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# Cross-referencing astronaut-observed lunar impact flashes with seismic data - lessons from Apollo for Artemis

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**Key Points:**

- During the Apollo 16 and 17 missions three likely impact flashes were observed on the lunar surface from orbit.
- We examined data from the Apollo seismic network to investigate whether any corresponding moonquake signature was detected.
- We identify no candidate matches were found, but nonetheless propose suggestions for Artemis impact flash observations.

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**Abstract**

During their orbits of the Moon in 1972, Apollo astronauts reported three impact flashes on the lunar surface, associated with meteoroids striking the surface and vaporizing. We examined data from the Apollo seismic network to investigate whether these flashes produced detectable moonquakes whose locations and timing could be independently validated. No candidate matches were found, though stream modelling indicates a high probability that both Apollo 17 impacts were associated with the Geminid meteor stream. Our analysis pipeline is likely instructive for coordinating observations made by future Artemis astronauts from orbit with seismic data from upcoming geophysical missions to the lunar surface.

**Plain Language Summary**

When asteroids and meteoroids hit the Moon, they are instantly vaporized. The release of energy during these impacts produces a visible flash of light that can be observed. During the Apollo 16 and 17 missions in 1972, astronauts reported three candidate impact flashes on the lunar surface. These occurred when four seismic stations on the Apollo Seismic Network were recording data on the Moon. Despite the suggestion of Apollo 17 astronaut Jack Schmitt that the timing and location of the impact flashes be cross-referenced against the seismic data, no results of this analysis have ever been published. We examined data from all Apollo Seismic Network stations for all three reported flashes. No potential match is observed. This pipeline for comparing eyewitness observations to seismic data is likely to prove instructive for future observations made by Artemis astronauts following the deployment of seismic sensors on the Moon later this decade.

# 1 Introduction

## 1.1 Impact flashes

When meteoroids strike the surface of the Moon, they produce flashes of light as they are vaporized. These flashes can be observed in either visible or infrared light from the Earth or from space. A great deal of information about small body populations in the Solar System, impact dynamics, and lunar surface properties can be gleaned from observations of these flashes (e.g. Ortiz et al. (2000); Yanagisawa and Kisaichi (2002); Ortiz et al. (2006); Bonanos et al. (2018); Avdellidou and Vaubaillon (2019)). Flashes are most easily detected on the darkened hemisphere of the Moon, where changes in brightness are most apparent; but in theory the brightest flashes should also be visible on the lit hemisphere as well.

There is also significant interest in using meteoroid impacts as natural seismic sources to better understand the lunar interior (G. V. Latham et al., 1970). In sparse or single-station seismic networks, there is normally significant uncertainty associated with determinations of event timing, location, and magnitude (Solomon et al., 1991). Having a source whose position, location, and approximate size can be independently constrained reduces these uncertainties, enabling more reliable inversions for source and structural parameters.

Impact sources made up a significant proportion of the events recorded on the Apollo Seismic Network between 1969 and 1977 (Nakamura et al., 1982) On Mars, NASA's In-Sight spacecraft similarly recorded seismic signatures from a number of impacts over its four-year mission (Garcia et al., 2022; Posiolova et al., 2022; Daubar et al., 2023).

In the coming years, there will be renewed opportunities to characterise impact flashes on the lunar surface. Specifically, NASA's crewed Artemis missions (i.e., Artemis II and beyond) will fly astronauts around, and eventually down to, the Moon (Creech et al.,

**Table 1.**   Reported lunar flash events during Apollo 16 and 17 orbital operations. Coordinates are selenographic, UTC and GET refer to Universal Coordinated Time and mission Ground Elapsed Time respectively.

| Flash | Date | UTC | GET | Earth phase | Observer | Reported location |
|---|---|---|---|---|---|---|
| 1 (A16) | 1972-04-21 | 19:01 | 123:07 | Waxing (60%) | K. Mattingly | Below local horizon |
| 2 (A17) | 1972-12-10 | 21:11 | 090:18:11 | Waxing (20%) | H. Schmitt | Grimaldi/Riccioli (66°W, 5°S) |
| 3 (A17) | 1972-12-11 | 22:28 | 115:36:35 | Waxing (29%) | R. Evans | Mare Orientale (88°W, 20°S) |

2022). Additionally, several independent seismometers will collectively form an informal lunar geophysical network made up of NASA's Lunar Environment Monitoring Station (LEMS, Benna et al. (2020)), Farside Seismic Suite (FSS), South Pole Seismic Suite (SPSS, Panning et al. (2022)), and China's Chang'e 7 (Zou et al., 2020).

