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Array-based seismic measurements of

OSIRIS-REx's re-entry

Benjamin A. Fernando¹, Constantinos Charalambous², Nick Schmerr³, Timothy J. Craig⁴,
Jonathan Wolf⁵, Kevin Lewis¹, Eleanor K. Sansom^{6,7}, Christelle Saliby⁸, Meaghan McCleary⁹,
Jennifer Inman¹⁰, Justin LaPierre¹¹, Miro Ronac Giannone¹², Karen Pearson¹³, Michael Fleigle¹⁴,
Carene Larmat¹⁵, Ozgur Karatekin¹⁶, Lavender Elle Hanson¹, Shivani Baliyan¹⁷, David Buttsworth¹⁸,
Hiu Ching Jupiter Cheng¹⁹, Neeraja S. Chinchalkar²⁰, Luke Daly²¹, Hadrien A. R. Devillepoix⁴,
Aly Muhammad Gajani²², Carina T. Gerritzen²³, Harish²⁴, Daniel C. Hicks²⁵, Roy Johnson²⁶,
Sabrina Y. Khan¹, Sarah N. Lamm²⁷, Cara Pesciotta¹, Tom Rivlin²⁸, Lucie Rolland²⁹,
Maxwell Marzban Thiemens³⁰, Alice R. Turner³¹, and Fabian Zander¹⁸

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[Supplemental Material](#)

Abstract

The return home of the OSIRIS-REx spacecraft in September 2023 marked only the fifth time that an artificial object entered the Earth's atmosphere at interplanetary velocities. Although rare, such events serve as valuable analogues for natural meteoroid re-entries; enabling study of hypersonic dynamics, shockwave generation, and acoustic-to-seismic coupling. Here, we report on the signatures recorded by a dense (100-m scale) 11-station array located almost directly underneath the capsule's point of peak atmospheric heating in northern Nevada. Seismic data are presented which allow inferences to be made about the shape of the shockwave's footprint on the surface, the capsule's trajectory, and its flight parameters.

Introduction

Sample return capsules and seismoacoustics

Sample return capsules arriving from deep space are the only artificial objects which re-enter the Earth's atmosphere at speeds and trajectories comparable to natural meteoroids. This makes them ideal for studying hypersonic re-entry dynamics as said

*Corresponding author: bfernan9@jh.edu

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24 capsules have known mass, dimension, speed, and trajectory (Silber et al., 2023). Because they have known parameters, they
25 can serve as controlled analogues for natural objects during the EDL (Entry, Descent, and Landing) phase of the mission.

26 In seismoacoustic studies of meteor phenomena, the atmospheric shockwaves and low-frequency sound produced by nat-
27 ural meteoroids re-entering the atmosphere are used to identify and track them on either infrasound sensors or seismometers
28 (e.g. Edwards et al. (2008)). The complexities of shockwave generation and propagation down through the turbulent atmo-
29 sphere (and coupling into the ground in the case of seismic recordings) mean that recordings of hypersonic capsules acting
30 as ‘artificial meteoroids’ are particularly valuable in understanding the seismoacoustic processes involved.

31 Such events are rare, having occurred only four times on Earth previously. ReVelle et al. (2005) made seismic and acoustic
32 measurements of NASA’s Genesis spacecraft’s EDL, and ReVelle and Edwards (2007) did the same for NASA’s Stardust.
33 More recently, comparable measurements were made during the EDLs of two JAXA missions, Hayabusa and Hayabusa2
34 (Yamamoto et al., 2011; Sansom et al., 2022).

35 The potential value of such recordings for being able to study shockwave propagation and air-to-ground coupling in partic-
36 ular also resulted in two (unsuccessful) attempts by NASA’s InSight spacecraft to record EDLs seismoacoustically on Mars,
37 of NASA’s Mars 2020 mission (Fernando et al., 2021, 2022) and China’s Tianwen-1 (Fernando et al., 2021).

38 The OSIRIS-REx mission

39 In September 2023, the OSIRIS-REx (ORX) sample return capsule became the fifth artificial object to re-enter the Earth’s
40 atmosphere at interplanetary speeds. With many improvements in instrumentation having been made since Stardust’s land-
41 ing in 2006, the ORX EDL presented an ideal opportunity to make seismoacoustic measurements of an ‘artificial meteoroid’
42 re-entry over a similar geographical area to two previous missions.

43 A number of different teams took part in this instrumentation campaign, using both ground-based and airborne infrasound
44 sensors, and conventional and optical seismometers. For a full review of the instruments deployed as part of this campaign
45 see Silber et al. (2024). Fernando et al. (2024) presented initial results from a separate part of this observation campaign,
46 using a single seismic-acoustic station 50 km from the array described in this paper at a site called Fish Creek from which
47 the data was live-streamed over the internet.

48 EDL profile

49 In this section, we briefly describe the planned trajectory of ORX between atmospheric interface and peak heating. Note
50 that all times and locations are based on pre-landing model predictions (e.g. Ajluni et al. (2015)), as a post-landing ‘as-flown’
51 trajectory has not yet been released.

52 Atmospheric interface was due to occur over the Pacific Ocean, west of San Francisco, California at 14:41:55 UTC on
53 Sunday, 2023-09-24. The defined altitude of interface was 132 km, at which time the spacecraft was expected to be travelling
54 at approximately Mach 25 (43,000 km/h; 11.9 km/s).

55 At the point of peak atmospheric heating from frictional drag, the capsule was expected to be in the mesosphere at around
56 62 km altitude over 39.5585°N, 116.3852°W in northern Nevada. This is a relatively remote region with no permanent seis-
57 mometers within several dozen kilometres, and we are not aware of any publicly accessible infrasound stations within the
58 wider area. This necessitated deployment of these temporary seismic arrays.

59 Temperatures during peak heating were expected to reach approximately 3100 K at a speed of Mach 30 (39,000 km/h;
60 10.8 km/s) and a deceleration approaching 300 m/s² (31 g). Note that the Mach number at peak heating is actually higher
61 than at atmospheric interface despite the capsule's deceleration, due to the increase in sound speed with altitude through
62 the thermosphere.

63 As the point of peak heating is where the maximum amount of energy is being dissipated into the atmosphere, the expect-
64 ation was for an intense shockwave to be generated in this area. This shock was expected to transition to a linear acoustic
65 wave during propagation down through the atmosphere and be audible at the surface as a sonic boom.

