrained by the saturated ground-based optical records, these values should be interpreted as model-dependent estimates rather than direct measurements of material strength.

Relative to meteorite-producing meter-scale events such as 2008 TC<sub>3</sub> and 2018 LA (P. Jenniskens et al. 2009; P. Jenniskens et al. 2021), where progressive fragmentation allowed macroscopic material to survive to the ground, the Queensland object appears to have transported a large fraction of its kinetic energy to lower altitude before catastrophic disruption, producing an extensive fine-grained dust cloud and no confirmed meteorite recovery. This behavior more closely resembles deep-penetrating meter-scale impactors such as Novo Mesto and 2023 CX1 (D. Vida et al. 2023b; A. Egal et al. 2025). From a planetary defense perspective, the event reinforces that surface effects depend not only on total impact energy, but also on the altitude and spatial concentration of energy deposition.

An estimate of mean recurrence interval for an event of this size or greater is about 1.5 yr, based on Figure 2 of M. Boslough et al. (2015) which consolidates observed bolides, infrasound events, and lunar impacts (also see E. A. Silber et al. 2018). There is significant aleatory uncertainty due to the small number of observations and epistemic uncertainty due to assumptions about



coupling and luminous efficiency, so our estimate ranges from 0.5 to 2.5 yr. This stochastic assumption also neglects the possibility of bolide swarms, such as the hypothetical Taurid resonant swarm, which crosses Earth at each node once every 61 yr, with the next crossings being in 2032 and 2036 (M. Boslough et al. 2026). The estimated  $\sim 3\text{--}4\text{ m}$  diameter of the Queensland impactor therefore places it within the population of relatively common meter-class near-Earth objects that collide with Earth on timescales of years (M. Boslough et al. 2015; A. W. Harris & P. W. Chodas 2021).

### 6.2. Integrated Constraints and Energy Cross-validation

Multiple independent observational modalities yield convergent constraints on the source altitude and total energy of the Queensland superbolide.

To make the parameter estimates used throughout this study easier to compare, Table 3 summarizes the principal trajectory, energy, mass, size, and fragmentation constraints. We adopt the CNEOS radiometric energy and velocity as the reference values for the event-scale mass and diameter estimates. Model-specific values from the semiempirical light-curve model and FCM are retained because they address different aspects of the entry physics and rely on different internal assumptions. These values should therefore be interpreted as sensitivity tests and physically plausible model realizations, rather than as competing preferred solutions.

The altitude of peak energy deposition is consistently constrained at  $\sim 29\text{--}30\text{ km}$ . The USG brightness profile peaks at 29.0 km. The infrasound source altitude analysis, based on travel-time residual minimization at the closest IMS stations (up to 5000 km), converges on  $30 \pm 5\text{ km}$ . The dust cloud originates at an altitude consistent with the airburst location. The seismic ray-tracing for the MTSU detection assumes a 30 km source height and yields a predicted arrival consistent with the observed signal. This convergence across optical, infrasonic, seismic, and satellite-based constraints strongly supports a dominant energy deposition event at approximately 29 km altitude.

The largest sensitivity in the mass and diameter estimates arises from the adopted total energy, rather than from the assumed bulk density. For fixed entry speed, preatmospheric mass scales linearly with energy, ( $m = 2E/v^2$ ). Thus, adopting the infrasound-based energy estimates of  $\sim 8.5\text{--}9.7\text{ kt}$  instead of the CNEOS radiometric energy of  $\sim 7.1\text{ kt}$  would increase the inferred mass by the same factor of  $\sim 1.2\text{--}1.4$ . The corresponding spherical-equivalent diameter is  $D = (6m/\pi\rho)^{1/3}$ , where  $D$  is diameter and  $\rho$  is bulk density. Therefore,  $D \propto E^{1/3} \rho^{-1/3} v^{-2/3}$ . Diameter is therefore much less sensitive than mass to the adopted energy or density. A change in bulk density from 3000 to 3500  $\text{kg m}^{-3}$  changes the inferred diameter by only  $\sim 5\%$ , while the revised infrasound energy range would increase the inferred diameter by  $\sim 6\%\text{--}11\%$  relative to the CNEOS-based estimate. Even a factor-of-1.5 increase in adopted energy would increase diameter by only  $\sim 15\%$ . The surviving meteorite mass is more uncertain because the dark flight calculation uses assumed terminal masses rather than solving for the terminal mass distribution. Consequently, the predicted fall zone and survival estimates should be interpreted as scenario-based constraints that depend on fragment mass, shape, drag coefficient, release altitude, and the wind field.

The CNEOS optical energy of  $\sim 7.1\text{ kt}$  is adopted here as the preferred absolute energy estimate because it is derived from direct radiometric observations of the fireball. The infrasound observations independently confirm that the Queensland superbolide was a multikiloton event, but the absolute energy inferred from dominant period depends on the empirical calibration used. The recent bolide-calibrated averaged-period-yield relations of E. A. Silber et al. (2025) and N. Gi & P. Brown (2017) lead to closely consistent estimates of  $\sim 9.7\text{ kt}$  and  $\sim 9\text{ kt}$ , respectively. The altitude-partitioned E. A. Silber et al. (2025) relation for sources below 30 km gives an estimate of  $\sim 8.5\text{ kt}$ , which is relevant here because the main energy deposition occurred at  $\sim 29\text{ km}$  altitude, where the higher ambient density promotes stronger acoustic coupling than for higher-altitude airbursts.

The higher period-based estimates are physically plausible for this event. First, the bolide entered on a relatively steep trajectory, with an entry angle of  $39.36^\circ$  from the local horizontal. Compared with shallow entries, this geometry concentrates the energy deposition into a narrower horizontal footprint and a more vertically localized atmospheric column, increasing the likelihood that the resulting acoustic field behaves more like a concentrated airburst than an extended, weakly coupled line source (A. Egal et al. 2025; E. A. Silber 2025; E. A. Silber et al. 2025). Second, the USG light curve shows multiple fragmentation episodes prior to the dominant flare, followed by catastrophic disruption near 29 km altitude. Empirical period-yield estimates for individual bolides can vary substantially with calibration, source geometry, fragmentation behavior, propagation path, and period-picking convention (e.g., T. A. Ens et al. 2012; E. A. Silber et al. 2025). Here, the altitude-partitioned E. A. Silber et al. (2025) estimate of  $\sim 8.5\text{ kt}$  is within  $\sim 20\%$  of the CNEOS radiometric energy, while the global averaged-period estimate of  $\sim 9.7\text{ kt}$  remains within expected empirical scatter. We therefore retain the CNEOS radiometric value as the preferred absolute energy estimate. We note that the CNEOS energy of  $\sim 7.1\text{ kt}$  and the  $\sim 9\text{--}10\text{ kt}$  values inferred from the most applicable infrasound period-yield relations are best viewed as complementary constraints on a deeply penetrating, fragmenting multikiloton airburst. The strongest cross-modal agreement is in the source altitude: the CNEOS peak brightness altitude of 29 km, the infrasound-derived source altitude of  $30 \pm 5\text{ km}$ , the dust cloud origin, and the seismic ray-tracing result all point to dominant energy deposition near 29–30 km altitude.