### 1.2  Paper aims

During the Apollo program, three impact flashes were reported by astronaut crew members. The first occurred during Apollo 16 in April 1972 (Howard et al., 1972), and the second and third during Apollo 17 in December 1972 (Parker et al., 1973). At that time, it was suggested that the timings and approximate locations of these flashes be cross-referenced to seismic data from the PSE stations, to see if any corresponding moonquakes had been recorded. For reasons unknown, this does not appear to have occurred systematically, either in 1972 or in the years since (as confirmed by co-author YN who worked on the PSE). Thus, in this paper, we examine the lunar seismic records for potential impact signatures associated with the 1972 flashes and investigate the origin of the meteoroids that produced them.

Furthermore, we note that the crewed Artemis II mission (with launch opportunities as early as March 2026) includes a scientific goal of characterizing impact flashes observed by the crew from lunar orbit. Sensing modalities include both human observations and visible-light cameras (attached to the Orion capsule and handheld by the crew). Thus, in this paper we also consider how future observations of impact flashes made from lunar orbits or flybys can be cross-referenced against Earth-based telescopic measurements and lunar seismic data in a timely and illustrative manner.

## 2  Methodology

### 2.1  Impact flash observations

The impact flashes considered in this paper were observed during the Apollo 16 and 17 missions, (Tab. 1). These events, along with a great many more observed from Earth, were collated by Cameron (1978).

It should be noted that these flashes are distinct from the cosmic ray phenomena noted by Apollo astronauts throughout the mission. The discrimination between impact flashes and cosmic ray flashes relies on the interpretation of the Apollo astronauts, who experienced many such cosmic ray flashes and studied them extensively (Wick, 1972).

For Flash 2, a small discrepancy in exact timing (less than 10 minutes) is unavoidable as the Command Module was in a loss-of-signal phase of flight during the observation; hence the note of a flash being seen was relayed to Earth following subsequent acquisition-of-signal. For Flash 3, the reported time is that of the Public Affairs Officer announcing that Evans has 'just seen a flash'.
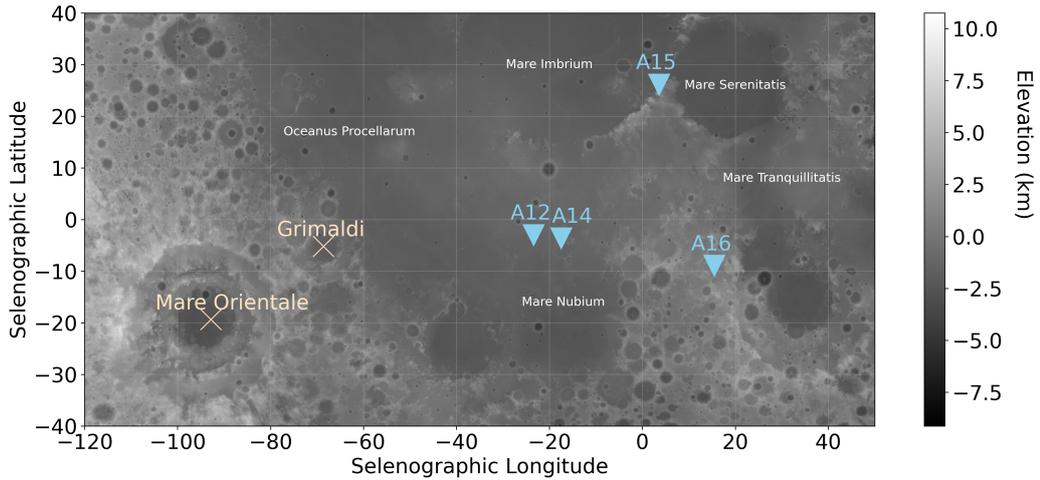
**Figure 1.** Identified impact flash locations from astronaut descriptions: Grimaldi Crater (Flash 2) and Mare Orientale (Flash 3). As Flash 1 occurred below the horizon, no precise location is given. Seismometers are marked with as blue triangles and the nearby major lunar mare are labelled. Apollo 11's PSE station is not shown as it had ceased recording by 1972. The background map in this image is from the Lunar Orbiter Laser Altimeter on the Lunar Reconnaissance Orbiter (Smith et al., 2010).