66 On a seismic network, the sonic booms themselves are primarily recorded via the production of an itinerant strain field in
67 response to the surface loading and unloading from wavefront-induced compression and rarefaction (Kanamori et al., 1992).
68 Small contributions to the observed displacement after the initial motion may also come about from more complex effects,
69 such as compliance-induced ground deformation (Sorrells, 1971; Kenda et al., 2020).

70 Instrumentation campaign

71 The deployment discussed in this paper involved eleven individual seismic stations, each consisting of a three-axis Fairfield
72 ZLand 3C Nodes set to 24dB gain and 2000 samples per second.

73 The deployment location for these nodes was chosen to be as close to the point of projected peak heating as possible, to
74 try to capture the shockwave at its strongest point. For natural meteoroids, peak emission is expected to occur around the
75 point of peak heating, and hence measurements made of artificial capsules in this region of flight are of particular interest
76 as analogues.

77 The array was located at Bean Flats, on United States Bureau of Land Management land, in an area shared with large
78 herbivorous creatures (cows). Despite the presence of topographic variation in the wider region, this area itself was very
79 flat, with less than 4 m of undulation between the array's centre and edge in any direction. Given a sound-speed in air of
80 approximately 330 m/s, this corresponds to a very small elevation-induced correction to phase arrival times, on the order of
81 0.01 s.

82 Instruments were deployed in a cross-shaped array, with an instrument spacing of approximately 100 m. This configura-
83 tion, and wider geographical context, are shown in Fig. 1 alongside the ORX EDL trajectory. The long axis of the array was
84 chosen to be parallel to ORX's trajectory footprint.

85 Each instrument was manually levelled and pointed toward north using multiple compasses as references, with errors in
86 orientation estimated to be less than $\pm 2^\circ$. The reported GPS coordinates of each station are the mean of readings made on
87 multiple handheld instruments.

88 The sensors were buried with their tops a few centimetres below the ground's surface to reduce environmental noise. Some
89 of the surface covering was removed by rain and wind (and possibly the actions of the previously mentioned herbivores)
90 between deployment and collection. Signals from instrument 4 (the most uprange) were found to be particularly noisy. The
91 ground at this location was ascertained to be soft, mostly dry superficial alluvium. Detailed geophysical surveys from this
92 area of Nevada suggest soil properties described by $V_p = 585$ m/s and $V_s = 350$ m/s, Poisson ratio $\nu = 0.22$, and Young's
93 Modulus $E = 0.45$ MPa (Allander and Berger, 2009).

94 Seismic data

95 Data were recorded at all eleven stations, and are shown in Fig. 2. Seismograms were processed by removing the instrument
96 response and Butterworth-bandpass filtering between 1 and 100 Hz. The beam shown in Fig. 4 a,b) uses a slightly broader
97 frequency range, 2 to 200 Hz.

98 Detailed N-wave structure

99 A clear, rounded (smoothed) N-wave signature is observed just after 14:46:04.5 UTC. A downwards, near-instantaneous first
100 motion associated with the acoustic compression is followed by an upwards ground motion associated with the atmospheric
101 rarefaction.

102 The rounding of the N-wave is characteristic of a shockwave which has decayed in the turbulent atmosphere (in particular
103 the planetary boundary layer) to become a linear sound wave, though retaining its characteristic N-wave shape in a more
104 rounded form (Ben-Menahem and Singh, 1981; Plotkin, 2002; Pierce and Maglieri, 1972). The arrival time is commensurate
105 with the expected capsule overflight a few minutes previously (around 14:42 UTC). The overall duration of the N-wave phase
106 within the wavetrain is around 0.15 s, depending on which station is examined and how the end of the rarefaction period is
107 chosen (we use the first zero-crossing after the rarefaction).

108 Differences are observed in the structure of the rounded N-wave (Fig. 2), even between stations which are separated by only
109 100 m. Frequencies up to 500 Hz are recorded at some stations (e.g., 2 and 10), while others (e.g., 1 and 3) are limited to highest
110 frequencies around 400 Hz. The rarefaction has a narrower frequency content than the compression, and is accordingly
111 broader.

112 The most significant origins of these differences are likely propagation effects associated with inhomogeneity and turbu-
113 lence in the atmosphere (Pierce and Maglieri, 1972) and local variations in sediment properties (causing different coupling
114 behaviour, McDonald and Goforth (1969)). The spatially varying nature of the seismic source itself (i.e., the fact that the
115 capsule is descending and decelerating over time) may also have had a small effect.