### 6.3. Infrasound Propagation and Seismic Detection

The Queensland superbolide was detected at six IMS infrasound stations at distances between 831 and 8029 km, yet no detections were recorded at western stations beyond the closest (I07AU at 831 km), despite several being within comparable range. As shown by the propagation modeling, this asymmetry is explained by the prevailing stratospheric wind structure: during May in the Southern Hemisphere, the stratospheric polar vortex drives strong westerly zonal winds at altitudes of 30–60 km, creating a favorable waveguide for eastward propagation and inhibiting westward transmission. The weak, low-celerity signal at I07AU ( $0.253\text{ km s}^{-1}$ ) is consistent with this interpretation. This observation illustrates that IMS infrasound detection capability is strongly modulated by seasonal atmospheric dynamics (e.g., A. Le Pichon et al. 2009; C. Pilger et al. 2015; P. Negraru & P. Golden 2017;

**Table 3**  
Summary of Principal Event Parameters, Preferred Values, Assumptions, and Methods

| Parameter                     | Value or Range             | Basis/Role                           | Main Assumption or Sensitivity                                                                                                                                                                  |
|-------------------------------|----------------------------|--------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Event time                    | 2023-05-20<br>11:22:23 UTC | CNEOS reference                      | Peak brightness time                                                                                                                                                                            |
| Peak brightness location      | 17.8°S, 141.9°E            | CNEOS reference                      | Nominal source location                                                                                                                                                                         |
| Entry speed                   | 27.9 km s <sup>-1</sup>    | CNEOS reference                      | Mass scales as $v^{-2}$                                                                                                                                                                         |
| Entry angle (from horizontal) | 39°36                      | CNEOS-derived                        | From velocity components                                                                                                                                                                        |
| Trajectory azimuth            | ~101°                      | CNEOS-derived; optical check         | Ground optical gives ~99°8                                                                                                                                                                      |
| Initial optical height        | ~127 km                    | Ground optical                       | Lower trajectory saturated                                                                                                                                                                      |
| Main airburst altitude        | 29.0 km                    | Preferred altitude                   | CNEOS peak brightness                                                                                                                                                                           |
| Infrasound source altitude    | 30 ± 5 km                  | Independent check                    | Atmosphere/path dependent                                                                                                                                                                       |
| Seismic source altitude       | 30 km assumed              | Consistency check                    | Matches MTSU arrival                                                                                                                                                                            |
| Total impact energy           | ~7.1 kt TNT                | Preferred energy                     | CNEOS radiometric estimate                                                                                                                                                                      |
| Infrasound energy             | ~8.5–9.7 kt TNT            | Independent check                    | Calibration, propagation, and period-picking dependent; if converted using $v = 27.9$ km s <sup>-1</sup> and $\rho = 3000$ –3500 kg m <sup>-3</sup> , implies ~91–104 t and $D \sim 3.7$ –4.1 m |
| Reference mass                | ~76 t                      | Preferred reference mass             | From CNEOS energy and velocity                                                                                                                                                                  |
| Reference diameter            | ~3.5–3.7 m                 | Preferred reference diameter (CNEOS) | $\rho = 3000$ –3500 kg m <sup>-3</sup>                                                                                                                                                          |
| Light-curve model mass        | ~150 t                     | Model-dependent                      | Semiempirical fragmentation model                                                                                                                                                               |
| Light-curve model diameter    | ~4.3–4.6 m                 | Model-dependent                      | $\rho = 3000$ –3500 kg m <sup>-3</sup>                                                                                                                                                          |
| FCM diameter                  | ~2.6–4.0 m                 | Model-dependent                      | Nonunique structural solution                                                                                                                                                                   |
| Major fragmentation interval  | ~33–29.5 km                | Model-supported                      | Progressive mass loss                                                                                                                                                                           |
| Catastrophic disruption       | ~29–29.4 km                | Strongly supported                   | CNEOS + modeling + infrasound                                                                                                                                                                   |
| Dynamic pressure at breakup   | Order 10–15 MPa            | Model-dependent                      | Velocity history not directly constrained                                                                                                                                                       |
| Dust cloud mass               | 10.9–32.8 t                | Independent mass constraint          | Grain size/absorption coefficient                                                                                                                                                               |
| Dust mass fraction            | 14%–43% of 76 t            | Derived                              | 7%–22% if normalized to 150 t                                                                                                                                                                   |
| Dark flight masses            | g–kg trial masses          | Scenario-based                       | Terminal masses assumed                                                                                                                                                                         |
| Fall zone                     | ~20 km elongated strip     | Scenario-based                       | Strongly wind and mass dependent                                                                                                                                                                |
| Meteorite recovery            | None confirmed             | Field result                         | Terrain and survivability limited                                                                                                                                                               |

C. Pilger et al. 2022), and that bolide energy estimates derived solely from detecting stations may carry a directional bias if nondetecting stations are not accounted for.

The infrasound-derived source altitude of  $30 \pm 5$  km, constrained primarily from stations within 5000 km through travel-time residual analysis, is consistent with the USG-reported peak brightness altitude of 29 km. This agreement demonstrates the robustness of the arrival-time-based source altitude method (E. A. Silber et al. 2011; E. A. Silber 2024b) for well-recorded events and supports its application to bolides lacking independent optical altitude constraints. On the seismic side, only the closest station (MTSU, ~260 km) yielded a detection, consistent with the expected detection threshold for atmospheric events of this energy class. The predicted acoustic arrival time from seismic ray-tracing is consistent with the observed signal, providing an additional independent confirmation of the source location and altitude (e.g., L. T. Scamfer et al. 2026).