The locations of these crew-reported events, along with the corresponding seismometers that could have potentially detected them, are shown in Fig. 1.

## 2.2 Seismic Data

In 1972, the stations of the Apollo Passive Seismic Experiment (PSE) deployed by the Apollo 12, 14, and 15 crews remained operational (that of Apollo 11 having failed in 1969). The crew of Apollo 16 deployed one further seismic station in April 1972 whilst that Ken Mattingly (observer of Flash 1) was onboard the orbiting command module. Full details of these deployments can be found in G. Latham et al. (1969) and Nakamura et al. (1982), with a modern review in Nunn et al. (2022).

These stations recorded both artificial impacts, such as spent spacecraft, and natural ones from meteoroids (McGarr et al., 1969). Although the PSE seismometers were operated at a much higher sensitivity than those on Earth, because of the lack of atmosphere and human activities on the Moon, they nonetheless came with certain limitations.

For example, at sunrise and sunset significant temperature variations produced large signals that entirely obscured small tectonic or impact signals. Furthermore, because of the occasional malfunction of data acquisition systems, certain artefacts (e.g. spikes) contaminate the recorded signals. Since the data were digitized on the Moon, signals smaller than the digitizing unit were not recorded. To compensate for the digitizing limitation, a special data processing technique was used to detect very small signals. In this way, signals whose amplitudes are mostly below the digitizing level but occasionally exceed it become visible, but at low signal-to-noise ratios. For further details, see Nakamura et al. (1980).

**Table 2.** Data availability during the times of these three flashes. Note that the PSE stations had three-component long-period sensors (MH) and a single, vertical-component (SH) short-period instrument. In the table below, Z corresponds to the vertical component and 1 and 2 are the two horizontal components.

| Station | Long period | Short period | Notes |
|---------|-------------|--------------|-------|
| S11 | Unavailable | Unavailable | |
| S12 | 12Z | Unavailable | Long period Z poor for Flash 1 |
| S14 | 12 | Unavailable | Extremely noisy throughout |
| S15 | 12Z | Z | |
| S16 | 12Z | Z | Available for Flashes 2&3 only |

Data availability for the PSE stations during the three flashes of interest is given in Table. 2.

### 2.2.1 *Lunar phase angle*

We briefly comment on the preponderance of thermal moonquakes in the data window that we examine. Whilst thermal moonquakes occurred frequently throughout the timeframe of PSE measurements, they were particularly pronounced around sunrise and sunset due to strong heating and cooling.

In parallel to this, a requirement during the Apollo missions was that the landing site needed to be in sunlight during the lunar surface operations phase. Because the PSE instruments were all located on the lunar nearside at near-equatorial latitudes, they experienced sunrise and sunset around the same time of lunar day as the lunar orbit and lunar surface portions of each Apollo mission. As such, at a number of stations the thermal noise and thermal moonquakes were particularly pronounced around the windows where astronauts were making flash observations; and the PSE instruments themselves are more noisy due to frequent calibration and re-levelling needed to compensate for thermal fluctuations. This does not preclude analysis of impact flash phenomena because thermal moonquakes present very differently from impact events in the seismic record (Nakamura et al., 1982), but it is important to note.

Future seismometers such as LEMS and FSS are all targeting the lunar south pole region, which is significant because the average great circle distance to the day-night terminator is much lower at the poles than the equator, meaning that sources of thermal moonquakes will on average be closer to LEMS and FSS than was the case for the PSE. The proximity to the terminator will also need to be accounted for when planning impact flash observations from Earth, as stray light can contaminate measurements on the darkened hemisphere if they are too close to the terminator (Sheward et al., 2024).