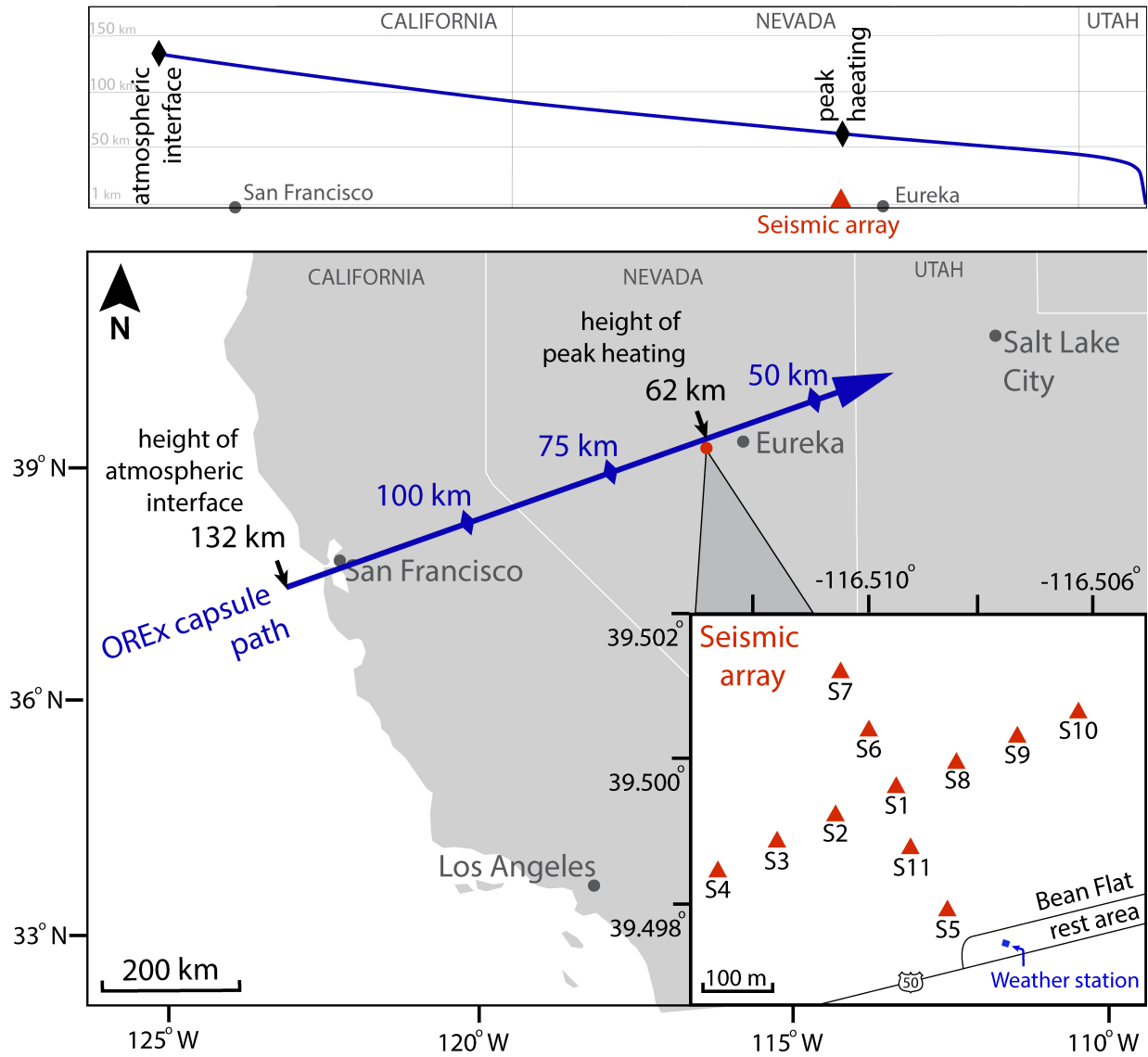


Figure 1. Top panel: the ORX EDL trajectory (side view), from the point of atmospheric interface to landing. Bottom panel: geographical context (top-down view) of the trajectory. We refer to directions towards landing as ‘downrange’ and those towards atmospheric interface as ‘uprange’. The inset panel shows the seismometer array deployment. Note that the long

arm of the array is parallel to the expected trajectory (i.e. runs uprange/downrange). The cross arm is perpendicular to the trajectory (i.e. crossrange). The lateral distance between the centre-line of the array and the trajectory footprint on the ground is approximately 2300 m.

116 We now consider a more detailed analysis of the signal recorded at a single station, as shown in Fig. 3. These data are for
 117 station 1, as it is located at the array centre, but similar features are recorded across the array.

118 As per Fig. 3A), the N-wave is most clearly detectable on the vertical component, as is expected for a wavefront travelling
 119 almost vertically downward (McDonald and Goforth, 1969). A peak ground velocity of 2.6×10^6 m/s is noted, which is slightly
 120 higher than that noted by Fernando et al. (2024) of 2.0×10^6 at a site 50 km away).

121 Fig. 3B) shows a vertical component spectrogram. Weak background noise, with energy predominantly at frequencies up
 122 to 30 Hz, is apparent before the rounded N-wave arrival. The amplitude variations across the array (higher noise levels closer

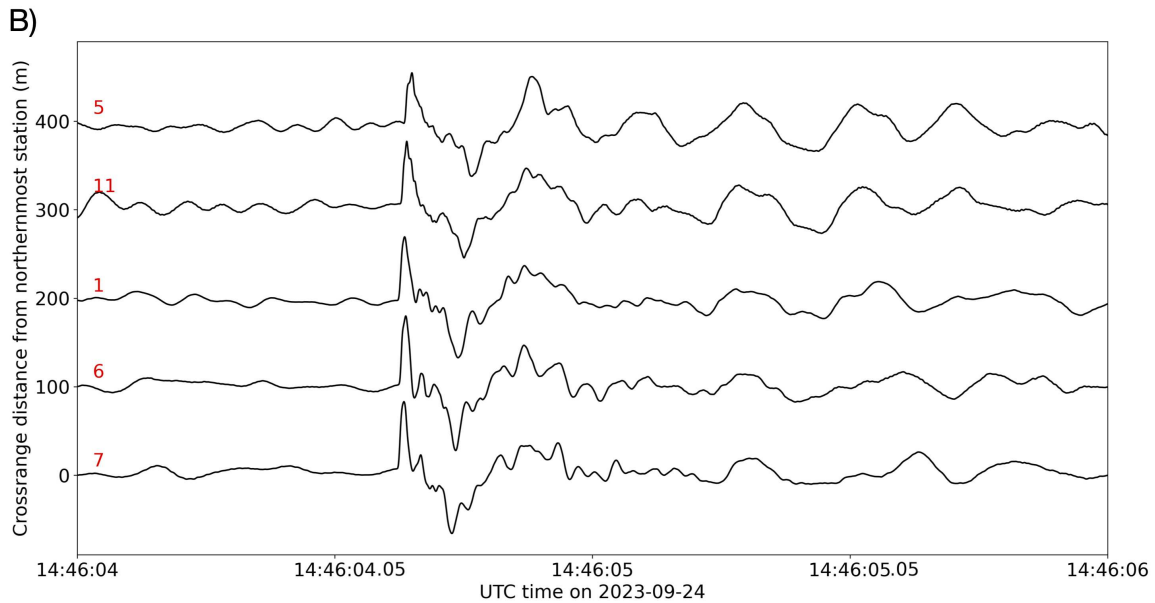
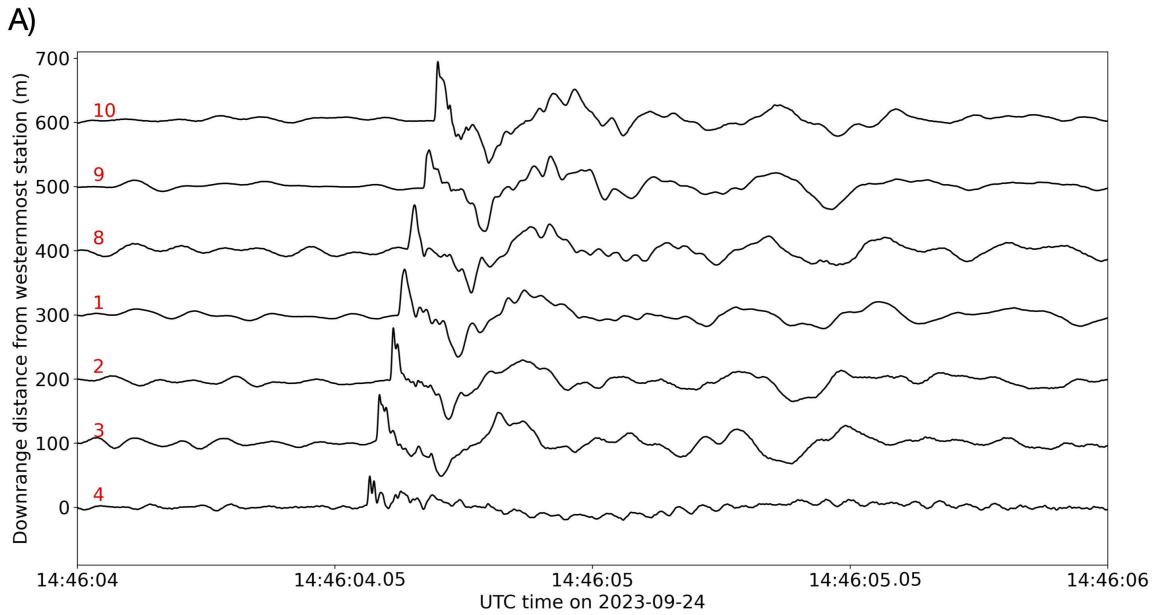


