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Atmospheric re-entry of the Falcon 9 rocket stage on May 14, 2025, detected by the Brasilia IS09 infrasound station

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Abstract

On May 14, 2025, a luminous object crossed the sky over Central Brazil and was identified by the Brazilian Meteor Observation Network (BRAMON) as the second stage of the Falcon 9 rocket, NORAD number 40108, undergoing atmospheric reentry. This stage is an example of space debris — artificial material launched into space that, upon losing orbital altitude, returns uncontrollably to Earth's atmosphere. Infrasound technology, one of the four verification technologies of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) verification regime, was used to detect and characterize the infrasound signals generated by the reentry of Falcon 9. The Brasília infrasound station (I09BR), part of the International Monitoring System (IMS) for atmospheric nuclear explosions, detected a signal consistent with the rocket's trajectory. This study analyzes the compatibility of the recorded infrasound signal with the orbital reentry, based on the trajectory geometry, propagation time, and recorded acoustic parameters.

Introduction

The intensification of space activities has contributed to the increase in orbital debris, such as rocket stages and decommissioned satellites. Over time, these objects lose altitude due to atmospheric drag and reenter the atmosphere. On May 14, 2025, at 21:24 UTC (18:24 BRT), observers across several Brazilian states (Fig.1) reported the passage of a luminous object in the sky. BRAMON (2025) identified the phenomenon as the reentry of the second stage of the Falcon 9 rocket (NORAD 40108), launched by SpaceX in April 2014, which remained in orbit for over a decade. The estimated trajectory was approximately 1,500 km, with the final reports recorded in southern Bahia.

***Figure 1**: Sequence showing the Falcon 9 second stage reentry over Brazil on May 14, 2025: initial reentry (Alto Paraíso, GO), fragmentation (Carbonita, MG), and final passage (Ponto dos Volantes, MG). **Fonte:** BRAMON. Créditos: J. H. Lima e Lívia Ferraz.*

During the reentry of high-velocity objects, a supersonic wavefront known as a ballistic wave is formed. Its "N-shaped" acoustic signature results from the compression and rarefaction of air (ReVelle, 1976). Although meteors can also produce this type of signal, the hypothesis was ruled out based on the observed velocity (~7.8 km/s), consistent with orbital reentries and significantly lower than typical meteor velocities (11–72 km/s) (Ceplecha et al., 1998; Silber et al., 2009).

The event generated infrasound waves — acoustic waves with frequencies below 20 Hz, inaudible to the human ear but capable of traveling thousands of kilometers due to their long wavelengths and low attenuation. These waves refract through the upper layers of the atmosphere, such as the stratosphere and thermosphere (Garces et al., 2004), and are generated by energetic events that disturb atmospheric pressure, such as quarry explosions (Georges, 1973; Lin & Langston, 2009; Bowman & Bedard, 1971), nuclear tests (Christie et al., 2001), and natural phenomena like meteors (ReVelle, 1976; Evers & Haak, 2001). Thus, infrasound stations can also be used to monitor severe storms, microbaroms, and supersonic aircraft.

Method

The infrasound station I09BR, located in Brasília and operated by the Brasília Seismological Observatory in partnership with the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), a UN agency headquartered in Vienna, Austria (Barros et al., 2022), recorded at 21:35 UTC an infrasonic signal with a dominant frequency of 0.951 Hz, back-azimuth of 20°, duration of 120 minutes, and a waveform consistent with a supersonic ballistic source (Fig.2). Based on an average sound propagation speed of 350 m/s at 20 °C, the source was estimated to be about 230 km away, coinciding with the Alto Paraíso region (GO), where the luminous object is believed to have generated the wavefront. The event analysis included data from BRAMON and the EXOSS Citizen Science Project, meteor monitoring initiatives that integrate citizen science with scientific institutions. The signal was processed using the DTK-GPMCC software (Cansi, 1995; Le Pichon & Cansi, 2003), allowing extraction of parameters such as arrival time, frequency, amplitude, and direction.