#### 6.4. Dust Cloud Detection from Geostationary Orbit

The detection and characterization of the postdisruption dust cloud in thermal infrared imagery from the Himawari-9 geostationary satellite provides an unconventional observational constraint on the fate of disrupted meteoroid material. Following catastrophic fragmentation, a substantial fraction of

the impactor mass is expected to be converted into fine-grained particulate material that remains suspended in the atmosphere for minutes to hours before dispersal by ambient winds and gravitational settling. Such debris clouds have been documented in previous events. Satellite observations of the 2018 December 18 Bering Sea bolide revealed a persistent debris cloud in the upper atmosphere that could be tracked as it was transported by stratospheric winds (J. Borovička et al. 2020). Earlier, A. R. Klekociuk et al. (2005) identified a long-lived stratospheric dust layer produced by meteoroid disintegration using satellite and lidar observations, demonstrating that meteoroid fragmentation can produce fine particulate material persisting in the stratosphere for extended periods.

The Queensland superbolide extends this observational record to nighttime long-wave thermal infrared imaging from a geostationary orbit. Because the event occurred at 21:22 local time, the cloud lacked solar illumination for visible-wavelength satellite detection. Instead, it produced a negative brightness-temperature anomaly by attenuating upwelling thermal emission from the surface and lower atmosphere in the Advanced Himawari Imager bands 11–16 (8.6–13.3  $\mu\text{m}$ ). The anomaly appeared in the first postevent scan, approximately 5 minutes after the bolide, and remained detectable for more than 1 hr in band 13 (10.4  $\mu\text{m}$ ). This geostationary viewing geometry and 10-minute imaging cadence allowed the same radiometric feature to be followed over successive scans,

while the measured absorption signal provided the basis for estimating dust column mass using an assumed meteoritic-dust mass absorption coefficient. Thus, the methodological advance lies in using nighttime geostationary thermal infrared radiance measurements to detect, track, and estimate the mass of a fine-grained bolide dust cloud. To our knowledge, this represents the first detection and mass quantification of a bolide dust cloud using nighttime thermal infrared observations from geostationary orbit, demonstrating that geostationary meteorological satellites can detect bolide debris clouds even in nighttime conditions. The derived dust mass of 10.9–32.8 metric tons corresponds to 14%–43% of the estimated preatmospheric mass, consistent with expectations for catastrophic disruption of meter-scale meteoroids where a substantial fraction of the body is converted into fine particulate material rather than surviving as macroscopic fragments (Z. Ceplecha et al. 1998). While uncertainties remain due to the assumed particle-size distribution and mass absorption coefficients, the estimate provides an independent check on the mass budget of the event. Unlike ground-based observing systems or infrasound networks, geostationary satellite platforms provide continuous regional coverage unaffected by acoustic propagation conditions, and the thermal infrared detection mode demonstrated here offers a new pathway for identifying and quantifying meteoroid debris clouds.

The directional discrepancy between observed cloud motion and the WRF wind model at 24–31 km (Section 5.1.2) illustrates the limitations of reanalysis wind products in the upper stratosphere, a region sparsely sampled by conventional meteorological observations. This finding has implications for dark flight modeling, which depends on the same wind fields to predict meteorite fall zones. In this context, weather radar provides a complementary capability: while geostationary TIR imagery captures the fine-grained dust cloud suspended at burst altitude, weather radar can detect macroscopic meteorite fragments during dark flight at lower altitudes, as demonstrated by the Next Generation Weather Radar (NEXRAD) system in the United States (M. Fries & J. Fries 2010, 2025) and the Woomera radar detection of the 2013 South Australian bolide (H. Devillepoix et al. 2022). These techniques sample different size fractions and altitude regimes of the disrupted meteoroid material.

### 6.5. Meteorite Survival and Recovery Prospects

Despite the significant energy of the Queensland superbolide, the meteorite recovery effort yielded no confirmed extraterrestrial material. The catastrophic fragmentation at 29 km altitude, evidenced by the abrupt termination of the USG brightness profile and the formation of a substantial dust cloud containing 14%–43% of the preatmospheric mass, suggests that the disruption was extensive. Any surviving fragments would be small, heavily ablated, and widely dispersed across a strewn field in remote, densely vegetated terrain. The dark flight simulations predict a strewn field elongated along the  $\sim 101^\circ$  azimuth trajectory, but the combination of high burst altitude, small predicted fragment masses, and challenging ground conditions makes recovery unlikely without substantially greater search resources or fortuitous discovery.

### 6.6. Implications for Planetary Defense

The Queensland superbolide provides a useful case study for evaluating the end-to-end observational response to a small asteroid impact. Events of this kind represent a critical gap in current planetary defense capabilities. At  $\sim 3.7$  m diameter, the impactor was far below the detection threshold of ground-based survey telescopes, which remain largely insensitive to asteroids smaller than  $\sim 10$ – $20$  m prior to impact (e.g., P. G. Brown et al. 2013; A. W. Harris & G. D’Abramo 2015; A. W. Harris & P. W. Chodas 2021). For the foreseeable future, the first indication of an impact by a meter-scale asteroid will almost always be the event itself. While a small number of objects have been detected hours before impact (e.g., 2008 TC3, P. Jenniskens et al. 2009; 2023 CX1, A. Egal et al. 2025), these cases remain exceptionally rare. This makes rapid postimpact characterization essential, both for understanding the immediate hazard and for building the empirical foundation needed to assess the risk posed by larger, as-yet-undetected objects.

The ground-level hazard potential from events in this energy class warrants careful consideration. While the Queensland superbolide deposited most of its  $\sim 7$ – $8$  kt energy at  $\sim 29$  km altitude, the manner in which that energy is released matters. Recent work on the much smaller 2023 CX1 impact (72 cm diameter,  $\sim 650$  kg; A. Egal et al. 2025) and the  $\sim 1$  m sized Novo Mesto event (D. Vida et al. 2023b) demonstrated that concentrated catastrophic fragmentation can produce spherical shock waves that deliver greater overpressures at ground level than progressive fragmentation at the same altitude. The Queensland superbolide also underwent catastrophic disruption, and for larger impactors with similar fragmentation behavior, the consequences at the surface could be significant (e.g., A. Egal et al. 2025). Understanding how energy deposition geometry and fragmentation mode affect ground-level hazard is therefore critical for risk assessment in this energy range (E. A. Silber et al. 2025).