Figure 2. Seismic data recorded by the array. Traces are vertical ground velocity in the 1-100 Hz range and are arranged in **A)** by downrange distance from the westernmost station in the array and in **B)** by crossrange distance from the northernmost station. Station numbers are indicated in red on the left hand side. The weak signal at station 4 is thought to be due to issues with the instrument, which displayed higher noise levels throughout the deployment.

123 to the road), the move-out of the energy, and the identification of similar signatures in the seismic record at a later time
 124 (15:25-15:27 UTC) collectively indicate a vehicular origin for this particular noise source. This is discussed further in the
 125 *Traffic* section.

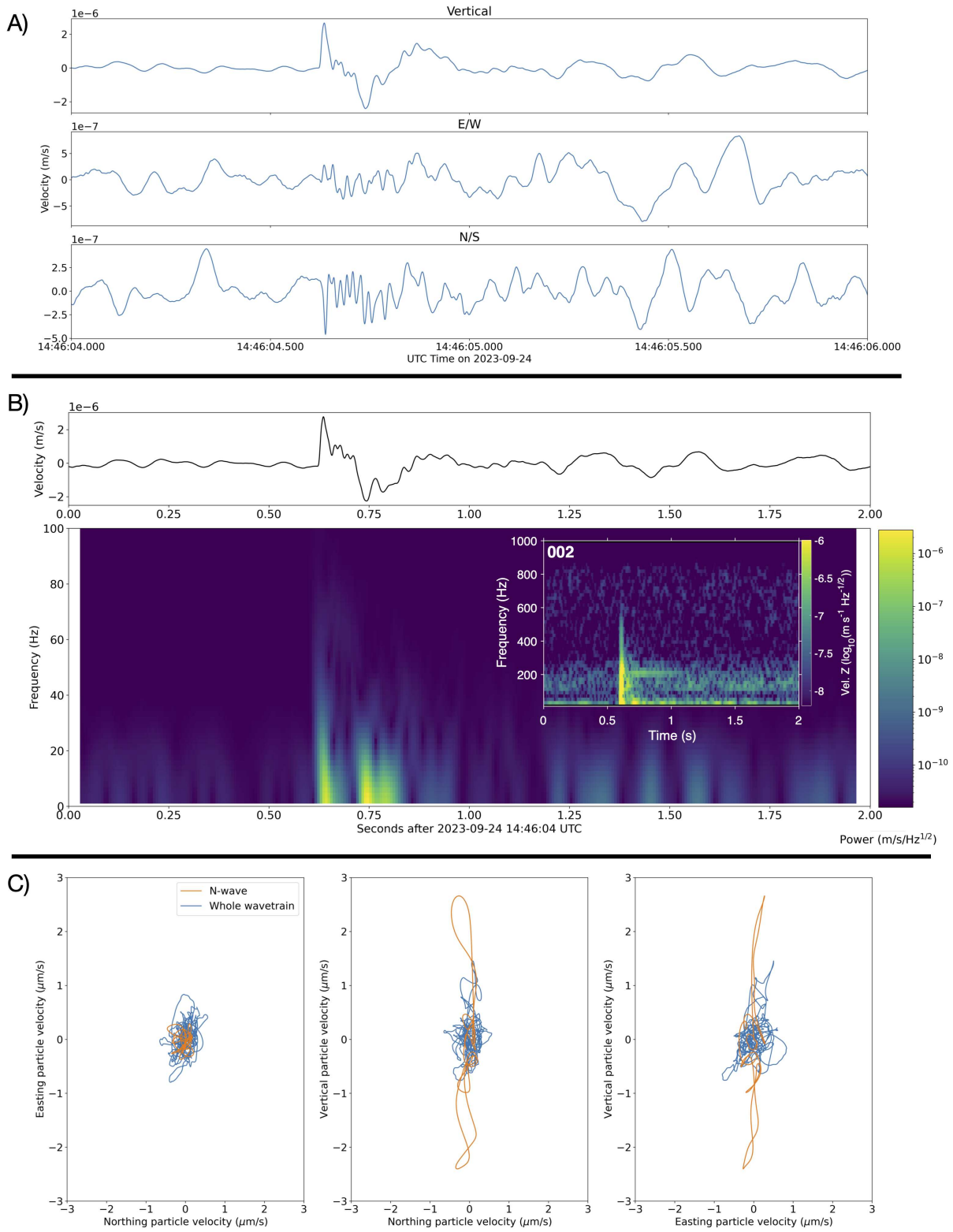


Figure 3. Data from the central station of the array (Station 1), bandpassed between 1 and 100 Hz. The N-wave is only clearly apparent on the vertical component. **A)** Three-component data, showing the dominance of the signal on the vertical component. **B)** Velocity spectrogram for the vertical component. A small inset is shown for Station 2 (one station uprange from Station 1), to illustrate the variation in

peak frequency recorded between different stations. At Station 2, a resonance around 200 Hz is also observed, which could correspond to excitation in a thin playa layer around 1-2 m thick. **C)** Particle motion, with the N wave shown in orange (14:46:04.4 - 14:46:04.8 UTC) and the remainder of the wavetrain in blue.