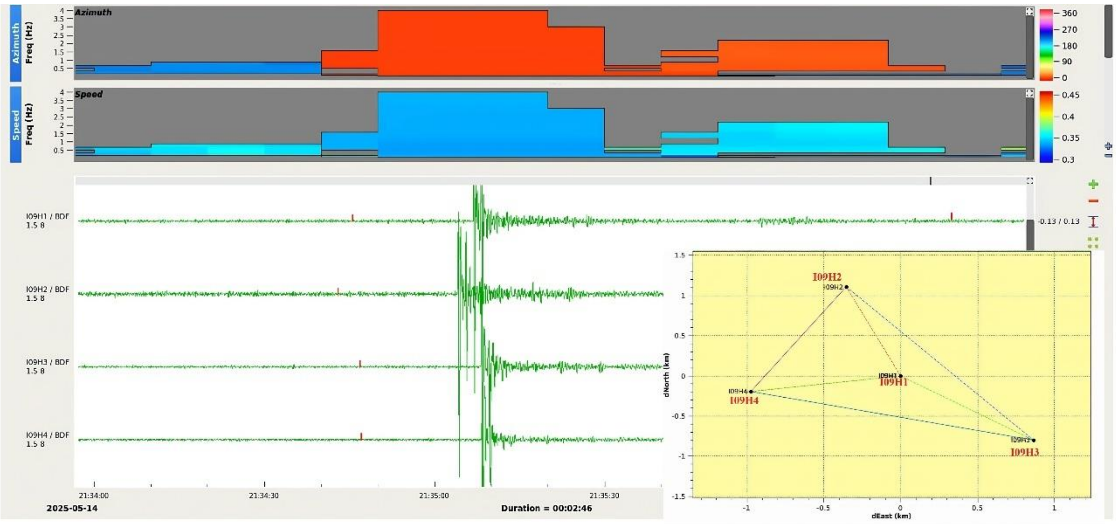

__Figure 2__: Infrasound signals generated by the Falcon 9 during its atmospheric reentry on May 14, 2025, detected by station I09BR, located in Brasília about 230 km from the source. The upper rectangle shows the average back-azimuth information (20°), and the central rectangle displays the average phase velocity (0.350 km/s). The four green traces are the infrasound signals, in the time domain, detected by each element of the infrasound array, shown in the lateral yellow rectangle. As observed, the wave arrived first at element H2 (top), then at element H1 (center), and finally arrived simultaneously at the two lower elements (H3 and H4) of the array.

Results

The spectrogram of the event (Fig. 3) revealed an N-wave form, highlighting compression and rarefaction characteristic of a ballistic wave generated by a hypersonic object in an atmospheric trajectory (ReVelle, 1976). The maximum observed phase velocity was 0.385 km/s, consistent with propagation in the lower tropospheric and stratospheric layers. The directional panel indicated that the signal source was to the north-northeast of the station, aligned with visual reports and the initial trajectory estimate. Although the reentry extended for about 1500 km, the detected infrasonic signal was predominantly generated in the initial region of the trajectory, possibly near Alto Paraíso de Goiás (Fig. 3). This is explained by the fact that at higher altitudes during the early reentry phase, the rocket stage maintains higher velocity and structural integrity, producing more coherent acoustic waves. As the object descends and decelerates, fragmentation and turbulence reduce the efficiency of infrasonic emission (Ens et al., 2012). Furthermore, local atmospheric conditions, including the presence of acoustic ducts in the stratosphere, may favor amplification of the signal emitted at certain points along the trajectory (Matoza et al., 2017). These patterns are consistent with previous observations of orbital reentries, such as those from the Hayabusa mission (2010) and Tiangong-1(2018), where infrasonic generation is concentrated in the initial phases and at higher altitudes of the ballistic trajectory.

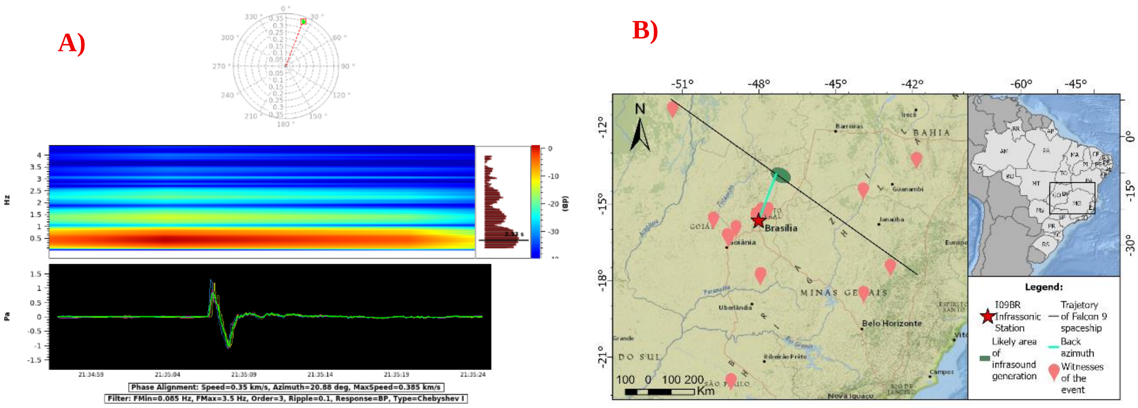

Figure 3: *A) Spectrogram of the event on May 14, 2025, showing the ballistic wave N and parameters such as azimuth, propagation velocity, and frequency; B) Map showing the location of the infrasound station I09BR (red star), the probable area of infrasound generation (in green), the trajectory of the Falcon 9 spacecraft (black line), the back-azimuth recorded by the station (light blue line), and the locations of eyewitnesses (pink markers).*