The Queensland event demonstrates that a robust multimodal characterization is achievable within hours to days of an unwarned impact, provided the requisite observational infrastructure is in place. Infrasound monitoring, a cornerstone of the global capability to detect and characterize atmospheric explosions from bolide airbursts (e.g., A. Le Pichon et al. 2002; E. A. Silber et al. 2011; S. Arrowsmith et al. 2021), space debris reentries (e.g., I. Clemente et al. 2025; B. Fernando & C. Charalambous 2026; I. R. Hatty et al. 2026), and other energetic sources (C. Pilger et al. 2021; D. C. Bowman et al. 2025; K. Kim 2025), delivered independent energy and source altitude estimates. The IMS infrasound network, originally designed for nuclear test ban treaty verification (e.g., D. R. Christie & P. Campus 2010; P. Hupe et al. 2022), has proven to be one of the most effective ground-based systems for bolide detection and energy estimation on a global scale (e.g., E. A. Silber et al. 2011; C. Pilger et al. 2015; C. Pilger et al. 2020). Modern analysis frameworks such as the Cardinal software package (M. Ronac Giannone et al. 2025) further enhance the utility of IMS data by enabling automated multifrequency array processing and robust detection across large propagation distances by leveraging array geometry and waveform coherence in low-SNR environments.

The infrasonic methods applied in this study have been validated across a wide range of source energies, from small bolide events (e.g., T. C. Wilson et al. 2025; L. T. Scamfer



et al. 2026) and controlled atmospheric entries such as the OSIRIS-REx Sample Return Capsule reentry (e.g., E. A. Silber et al. 2024; Y. Nishikawa et al. 2026) to the multikiloton Queensland event described here. The directional asymmetry in IMS detections observed here, driven by seasonal stratospheric wind patterns, is a well-characterized feature of infrasound propagation that can be quantified through propagation modeling, allowing directional biases to be identified and accounted for in energy estimation (e.g., C. Pilger et al. 2015).

Geostationary satellite thermal infrared imagery, as demonstrated by the Himawari-9 dust cloud detection, offers a detection mode that is unaffected by atmospheric propagation conditions and provides near-global coverage with high temporal cadence, and its systematic application to bolide events represents an underexploited capability. The integration of infrasound, satellite, seismic, and optical observations, as achieved for the Queensland superbolide, provides the comprehensive, multimodal characterization that planetary defense requires. Each event of this kind contributes to refining the empirical models and observational methods that will be needed to assess and respond to larger future impacts.

## 7. Conclusions

We have presented a comprehensive, multimodal analysis of the 2023 May 20 Queensland superbolide, one of the 20 most energetic events recorded by USG space-based sensors since 1988 and the largest over Australia. A small asteroid of approximately 3.7 m diameter entered the atmosphere at  $27.9 \text{ km s}^{-1}$  on an entry angle of  $39.4^\circ$  from horizontal and underwent catastrophic fragmentation at  $\sim 29$  km altitude, depositing a total energy of  $\sim 7\text{--}8$  kt TNT equivalent. USG optical sensors indicate a total impact energy of  $\sim 7.1$  kt. Using averaged-period and low-altitude bolide calibrations, the infrasound period-based yield estimates of  $\sim 8.5\text{--}9.7$  kt are higher than the radiometric value but remain physically plausible for a steep, deeply penetrating, fragmenting object, where source altitude, entry geometry, fragmentation, and propagation can broaden the dominant acoustic period.

Infrasound signals were detected at six IMS stations at distances up to 8030 km, with a pronounced directional asymmetry driven by prevailing stratospheric wind structure. The infrasound-derived source altitude of  $30 \pm 5$  km is consistent with the USG-reported peak brightness altitude of 29.0 km. Thermal infrared imagery from the Himawari-9 geostationary satellite captured the postdisruption dust cloud within  $\sim 5$  minutes, persisting for over 1 hr, constituting the first nighttime thermal infrared detection and mass quantification of a bolide dust cloud from geostationary orbit. A seismic signal at MTSU ( $\sim 260$  km) and three-dimensional hydrocode simulations provide additional constraints on the airburst dynamics. A seven-day ground search recovered no meteorites, consistent with the catastrophic nature of the disruption.

These results demonstrate that end-to-end multimodal characterization of superbolide events, from preatmospheric orbit to postdisruption dust cloud mass, is achievable with existing observational infrastructure and provide new empirical constraints for atmospheric entry models and planetary defense. With an estimated mean recurrence interval of  $\sim 1.5$  yr (range 0.5–2.5 yr) for events of this energy or greater, opportunities to acquire such comprehensive datasets will arise regularly, and each contributes to refining the observational

and modeling capabilities needed to assess and respond to larger future impacts.

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## Data Availability

The optical astrometric and photometric solutions, together with the associated trajectory and ablation-modeling data products, are archived on Zenodo at DOI: [10.5281/zenodo.20739713](https://doi.org/10.5281/zenodo.20739713). All explanatory supporting material is included in the appendix.

CNEOS database of fireballs detected by US government sensors is available at <https://cneos.jpl.nasa.gov/fireballs/>.

The light curves are available at <https://cneos.jpl.nasa.gov/fireballs/lc/>.

The IMS data are restricted. Access to the IMS network’s data, including raw waveform recordings of the infrasound stations can be granted upon request through the virtual Data Exploitation Center (vDEC) of the IDC at <https://www.ctbto.org/specials/vdec>.

The KUT data are open access through the web application “Kochi University of Technology (KUT) Infrasound Observation Network System” at <https://geosci.mydns.jp/infrasound/graph.php>.

Cardinal, array processing software, is available on GitHub: <https://github.com/sjarrowsmith/cardinal>.

Propagation modeling was performed using InfraGA (<https://github.com/LANL-Seismoacoustics/infraGA>) and NCPAProp (<https://github.com/chetzer-ncpa/ncpapropp-release>).

G2S atmospheric specifications can be obtained freely, using the Python code at <https://github.com/chetzer-ncpa/ncpag2s-clc>.

Information about the high-resolution (HRES) operational atmospheric model analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF), produced by the Integrated Forecast System (IFS), can be found at <https://www.ecmwf.int/en/forecasts/datasets>.

### Conflict of Interest

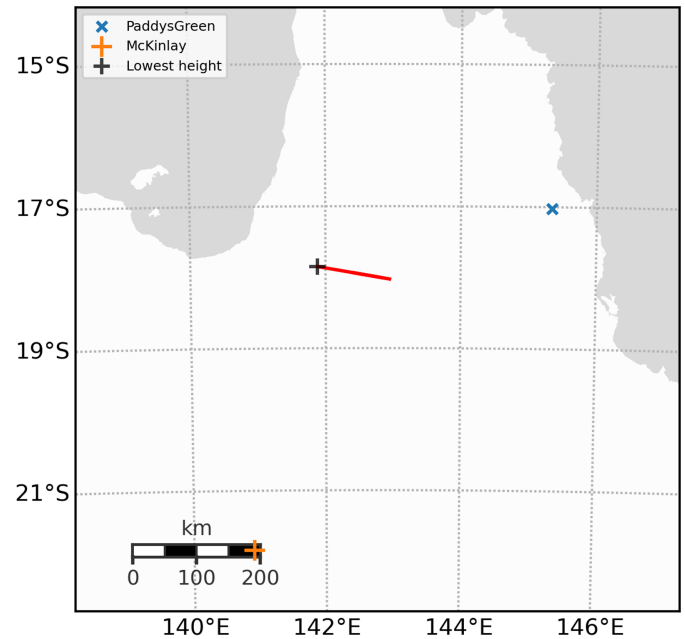
The authors declare no conflict of interest.