126 Finally, Fig. 3C) shows the ground particle motion associated with the initial N-wave (orange) and the rest of the wavetrain
127 (blue). The overwhelmingly vertical motion associated with the N-wave is clear. A potential elliptical polarisation can be seen
128 in the rest of the wavetrain, suggesting the presence of Rayleigh waves here.

129 Slowness and origin azimuth

130 In considering the passage of the sonic boom over the array, it is important to consider that the capsule does not act as a point
131 source. Rather, whilst travelling at supersonic speeds it is more appropriately described as a line source producing a conical
132 shock front (Carlson and Maglieri, 1972). The opening angle of the cone, μ , is given by:

$$133 \mu = \arcsin \frac{1}{M} \quad (1)$$

134 where M is the Mach number, in this case 30 – corresponding to an opening angle of 1.9° . This narrow Mach cone means
135 that the seismic source may effectively be considered to be a cylinder (Karakostas et al., 2018). The acoustic rays themselves
136 are emitted at the complement of the Mach angle (Cates and Sturtevant, 2002), which in this case is 88.1° , i.e., nearly normal
137 to the shock front.

138 The intersection of the Mach cone with the ground produces a hyperbola along which a sonic boom is audible, and the
139 passage of the hyperbola over the surface sweeps out a sonic boom ‘carpet’. As per Eqn. 1, the hyperbolic footprint also
140 becomes narrower with increasing Mach number.

141 In Figure 4, we first show the results of a beampack aimed at determining the 2D slowness of the overpressure wavefront,
142 followed by vespagrams showing beams in slowness s_x and s_y space. These are constructed under the assumption that the
143 wave propagates across the array as a plane wave at consistent velocity. We do not find it necessary to compensate for the
144 small variation in topographic elevation across the array as this is < 4 m across an array aperture of ~ 600 m and hence the
145 impact of elevation variation is small.

146 The beampack shows the maximum arrival amplitude with a 0.025 s window around the overall maximum amplitude
147 stack, as a function of slowness in east (s_x) and north (s_y) directions. As Figure 4A,B) shows, there is a clear peak in amplitude
148 associated with wavefront arrival at a slowness of $[s_x, s_y] = [-0.209, -0.063]$. The actual signal is convolved with an array
149 response function leading to amplitude artefacts associated with the orientation of the arms of the array in the uprange and
150 crossrange directions, these are visible as bright lines in the beampack. The fact that the array response function passes
151 slightly northwest of $[0,0]$ in slowness space indicates the array was slightly to the south of the actual re-entry trajectory
152 (consistent with pre-landing predictions, and indicating that the spacecraft was either on or ever so slightly south of its
153 nominal re-entry line).

154 The 2D slowness of the wavefront arrival indicates that the point of apparent wavefront emission is at an azimuth of
155 253° (roughly WSW), and an apparent slowness of 0.214 s/km. The derived azimuth is very close to the pre-landing nominal
156 prediction of 249° . The beampack is extremely well resolved, given the frequency of the overpressure wave and array aperture.

157 The vespagrams in Figure 4C,D) show evidence for either a slight variation in slowness across the array, or equivalently, the
158 detection of wavefront curvature. In this case, where source-array distance is likely to be only around two orders of magnitude
159 higher than the array aperture, slight wavefront curvature is more likely than the impact of a consistent atmospheric gradient
160 on the lengthscale of the array aperture. The latter would also be expected given that the sonic boom footprint on the ground
161 is a hyperbola.

162 Source location analysis

163 Given the azimuth and slowness resolution of the array, we are also able to estimate origin location of the shockwave. Without
164 a full atmospheric model and inversion of the data, which are beyond the scope of this paper, this involves making a number
165 of assumptions.

166 Firstly, we assume that the sonic boom can be represented as a plane wave propagating through the atmosphere, which,
167 as we justify above, is an approximation which is reasonable in the far-field. Secondly, we assume that the shockwave has
168 decayed sufficiently such that it propagates at the speed of sound v_0 , which we calculate to be 332 m/s (see *Weather* section
169 for more details on this calculation).

170 Geometrically, we consider the apparent slowness ($s_{app} = \frac{1}{v_{app}}$) of the wavefront across the array (e.g. [Rost and Thomas](#)
171 [\(2002\)](#)) as:

$$172 s_{app} = \frac{\sin\theta}{v_0} \quad (2)$$

173 In the downrange direction, the apparent velocity v_{app} of the wavefront across the array is 4,581 m/s. Note that this is an
174 apparent, rather than physical, velocity and yields an estimated angle of emission which is 4.15° from the vertical. This is
175 the equivalent point-source angle of emission, and does not reproduce the actual, extended-line source nature of the capsule
176 as a seismic source; but it does indicate that the signal was produced almost exactly overhead the array, as expected. When
177 combined with the derived bearing from the previous section of 253° , this indicates an origin for the shockwave which
178 is slightly to the south-west of the array and almost vertically above it. Note that this result also suggests that the effects
179 of atmospheric refraction of the acoustic rays is minimal, as each different layer of the vertically stratified atmosphere is
180 encountered at a near-normal angle to its interface.

181 Pre- and post-cursors

182 Similarly to [Fernando et al. \(2024\)](#), no clear pre-cursor phases are noted, and there are no coherent sources detected by our
183 array. This is as expected, because pre-cursors are normally restricted to settings where the supersonic source is 'slow' as
184 compared to the compressional speed in the ground, such that surface waves induced immediately beneath the source can
185 'overtake' a slower direct airwave due to the higher wave speeds in the ground ([Cook and Goforth, 1970](#)). In this case, the