## 2.3 Candidate signal identification criteria

We set clear criteria that recorded seismic signals must meet to be considered candidate detections of an impact flash. This is necessary as there are many different sorts of signals recorded by the PSE, including genuine moonquakes, background noise, and instrument artefacts. We consider that potential matches must:

- Occur within the first 10 minutes after the flash occurred, which is long enough for the first-arrival seismic wave to reach a station anywhere on the moon (the max-

| Station | Signals of interest (UTC Time) | Origin(s) |
| --- | --- | --- |
| S11 | N/A | N/A |
| S12 | 19:33 | Bit-swapping (noise at the digitisation level) |
| S14 | 19:27; 20:16 | Instrument levelling, impact moonquake |
| S15* | 19:15; Ongoing | Thermal moonquake; 5 Hz thermal events |
| S16 | N/A | N/A |

**Table 3.**    Summary of signals present in the 60 minute window after Flash 1. Asterisks indicate stations in sunlight.

imum first-arrival travel time in the standard lunar interior model of Weber et al. (2011) model is less than 9 minutes so this estimate is conservative),

- Be distinct from known sources of noise or interference, such as the noise from the activation of the centering motors on the instruments or electronic glitches (spikes) in the data,
- Have distinctly different characteristics (e.g. waveform shape, frequency content) from tectonic or tidal events like shallow or deep moonquakes, and
- Have similar characteristics (e.g. rise time, coda length) to other known impact events, including the more energetic artificial impacts of the Saturn IV-B boosters and other, comparably energetic natural meteoroids.

## 3  Results

In this section, we show data from each flash where seismic signals of potential interest are present. We examined all components of data on each station, but for brevity show only traces of particular interest here. For a complete list of all data for each flash, including a complete catalogue of signals and their timings both before and after the flash, see the Supplement. Data are visualized as both seismograms in their original digital units, and instrument corrected spectrograms constructed using a Stockwell transform to illustrate the frequency content of the signals over time.

### 3.1  Flash 1 (Apollo 16)

Data for Flash 1 are summarised in Tab. 3, for the 60 minutes subsequent to the flash. As noted previously, we expect a seismic first arrival from any candidate impact event within less than 10 minutes, but show a larger window in order to offer more context as to the seismic environment at the time in question.

A synopsis of these data are also shown for one component each of stations S12, S14, and S15 in Fig. 2, with all data shown in the Supplement.

As per Fig. 2, moonquakes were recorded on stations 14 and 15 but not within the timeframe required for a match to the impact flash recorded at 19:01 UTC. A number of different noise sources, including internal instrument noise in **a)** and thermal noise in **c)** are also noted. Station 15 was the only station already in sunlight for this flash, and hence shows both a thermal moonquake and repeating bursts of 3-4 minute codas and other noises around 5 Hz. In summary, there is no candidate seismic signal which matches flash 1.
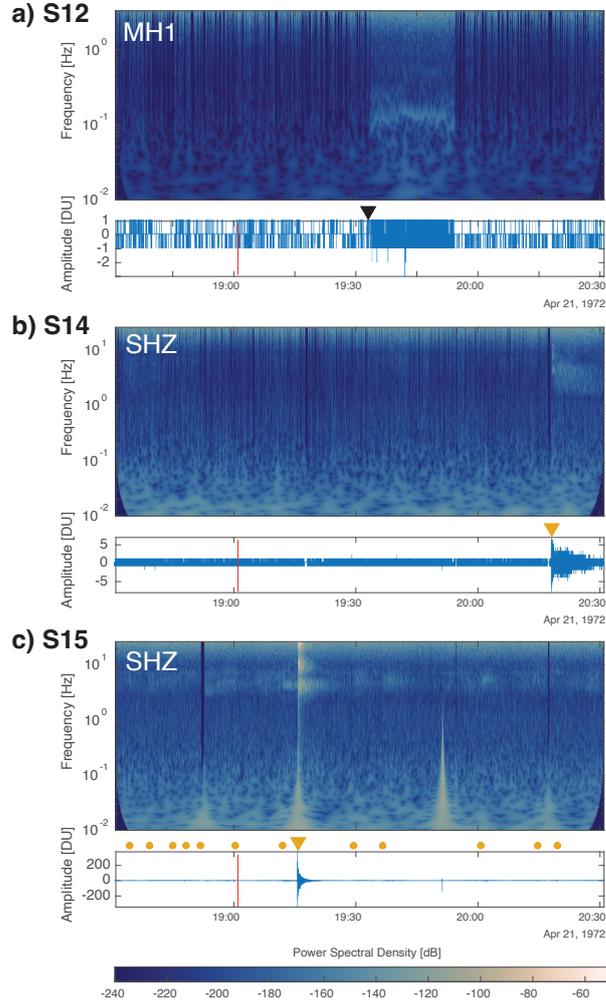
**Figure 2.** Seismic data from 30 minutes prior to Flash 1 (which occurred at 19:01 UTC, red line in seismogram) to 90 minutes afterward. Black triangles denote signals likely to originate within the instrument itself, orange circles denote signals identified as nearby seismic noise (e.g. from thermal fluctuations), and orange triangles denote moonquakes (though none of these are within the time window for an arrival). **a)** - data from component MH1 (horizontal) for station 12, showing the bit-swapping occurring around 19:34 which is internal to the instrument, **b)** - data from the short-period vertical instrument at station 14, with a moonquake that occurs far outside the arrival window, **c)** - data from the short-period vertical instrument at station 15, with a likely thermal moonquake at 19:15 UTC and other repeated bursts of energy around 5 Hz before and after the event.