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## Appendix A Optical Detection

Table A1 lists the optical station coordinates. Figures A1 and A2 show the map and the trajectory solution, respectively.



**Figure A1.** Contextual map showing the locations of the cameras and the derived trajectory.

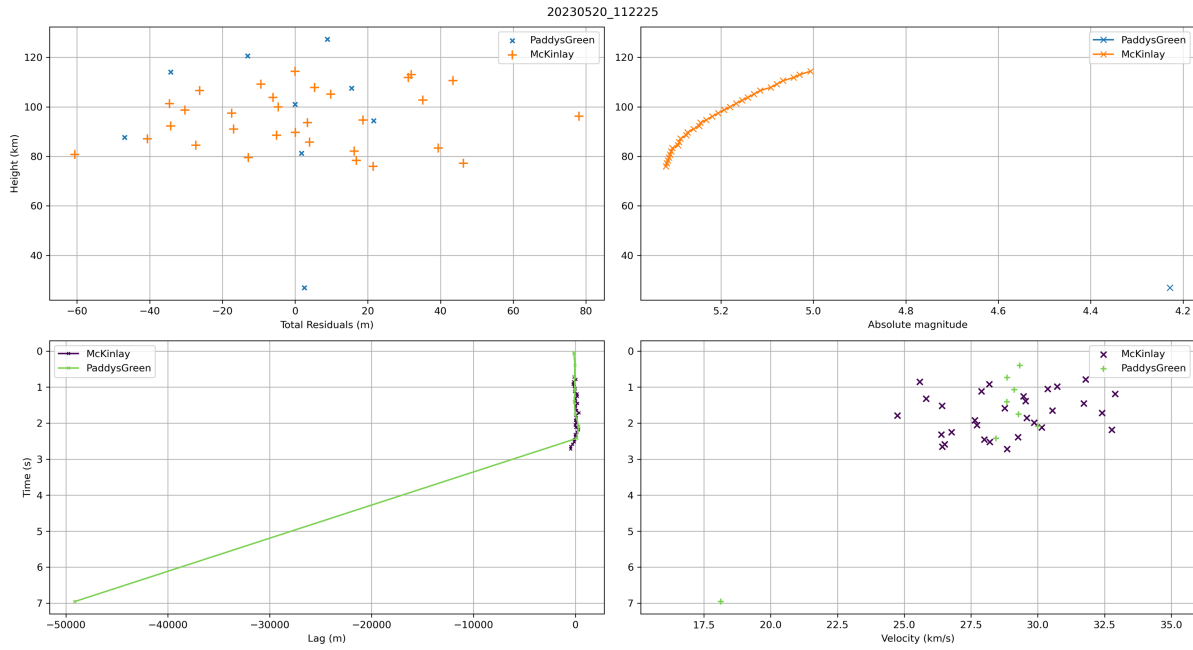


Figure A2. Trajectory solution from optical data.

Table A1

Geographic Coordinates and Elevations of the Optical Stations Used for Trajectory Reconstruction

| Station ID   | Latitude (N) | Longitude (E) | Elevation (m) |
|--------------|--------------|---------------|---------------|
| McKinlay     | −21.834141   | 140.911796    | 269           |
| Paddys Green | −17.019531   | 145.340566    | 536           |

**Note.** McKinlay and Paddys Green were used for astrometric trajectory determination. Normanton was recorded but not used for astrometry, and therefore we do not report its location.

## Appendix B Infrasound and Seismic

### B1. IMS Infrasound Array Processing and Detection Summary

Array processing for IMS infrasound stations was performed using the Cardinal array processing framework (M. Ronac Giannone et al. 2025), which implements multifrequency frequency-wavenumber ( $f$ - $k$ ) beamforming to estimate signal directionality, apparent velocity, and coherence. The data were analyzed using a set of logarithmically spaced frequency bands, with time-window lengths scaled according to the inverse of the band center frequency to ensure stable beamforming across a broad frequency range. Moreover, the software implements a convolutional-Transformer to determine optimal subarray configuration for each frequency band. For each analysis window, Cardinal performs a grid search over horizontal slowness to identify the peak in the  $f$ - $k$  spectrum, from which back azimuth, apparent velocity, and semblance are obtained. Individual detections in time-frequency space are subsequently grouped into coherent solution families using Cardinal’s Aggregator clustering algorithm, allowing stable signal characteristics to be summarized for each station. The list of IMS stations and the

predicted infrasound arrivals are listed in Table B1. The observational results are shown in Table B2.

### B2. InfraGA Ray-tracing Configuration and Arrivals

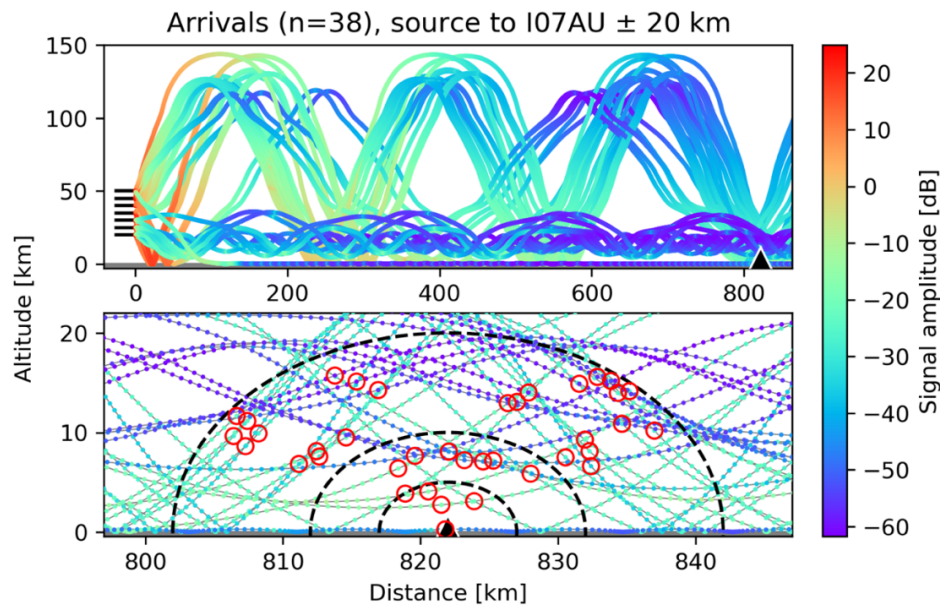
Infrasound propagation modeling was performed using InfraGA in spherical range-dependent mode (P. Blom 2014), with atmospheric specifications from the G2S repository (D. P. Drob et al. 2003; C. H. Hetzer 2024) sampled at every integer latitude–longitude node in a grid encompassing the source and each receiving station. G2S profiles were extracted at a single hour approximately midway between the event origin time (11:22:23 UTC) and the estimated time of arrival at each station, computed assuming a celerity of  $285 \text{ m s}^{-1}$ .