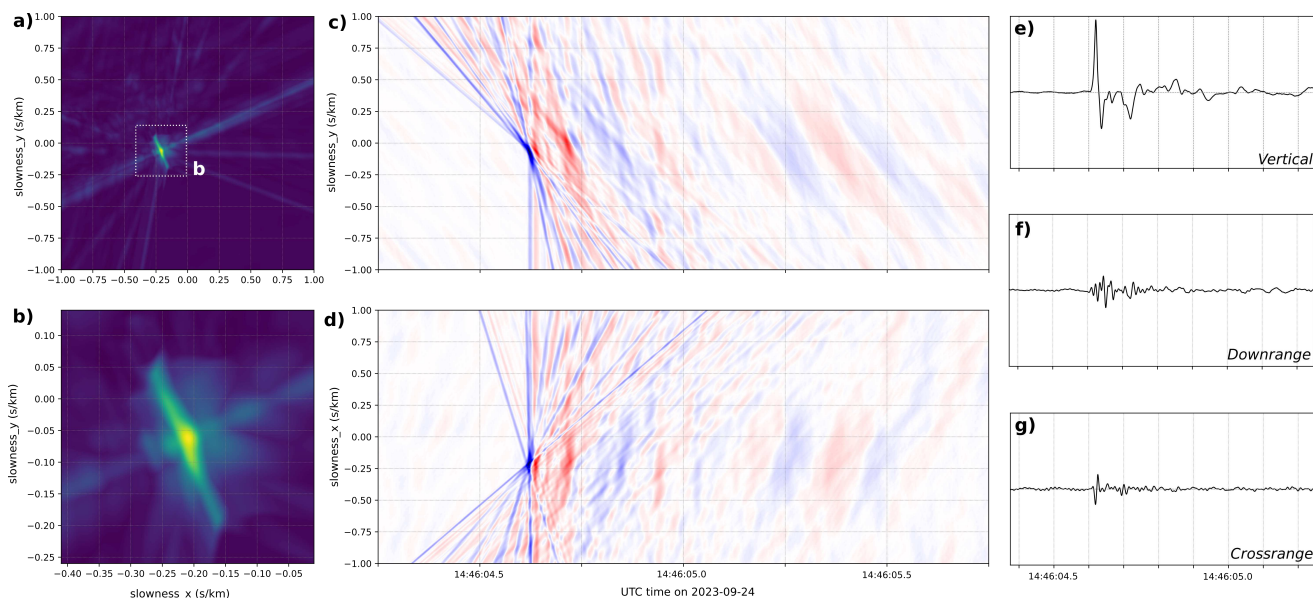


Figure 4. Array analysis of the ORX re-entry signal. **(a)** and **(b)** show the results of a beampack through slowness in x and y, taking the maximum amplitude with +/- 50 samples (0.025 seconds) of the absolute maximum amplitude for the shockwave arrival (at 14:46:04.621 and at a slowness of [-0.209, -0.063]). **(c)** and **(d)** show vespagrams in y and x slowness space, respectively. In each vespagram, the other

slowness is fixed at the value giving the absolute maximum amplitude for the shockwave arrival. All plots are normalised to the peak value. **(e)-(g)** show the optimal-slowness beam for vertical, downrange and crossrange components, respectively in the pass band 1 – 100 Hz. All beams are normalised to the peak value of the vertical component beam.

186 capsule's velocity is very much greater than V_p , thus explaining the absence of pre-cursor phases (McDonald and Goforth,
187 1969). Furthermore, the sound speed in the ground is only slightly higher (less than factor 2) than the sound speed in the air.

188 We do note that there is an increase in noise levels around 14:45:50 UTC, around twenty seconds before the ORX signal
189 (see *Traffic* section for more details). We exclude this as being a pre-cursor, as it arrives too early as compared to the airwave
190 and has a move-out consistent with a vehicular origin, specifically a lorry/truck that arrived at the nearby rest area and idled
191 until 14:47 UTC.

192 Conversely, a relatively rich set of seismic waves is apparent immediately after the initial rounded N-wave. These are
193 visible as an extended set of oscillations in Figs. 2A) and B). These have similar slowness to the airwave arrival, and hence
194 are potentially associated with acoustic waves propagating in the atmosphere after the initial compression/rarefaction, or
195 longer-duration complex deformation associated with the wavefront's passage over the station. It is also likely that Rayleigh
196 waves are present in this wavetrain. Given that V_s in play is extremely close to the sound-speed in air, the air-to-ground
197 coupling should be strong. However, this closeness of speeds also makes phase separation challenging.

198 Comparison to known flight parameters

199 In theory, the detailed seismic recordings made at this array could be inverted for the capsule's trajectory and flight param-
200 eters. However, this is extremely challenging in practice, due to the lack of an exact atmospheric state model or an as-flown
201 trajectory.

202 Nonetheless, we note that a comparison of the boom duration (τ) to theoretical predictions given by [Kanamori et al. \(1992\)](#)
 203 is possible. Following the approach of [Whitham \(1974\)](#) (though with slightly different notation, and correction for a missing
 204 exponent noted by [Kanamori et al. \(1992\)](#)), given a capsule speed u at height h we expect τ to be approximately given by:

$$205 \tau \approx \frac{2\sqrt{2k_2k_3}h^{\frac{1}{4}}}{u} \quad (3)$$

206 where k_2 is a constant dependent on the ratio of specific heats within the atmosphere γ and the Mach number M :

$$207 k_2 = \frac{(\gamma + 1)M^4}{\sqrt{2}(M^2 - 1)^{\frac{3}{4}}} \quad (4)$$

208 and k_3 is a constant related to the capsule's geometry,

$$209 k_3 = \delta l^{\frac{3}{4}} \quad (5)$$

210 where δ is the ratio of maximum effective capsule radius to capsule length l .

211 For the ORX capsule with radius 0.4 m and length 0.5 m, $k_3 = 0.48$ (noting that in practice, the effective radius of the
 212 capsule may be larger due to shockwave stand-off).

213 Given the nominal pre-landing predictions of $h = 62,000$ m and $u = 10,800$ m/s, and assuming a canonical $\gamma = 1.4$ (as per
 214 [Kanamori et al. \(1992\)](#), though it is likely lower at $M = 30$), we derive $k_2 \approx 8,370$. Using the 'effective' (slant) height makes
 215 little difference to this calculation given that the capsule is almost directly overhead.

216 These results yield an estimate of $\tau = 0.18$ s. This is in remarkably close agreement with our measured value of 0.15 s
 217 given the significant simplifications made in the calculation of the constants above and the unknown capsule height and
 218 atmospheric conditions at the time of overflight. Calculation of a more accurate ratio of specific heats or applying a correction
 219 for atmospheric structure and wind structure may enable an even more accurate match.