| Station | Signals of interest (UTC Time) | Origin(s) |
|---------|-------------------------------|-----------|
| S11 | N/A | N/A |
| S12 | Ongoing | S IV-B impact coda |
| S14 | Ongoing | S IV-B impact coda |
| S15 | Ongoing, also 21:42-22:23 | S IV-B impact coda, recurring 5 Hz events |
| S16 | Ongoing, also 21:48 | S IV-B impact coda, thermal moonquake |

**Table 4.**   Summary of signals present in the 60 minute window after Flash 2.

| Station | Signals of interest (UTC Time) | Origin(s) |
|---------|-------------------------------|-----------|
| S11 | N/A | N/A |
| S12 | 22:52 | Gain change |
| S14 | Ongoing; 23:14 | Data drop-outs/glitches; incomplete anomalous noise pulse |
| S15 | 22:38-00:00; 23:26 | Recurrent 5 Hz events; thermal moonquake |
| S16* | 22:55 onward | Sunrise noise and associated instrument levelling |

**Table 5.**   Summary of signals present in the 60 minute window after Flash 3. Asterisks indicate stations in sunlight.

### 3.2  Flash 2 (Apollo 17)

Flash 2, reported to have impacted at Grimaldi crater, occurred less than an hour after the Saturn IV-B upper stage impacted the lunar surface (21:11 UTC versus 20:32 UTC). At this time co-author HJS was observing Grimaldi crater obliquely from the south. The Saturn IV-B impact was intended to be a controlled seismic source has been extensively studied (Nakamura et al., 1982). Its impact was recorded across the entire network, and had a strong coda (a tail of low-amplitude waves on a seismogram) that was several hours in length. Data for this event is summarised in Tab. 4 and shown in Fig. 3 for three stations, with further data shown in the supplement.

The detection of an impact flash signal beneath the Saturn IV-B impact coda was hence unlikely given that the mass of the Saturn IV-B upper stage was several tons, while the mass of a typical lunar impact is on the order of grams. This difference in mass of several orders of magnitude likely places the amplitudes of the meteoroid-generated seismic waves well below those of the Saturn IV-B's coda, despite the natural meteoroid's higher impact velocity.

### 3.3  Flash 3 (Apollo 17)

Flash 3 occurred on the subsequent UTC day (at 22:28) to Flash 2, at which point the coda of the Saturn IV-B impact had finally attenuated away. Data for Flash 3 are summarised in Tab. 5 and shown in Fig. 4; again the data for all available components is shown in the Supplement.