For each of the six detecting IMS stations, ray paths were computed from the source location ( $-17.8^\circ\text{S}$ ,  $141.9^\circ\text{E}$ ) along the great-circle azimuth to the station, for source altitudes of 20, 25, 30, 35, 40, 45, and 50 km. Launch inclinations ranged from  $-89^\circ$  to  $+89^\circ$  in  $5^\circ$  increments. For each ray path, the point of closest approach to the station was computed as the Pythagorean combination of great-circle distance and altitude difference. Rays for which this closest approach fell within 20 km of the station were retained as candidate arrivals. For each arrival, the modeled travel time, amplitude (geometric spreading plus L. C. Sutherland and H. E. Bass 2004 absorption loss at 0.1 Hz), closest-approach distance, maximum ray altitude, and source altitude were recorded. An example of the ray-tracing output and analysis for station I07AU are shown in Figures B1–B3, illustrating the ray paths containing arrivals and the distribution of closest-approach points near the station.

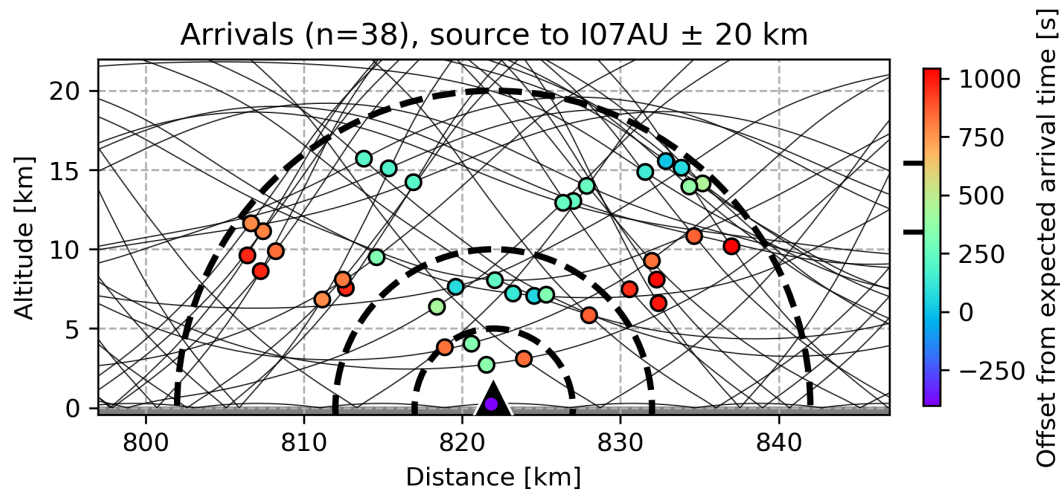
### B3. KUT Regional Infrasound Network

The Kochi University of Technology (KUT) Infrasound Sensor Network is described in Section 3.2.1. In 2023 May, the network comprised 32 single-sensor stations, each





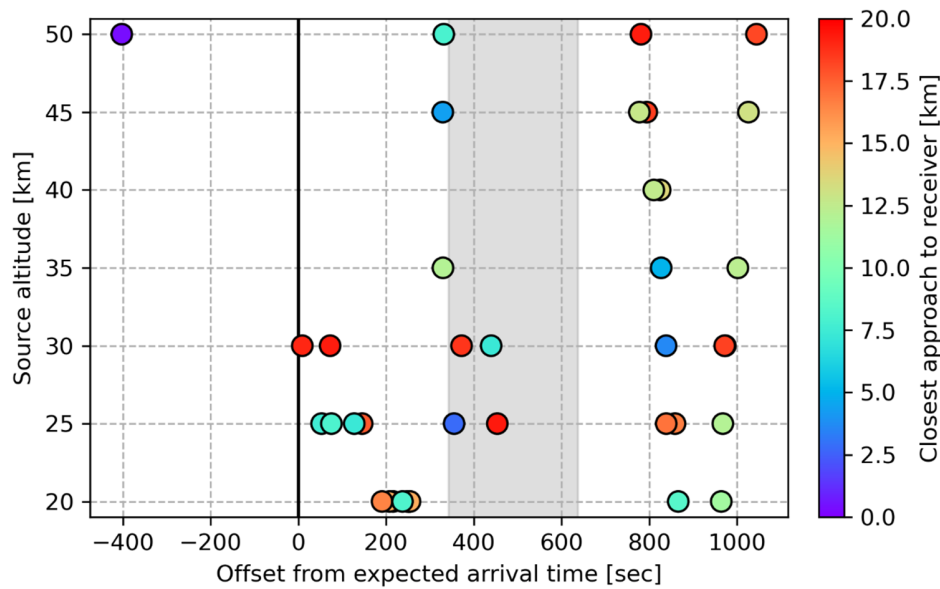
**Figure B1.** Ray paths from the source that come within 20 km of the station, colored by signal amplitude. (Bottom) Close-up of the station vicinity showing the closest-approach point on each ray (red circles), with concentric semicircles at 5, 10, and 20 km radii.



**Figure B2.** Ray paths containing arrivals shown as a function of distance and altitude, with circles marking individual arrivals. Color indicates the arrival time residual relative to the predicted arrival assuming a celerity of  $285 \text{ m s}^{-1}$ . Heavy black ticks on the left side of the colorbar denote the observed signal window

equipped with a SAYA INF01-type comprehensive sensor recording differential pressure infrasound data with membrane-type transducers, along with three-component acceleration, absolute atmospheric pressure, and temperature via

MEMS sensor chips. KUT data are publicly accessible through the Kochi University of Technology Infrasound Observation Network System (<https://geosci.mydns.jp/infrasound/graph.php>).