220 [Kanamori et al. \(1992\)](#) also gives an approximate relation for theoretical overpressure as a function of aspect ratio and
 221 altitude:

$$222 \frac{\Delta P}{P} \approx k_1 k_3 h^{-\frac{3}{4}} \quad (6)$$

223 Where k_1 is another constant given by:

$$224 k_1 = \frac{2^{\frac{1}{4}}\gamma}{(\gamma + 1)^{\frac{1}{2}}}(M^2 - 1)^{\frac{1}{8}} \quad (7)$$

225 We compute $k_1 = 2.5$ and hence $\frac{\Delta P}{P} = 0.00030$. Based on a receiver altitude of 1,920 m and an ambient air temperature
 226 of $+4.5^\circ\text{C}$, $P = 79,600$ Pa and hence $\Delta P \approx 24$ Pa. We are not able to directly compare this to the actual overpressure as the
 227 ground compliance at the array site was not measured.

228 However, we note that the the theoretical overpressure is still significantly larger than that recorded by [Fernando et al.](#)
 229 (2024) of 0.7 Pa at the Fish Creek site approximately 50 km away. Computing the expected overpressure at Fish Creek whilst

TABLE 1.

Meteorological data recorded by the Nevada Department of Transport Weather Station at US 50 Bean Flats Rest Area at 14:46:00 UTC. Data are shared as provided, surface temperature has been averaged over two sensors.

Variable	Value
Air temperature	+4.5°C
Surface temperature	+8.2°C
Dewpoint	-3.3°C
Relative humidity	56%
Wind direction	302°
Wind speed	0.0 m/s
Gust direction	291°
Gust speed	0.22 m/s
Precipitation	None

230 accounting for the longer slant height at this laterally offset station yields a predicted overpressure of 21 Pa, still around 30
231 times too large.

232 Therefore, we conclude that this formula for ΔP is not valid in this regime. This may be due to the capsule's hypersonic speed
233 producing a substantially modified bow shock, or its extreme altitude producing different interactions with the surrounding
234 airflow, as compared to tests conducted at lower altitudes and lower Mach numbers.

235 Ancillary data

236 We will briefly discuss ancillary data which was collected as part of this deployment by part of a team of volunteers, working
237 remotely with data provided online by the Nevada Department of Transport (NVDOT). All of this data, and similar readings
238 from nearby potentially of interest to other portions of the ORX EDL instrumentation campaign, are available in our online
239 repository (see Data and Resources section for link).

240 Weather data

241 The proximity of the array to US Highway 50 ('The Loneliest Road in America') had the advantage that meteorological data
242 could be sourced from a nearby NVDOT weather station. This station ('US50 Bean Flats Rest Area') was only 275 m from the
243 array centrepoint. The closest reading to the capsule's overflight and the arrival of the sonic boom was made at 14:44:00 UTC,
244 with measurements shown in Table 1.

245 Whilst the lack of wind during this period represents only a single measurement at the surface, it may be indicative of a
246 quiescent planetary boundary layer at the time in question. This may have led to less turbulent dissipation of the wavefront
247 (one of the sources of rounding in the N-wave).

TABLE 2.

Traffic data recorded by the cameras at the US 50 Bean Flat Rest Area. Note that ‘Away’ and ‘Towards’ refer to whether the vehicle was moving away from (westbound) or towards (eastbound) relative to the westward-facing traffic camera. Speeds were judged by each individual relative to the average in the 30 minutes or so preceding the interval of interest

UTC Time - Lower Bound	UTC Time - Mean	UTC Time - Upper Bound	Direction	Speed	Type
14:39:26	14:39:47	14:40:03	Away	Medium/Fast	Car
14:41:23	14:41:35	14:41:53	Towards	Medium	Car (with trailer?)
14:41:38	14:41:39	14:41:39	Towards	Medium	Car (with trailer?)
14:47:49	14:47:57	14:48:00	Away	Slow/stationary	Lorry/truck
14:51:47	14:51:52	14:52:00	Towards	Medium/Slow	Car with trailer

248 Traffic data

249 We also made use of the traffic camera installed at the Bean Flats Rest area to record traffic movements, with the aim of being
250 able to identify contamination in the ORX signal if needed.

251 Data for around five minutes before and after the overflight are given in Table 2. Because the traffic camera feeds are
252 not archived, multiple volunteers were asked to record vehicles passing the array in real time, thereby eliminating some of
253 random the error associated with streaming lag (we find a systematic error of around 40 s delay in video data as compared
254 to when a vehicle becomes apparent in the seismic data). The data provided is a synthesis of that from all volunteers, with
255 the lower, mean, and upper bounds on vehicle passage times given. The streaming lag has not been corrected for in Fig. 2.

256 In two cases, the vehicle may have been towing a trailer, but this could not be determined due to poor video resolution.
257 In order to corroborate readings between different volunteers who recorded slightly different vehicle arrival times due to
258 streaming lag, car colour was also recorded – but this is not noted in Table 2 as it is not relevant to seismic observations.

259 As per Table 2, no moving vehicles were noted at 14:46 UTC, when the ORX signal was detected. A truck which passed
260 the camera at 14:47 UTC was identified in the seismic dataset as being a source of noise beginning at 14:45:50 UTC, and
261 extending out to 14:49 UTC. Given this long duration, and its slow speed observed in the video data, we suspect it was idling
262 in the layby prior to driving away.

263 Summary

264 Seismic signatures associated with the EDL of the OSIRIS-REx spacecraft were recorded by an 11-instrument seismic array
265 located almost immediately under the point of peak heating over northern Nevada.

266 A classic rounded N-wave, characteristic of a decayed sonic boom, is observed propagating across the array. The entire N-
267 wave (compression and rarefaction) lasts approximately 0.15 s, with the compressional wave extending to higher frequencies
268 (up to at least ~450 Hz at some stations) than the rarefaction (~40 Hz). The measured duration of the N-wave is in very good
269 agreement with theoretical predictions.

270 The wavefront's moveout across the array is predominantly in the downrange direction (at an azimuth of 253°, close to
271 the pre-landing prediction of 249°. The wave is also propagating almost vertically downward (around 4° from the vertical).
272 Following the N-wave, a set of seismic post-cursors are recorded, likely some combination of air-coupled seismic waves,
273 additional (slower) airwaves, and long-period ground deformation induced by the initial wavefront.

274 Data from this array are able to exclude the spacecraft being well south of its nominal trajectory. Analysis of the apparent
275 slowness of the N-wave across the array also indicates an equivalent point-source origin which is almost exactly overhead in
276 both the uprange-downrange and crossrange planes.