Conclusions

The signal detected by the Brasília I09BR infrasound station on May 14, 2025, is strongly consistent with the reentry of the second stage of the Falcon 9 rocket. This event involves space debris reentry, consisting of leftover parts from a launch vehicle that completed its mission years earlier. The acoustic wave parameters, including its shape, frequency, direction, and arrival time, corroborate the optical data and visual reports from BRAMON. The efficient propagation of the infrasonic ballistic wave and its detection over long distances confirms the usefulness of infrasound technology, not only for detecting clandestine atmospheric nuclear explosions but also for monitoring anthropogenic atmospheric reentries.

References

BARROS, L. V.; NERI, B. L.; FONTENELE, D. P.; CARVALHO, J. M. *A participação Brasileira na Verificação do Tratado de Proibição Total de Testes Nucleares*. Brasília: Editora Copiarte, 2020.

BRAMON. Relatório preliminar da reentrada orbital de 14/05/2025. 2025. Disponível em: https://bramonmeteor.org. Acesso em: 19 maio 2025.

BROWN, P. G.; REVELLE, D. O.; SILBER, E. A. Infrasound detection of atmospheric entries. *Journal of Atmospheric and Solar-Terrestrial Physics*, v. 119, p. 98–111, 2015. Disponível em: https://doi.org/10.1016/j.jastp.2014.04.001. Acesso em: 19 maio 2025.

BOWMAN, H. S.; BEDARD, A. J. Observations of infrasound and subsonic disturbances related to severe weather. *Geophysical Journal International*, v. 26, n. 1-4, p. 215-242, 1971.

CANSI, Y. An automatic seismic event processing for detection and location: The P.M.C.C. Method. *Geophysical Research Letters*, v. 22, n. 9, p. 1021-1024, 1995. Disponível em: https://doi.org/10.1029/95GL00468.

CEPLECHA, Z. et al. Meteor phenomena and bodies. *Space Science Reviews*, v. 84, n. 3–4, p. 327–471, 1998. Disponível em: https://doi.org/10.1023/A:1005069928850.

CHRISTIE, D. R.; VELOSO, J. A. V.; CAMPUS, P.; BELL, M.; HOFFMANN, T.; LANGLOIS, A.; MARTYSEVICH, P.; DEMIROVIC, E.; CARVALHO, J. Detection of atmospheric nuclear explosions: the infrasound component of the International Monitoring System. *Kerntechnik*, v. 66, n. 3, p. 96-101, 2001. Disponível em: https://doi.org/10.1515/kern-2001-0058.

ENS, T. A. et al. Infrasound observations of the atmospheric re-entry of the Hayabusa spacecraft. *Geophysical Research Letters*, v. 39, n. 24, 2012. Disponível em: https://doi.org/10.1029/2012GL053392. Acesso em: 19 maio 2025.

GARCES, M. A. et al. Forensic studies of infrasound from massive hypersonic sources. *Eos Transactions*, v. 85, n. 43, p. 433–436, 2004.

GEORGES, T. M. Infrasound from Convective Storms: Examining the Evidence. *Reviews of Geophysics*, v. 11, n. 3, p. 571-594, 1973.

LE PICHON, A.; BLANC, E.; HAUCHECORNE, A. *Infrasound monitoring for atmospheric studies*. Dordrecht: Springer, 2008.

LIN, T. L.; LANGSTON, C. A. Thunder-induced ground motions: 1. Observations. *Journal of Geophysical Research: Solid Earth*, v. 114, B4, 2009.

MATOZA, R. S. et al. Highlights from 10 years of infrasound observations with the IMS. *Seismological Research Letters*, v. 88, n. 3, p. 1060–1072, 2017.

REVELLE, D. O. On meteor-generated infrasound. *Journal of Geophysical Research*, v. 81, n. 7, p. 1217–1230, 1976.

SILBER, E. A.; REVELLE, D. O.; BROWN, P. G.; EDWARDS, W. N. An estimate of the terrestrial influx of large meteoroids from infrasonic measurements. *Journal of Geophysical Research: Atmospheres*, v. 114, n. D9, 2009. Disponível em: https://doi.org/10.1029/2008JD011290.