**Figure B3.** Modeled arrival time residuals (relative to the predicted arrival assuming a celerity of  $285 \text{ m s}^{-1}$ ) as a function of source altitude for station I07AU ( $\sim 831 \text{ km}$ ). The gray band indicates the time window over which the signal was observed. Color indicates the closest-approach distance of each ray to the station.

**Table B1**  
Source-receiver Geometry and Predicted Arrival Times for the Six IMS Stations That Detected the Queensland Superbolide

| Station ID | Distance (km) | Predicted Back Azimuth (deg) | Predicted Stratospheric Arrival (UTC) | Predicted Thermospheric Arrival (UTC) |
|------------|---------------|------------------------------|---------------------------------------|---------------------------------------|
| I07AU      | 831           | 74.7                         | 12:10:59                              | 12:25:21                              |
| I22FR      | 2648          | 276.1                        | 13:57:16                              | 14:43:02                              |
| I05AU      | 2799          | 347                          | 14:06:06                              | 14:54:28                              |
| I39PW      | 2930          | 164.1                        | 14:13:46                              | 15:04:24                              |
| I30JP      | 5907          | 178.1                        | 17:07:52                              | 18:49:56                              |
| I44RU      | 8029          | 195.8                        | 19:11:57                              | 21:30:41                              |

**Note.** Distances and predicted back azimuths were calculated relative to the CNEOS peak brightness location. Predicted stratospheric and thermospheric arrival times were estimated from the CNEOS origin time using representative celerities of  $0.285 \text{ km s}^{-1}$  and  $0.220 \text{ km s}^{-1}$ , respectively, and are used only as reference windows for signal association (E. A. Silber 2024a).

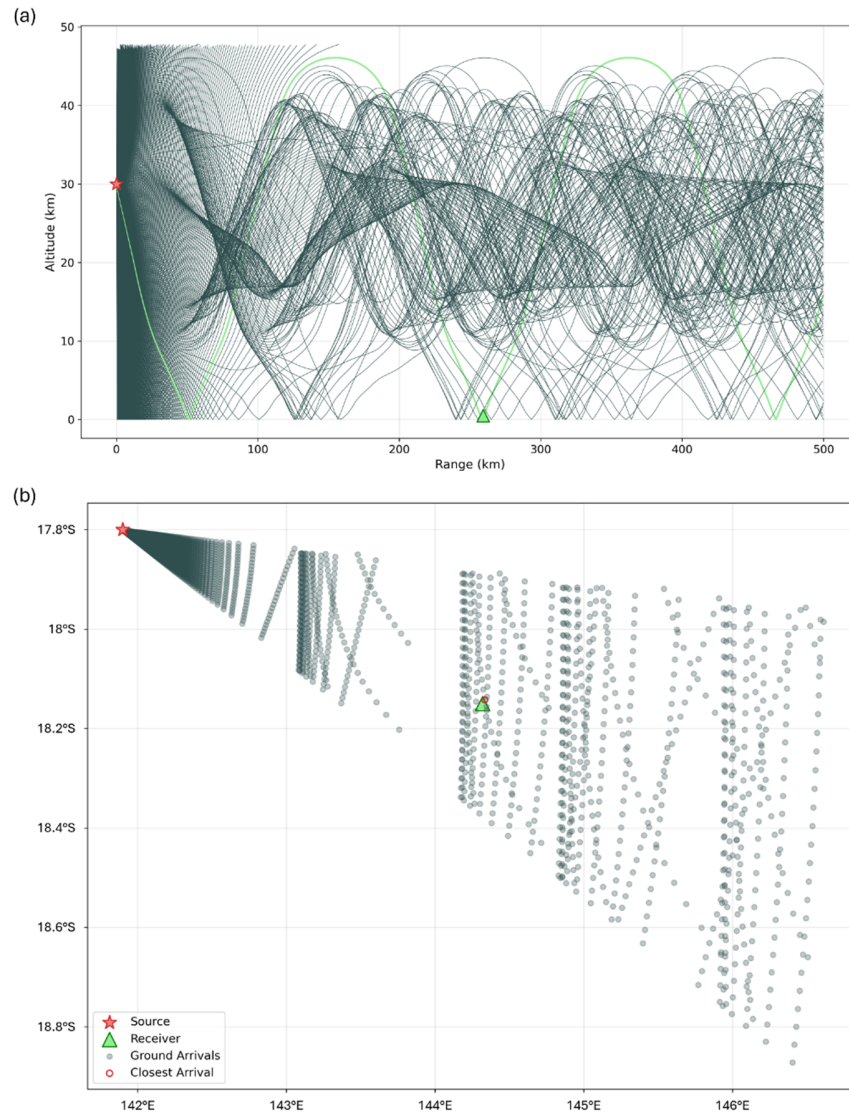
**Table B2**  
Array Processing Results and Infrasound Signal Measurements for the Six IMS Stations That Detected the Queensland Superbolide

| Station ID | Arrival Time (UTC) | Duration (s) | Celerity ( $\text{km s}^{-1}$ ) | Back Azimuth (deg) | Dominant Frequency (Hz) | Filter Frequency Bands (Hz) | Trace Velocity ( $\text{km s}^{-1}$ ) | Period (s) | $\pm$ Period Uncertainty (s) | Amplitude (Pa) |
|------------|--------------------|--------------|---------------------------------|--------------------|-------------------------|-----------------------------|---------------------------------------|------------|------------------------------|----------------|
| I07AU      | 12:17:06           | 203          | 0.253                           | 75.5               | 0.352                   | 0.3–0.6                     | 0.341                                 | 2.62       | 0.01                         | 0.058          |
| I22FR      | 13:34:30           | 3111         | 0.334                           | 274.9              | 0.098                   | 0.05–0.125                  | 0.405                                 | 5.76       | 0.10                         | 0.117          |
| I05AU      | 14:00:48           | 276          | 0.295                           | 348.1              | 0.098                   | 0.09–0.125                  | 0.349                                 | 9.46       | 0.02                         | 0.083          |
| I39PW      | 14:03:21           | 1116         | 0.303                           | 159.1              | 0.117                   | 0.05–3                      | 0.371                                 | 7.96       | 0.39                         | 0.125          |
| I30JP      | 16:59:24           | 1281         | 0.292                           | 182.8              | 0.117                   | 0.05–0.175                  | 0.380                                 | 8.11       | 0.16                         | 0.064          |
| I44RU      | 19:01:51           | 477          | 0.291                           | 192.2              | 0.137                   | 0.1–0.2                     | 0.354                                 | 6.07       | 0.05                         | 0.064          |

**Note.** For each station, the table lists the station code, the signal arrival time, and the observed signal parameters. Back azimuth, apparent velocity, and semblance were computed using frequency-wavenumber ( $f$ - $k$ ) analysis via the Cardinal software package (M. Ronac Giannone et al. 2025). Dominant periods were measured from beamformed waveforms using the zero-crossing method described in Section 3.2.2 in the main text.