277 Further work would likely enable a more thorough inversion of the capsule's trajectory, accounting for the extended nature
278 of the source and the effects of refraction arising from atmospheric stratification. This would enable this dataset to be used
279 as a more reliable test-case for trajectory determinations of natural meteoroids using their seismic signatures.

280 Data and Resources

281 Deployment locations and ancillary data (weather and traffic data) are available via in this Zenodo repository: <https://doi.org/10.5281/zenodo.12210877>. Seismic data are available from the FDSN under network code 2X (Benjamin A. Fernando et al., 2023) at
282 DOI [10.7914/8ZEK-PE59](https://doi.org/10.7914/8ZEK-PE59).
283

284 Declaration of Competing Interests

285 The authors acknowledge that there are no conflicts of interest recorded.

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347 Author affiliations

348 (BF, KL, LEH, SK, CP) Department of Earth and Planetary Sciences, Johns Hopkins University, 3400 N Charles St, Baltimore,
349 Maryland, 21218, United States (CC) Department of Electrical and Electronic Engineering, Imperial College London,
350 London, United Kingdom (NS) Department of Geology, University of Maryland, College Park, Maryland, 20742, United
351 States (TC) Institute of Geophysics and Tectonics, School of Earth and Environment, University of Leeds, Leeds, United
352 Kingdom (JW) Department of Earth and Planetary Sciences, University of California, Berkeley, California, 94720, United
353 States; Miller Institute for Basic Research in Science, Berkeley, California, 94720, United States (ES, HD) International Centre
354 for Radio Astronomy Research, Space Science and Technology Centre, Curtin University, Perth, Western Australia, Australia
355 (ES) Space Science and Technology Centre, School of Earth and Planetary Science, Curtin University, Perth, Australia (CS)
356 Observatoire de la Côte d’Azur, Université Côte d’Azur, CNRS, IRD, Géoazur, Valbonne, France (MM) Analytical Mechanics
357 Associates, Inc./NASA Langley Research Center, Hampton, Virginia, 23681, United States (JI) NASA Langley Research
358 Center, Hampton, Virginia, 23681, United States (JL) Sandia National Laboratories, Albuquerque, New Mexico, 87185,
359 United States (MRG) Department of Earth Sciences, Southern Methodist University, Dallas, Texas, 75275, United States
360 (KP) Independent Researcher, Bowie, Maryland, 20715, United States (MF) Sandia National Laboratories, Albuquerque,
361 New Mexico, 87185, United States (CL) Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, United States
362 (OK) Royal Observatory of Belgium, Uccle, Belgium (SB) Independent Researcher, Boulder, Colorado, 80304, United States
363 (DB, FZ) Institute for Advanced Engineering and Space Sciences, University of Southern Queensland, Queensland, Australia
364 (JC) Department of Geological Sciences, University of Alabama, Tuscaloosa, Alabama, 35487, United States (NC) University
365 of Western Ontario, London, Ontario, Canada (LD) School of Geographical and Earth Sciences, University of Glasgow,
366 Glasgow, United Kingdom (AMG) Institute of Space Science and Technology, University of Karachi, Karachi, Pakistan
367 (CTG) Archaeology, Environmental Changes & Geo-Chemistry, Vrije Universiteit Brussel, Brussels, Belgium (H) Laboratory

368 for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, 80303, United States (DCH) United States
369 Department of Defense (KBR Consultant), Las Cruces, New Mexico, 88001, United States (RJ) NASA Ames Research
370 Center, Moffett Field, California, 94035, United States (SNL) Earth, Energy, and Environment Centre, University of Kansas,
371 Lawrence, Kansas, 66045, United States (TR) Atominstitut, Technische Universität Wien, Vienna, Austria (LR) Laboratoire
372 Géoazur - Université de Nice Côte d'Azur (MMT) Department of Geosciences, University of Edinburgh, Edinburgh, Scotland
373 (ART) Institute for Geophysics, University of Texas, Austin, Texas, 78712, United States

374 Figure Legends

375 **Figure 1:** Top panel: the ORX EDL trajectory (side view), from the point of atmospheric interface to landing. Bottom panel:
376 geographical context (top-down view) of the trajectory. We refer to directions towards landing as ‘downrange’ and those
377 towards atmospheric interface as ‘uprange’. The inset panel shows the seismometer array deployment. Note that the long
378 arm of the array is parallel to the expected trajectory (i.e. runs uprange/downrange). The cross arm is perpendicular to the
379 trajectory (i.e. crossrange). The lateral distance between the centre-line of the array and the trajectory footprint on the ground
380 is approximately 2300 m.

381 **Figure 2:** Seismic data recorded by the array. Traces are vertical ground velocity in the 1-100 Hz range and are arranged in
382 **A)** by downrange distance from the westernmost station in the array and in **B)** by crossrange distance from the northernmost
383 station. Station numbers are indicated in red on the left hand side. The weak signal at station 4 is thought to be due to issues
384 with the instrument, which displayed higher noise levels throughout the deployment.

385 **Figure 3:** Data from the central station of the array (Station 1), bandpassed between 1 and 100 Hz. The N-wave is only
386 clearly apparent on the vertical component. **A)** Three-component data, showing the dominance of the signal on the vertical
387 component. **B)** Velocity spectrogram for the vertical component. A small inset is shown for Station 2 (one station uprange
388 from Station 1), to illustrate the variation in peak frequency recorded between different stations. At Station 2, a resonance
389 around 200 Hz is also observed, which could correspond to excitation in a thin playa layer around 1-2 m thick. **C)** Particle
390 motion, with the N wave shown in orange (14:46:04.4 - 14:46:04.8 UTC) and the remainder of the wavetrain in blue.

391 **Figure 4:** Array analysis of the ORX re-entry signal. **(a)** and **(b)** show the results of a beampack through
392 slowness in x and y, taking the maximum amplitude with +/- 50 samples (0.025 seconds) of the absolute max-
393 imum amplitude for the shockwave arrival (at 14:46:04.621 and at a slowness of [-0.209, -0.063]). **(c)** and **(d)**
394 show vespagrams in y and x slowness space, respectively. In each vespagram, the other slowness is fixed at the
395 value giving the absolute maximum amplitude for the shockwave arrival. All plots are normalised to the peak
396 value. **(e)-(g)** show the optimal-slowness beam for vertical, downrange and crossrange components, respectively
397 in the pass band 1 - 100 Hz. All beams are normalised to the peak value of the vertical component beam.

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