Stations 12, 14, and 16 show no signals of interest in the given time window, and station 15 shows only the repeated 5 Hz events. A moonquake appears on station 15 and then 16 well after the flash. In summary, there are no candidate seismic events matching the timing of Flash 3 either.
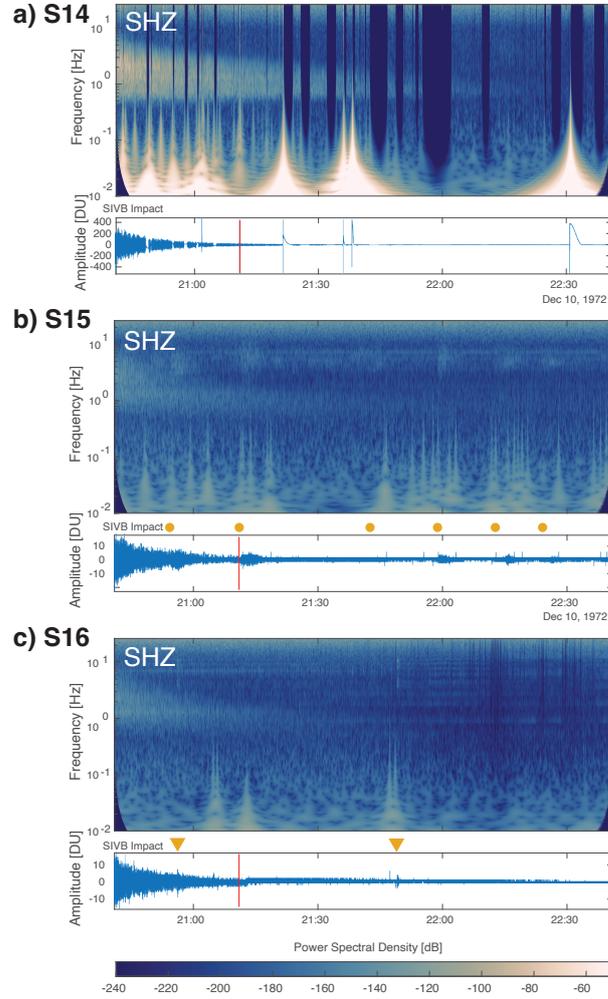
**Figure 3.** Data from 30 minutes prior to Flash 2 (which occurred at 21:11 UTC, red line in seismogram) to 90 minutes afterward for **a)** S15 and **b)** S16. The Saturn IV-B impact occurred at 20:32 UTC and the coda of the event is clearly visible on all stations, and indeed lasts several hours longer than the above traces. Orange triangles mark small increases in amplitude during the coda which may be overlapping moonquakes (on station 16), but none of these are a match in time for the seismic waves from a flash at 21:11 UTC. Station 15 also shows the repeated bursts of instrument noise at around 5 Hz observed during Flash 1.
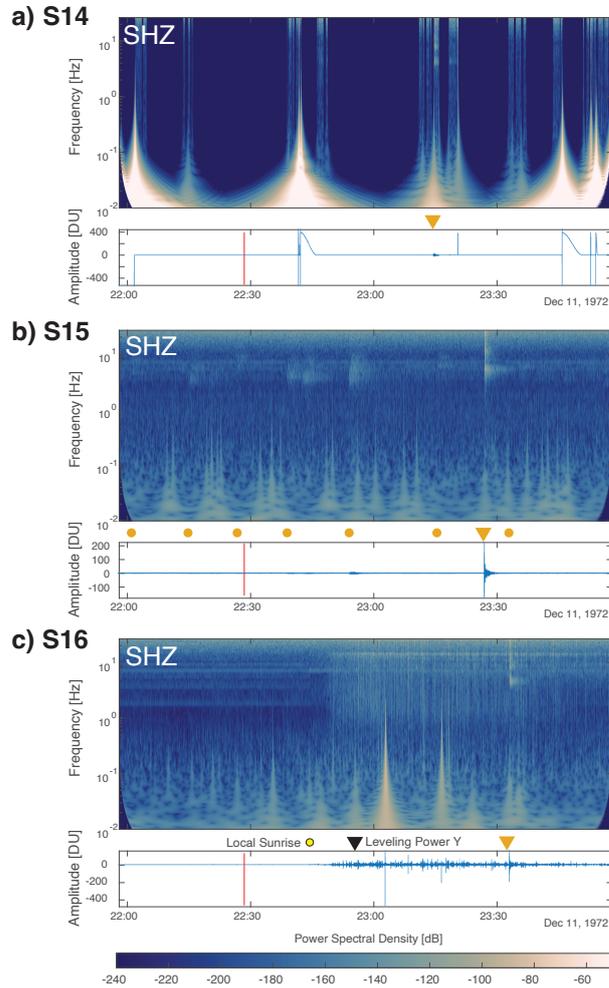
**Figure 4.** Data from the short-period vertical-component instruments for Flash 3 (22:28 UTC, red line in seismograms) for **a)** S14, **b)** S15, and **c)** S16 (no SHZ data is available for S12). S14 shows numerous glitches and other artefacts associated with the internal workings of the sensor and its electronics, a potential moonquake that is both weak and outside our window is marked with an orange triangle. S15 has a thermal moonquake well outside the window at around 23:27 UTC, and the regular 5 Hz events throughout (both before and after the flash), marked with orange circles. A levelling command is indicated with a black triangle for S16 just before 22:55 UTC, at which point the background noise has increased substantially following local sunrise at 22:30 UTC. A thermal moonquake, again well outside the window, is also marked with an orange triangle.