#### B4. Seismic Ray Tracing

Seismic network coverage and the MTSU detection are described in the main text. Figure B4 shows the ray-tracing results for the predicted acoustic arrival at MTSU.

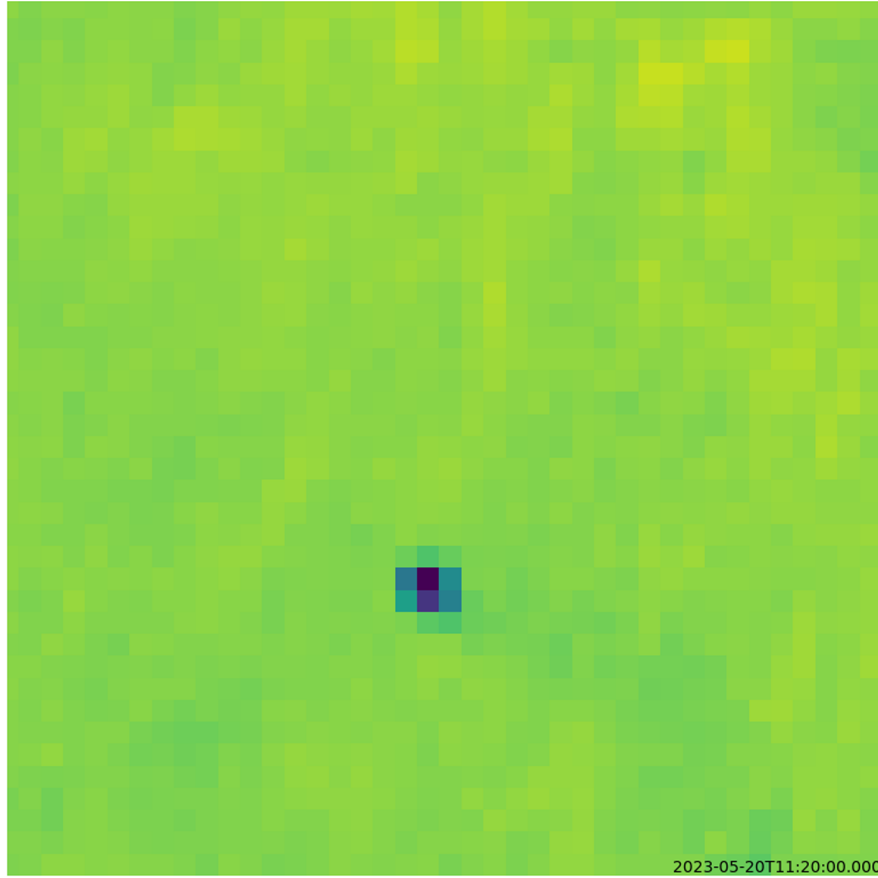


**Figure B4.** Results of infraGA ray-tracing simulations of shock wave propagation, using an atmospheric profile obtained from Era5 reanalysis (H. Hersbach et al. 2020, 2018). The source height of 30 km corresponds to the estimated peak brightness location along the Queensland fireball trajectory (red star). (a) Altitude-range profile of ray propagation over 500 km. Rays were sampled every 0.5 from vertical to horizontal, directed toward the MTSU seismic station (azimuth 98.9). (b) Map view of arrivals reaching the ground, where the green triangle marks the MTSU seismic station and the red circled arrival indicates the closest arrival to the sensor. Rays were sampled every 0.5 from vertical to horizontal, directed toward azimuths between 92° and 104° in steps of 0.5. Panel (b) shows an arrival (red circle) reaching the ground at a location of approximately 1.9 km from the MTSU station (−18.15°S, 144.32°E). The corresponding travel time of this arrival is 893.85 seconds. Based on this prediction, the signal recorded at MTSU was examined for evidence of an arrival at this time. A feature consistent with such an arrival is visible in Figure 6 in the main text.

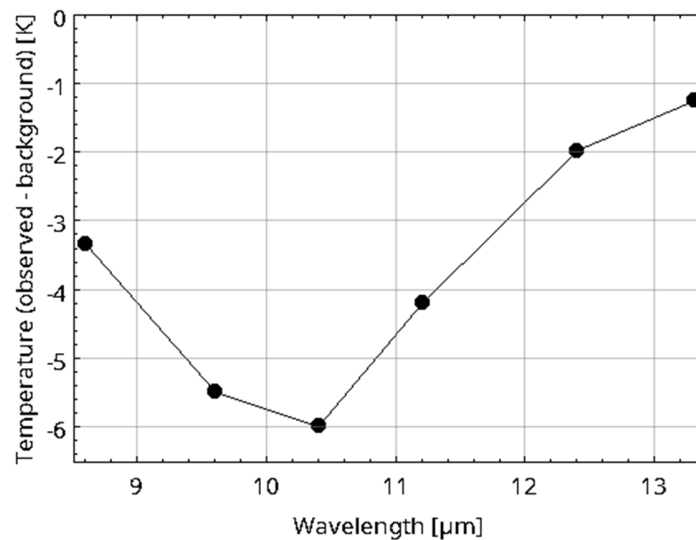
### Appendix C

This appendix includes supporting figures associated with the dust cloud analysis (Figures C1 and C2) and the meteorite search (Figure C3).

#### C1. Dust Cloud



**Figure C1.** Background-subtracted thermal infrared image of the dust cloud, captured  $\sim 5$  minutes after the bolide by the Advanced Himawari Imager onboard the Japanese Himawari-9 weather satellite (Band 13, centered on  $10.4 \mu\text{m}$ ). Pixel size is  $\sim 2.1 \text{ km}$ . The time stamp in the image reflects the start of full Earth disk data capture but the dust cloud pixels correspond to a capture time of 11:27:17.



**Figure C2.** Calibrated absorption spectrum of the dust cloud at thermal infrared wavelengths in the brightest pixel.



## C2. Meteorite Recovery Expedition



**Figure C3.** Photo showing the meteorite searching ground. Significant coverage of the ground by grasses and vegetation made searching for meteorite fragments extremely difficult.

## ORCID iDs

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