## 4 Discussion

### 4.1 Potential subsequent analysis

We identified no candidate seismic signals for any of our three flashes. Nonetheless, further analysis of these non-detections is still possible. In this section, we outline three possible routes to undertaking further analysis: stream association (which we carry out for these three events), comparison to historical records of 'lunar transient phenomena' in the same geographical area of the Moon (which is only possible in this case for Flash 2), and the use of the seismic noise floor during a non-detection to constrain the momentum of the incoming meteoroid (which we summarise but do not undertake for our events).

#### *4.1.1 Stream Association*

In addition to sporadic background meteors which are randomly distributed in time, meteor activity is known to be higher in the Earth-Moon system during times of intersection with certain debris streams. These streams cause famous showers such as the Geminids and Perseids (Jenniskens, 1994).

To determine the probability that the impact flashes belong to an active meteoroid stream, we use the method based on Madiedo et al. (2015). This method considers the activity of the stream relative to the background sporadic flux, accounting for the geometry at the time of impact (i.e., the position of the flash on the lunar surface). The latter effect is important because flashes from a particular stream are most likely to occur at the point on the surface which is close to the subradiant (i.e. where the radiant is at the zenith).

Under the model of Madiedo et al. (2015), the probability of a meteoroid being associated with a particular stream ST is given by:

$$p^{ST} = \frac{\gamma^{ST} cos(\phi) \sigma ZHR_{Earth}^{ST}(max) 10^{-b(\lambda - \lambda_{max})}}{\gamma^{SPO} HR_{Earth}^{SPO} + \gamma^{ST} cos(\phi) \sigma ZHR_{Earth}^{ST}(max) 10^{-b(\lambda - \lambda_{max})}} \tag{1}$$

Where 'ST' stands for stream meteoroids and 'SPO' for Sporadics. 'ZHR' is the Zenithal Hourly Rate (the rate of meteor flashes that would be seen by an observer under perfect conditions who had the radiant of the meteor shower directly overhead), and 'HR' the Hourly Rate of sporadic meteors. $\lambda$ is the solar longitude at the given epoch, $\lambda_{max}$ the solar longitude at the time of maximum meteoroid activity. $\gamma$ is a focussing factor which describes how the gravitational effects of the Earth and the Moon (the latter having weaker gravity) change the number of incident meteors.

We used activity profiles as described by Jenniskens (1994) to determine the activity of a meteoroid stream during recorded impact flash times. This model parameterises the meteoroid stream activity by logarithmic slope parameters as a function of solar longitude (i.e., date). For the Apollo 16 flash, reported on 21 Apr 1972, no major meteoroid stream was active. The impact flash was hence almost certainly caused by a sporadic meteoroid.

For the Apollo 17 flashes reported on 10 and 11 Dec 1972, the Geminid meteoroid stream was active, and we find a high probability of these meteors being associated with the Geminid stream.

In the future, combined impact flash and seismic measurements during times of stream activity are most likely to produce matching events, i.e. those which are detected both visually and seismically. The procedure outlined here can hence be used to study the dynamics of these streams through multiple sensing modalities, and potentially the prop-

erties of their parent bodies as well. Furthermore, where activity from a particular stream was recorded seismically in the Apollo era, this procedure will enable determination of how the stream has evolved (or not) over the time since Apollo (Madiedo et al., 2015).

### 4.1.2 Historical lunar transient phenomena

For completeness, we also examined the records of Cameron (1978) to search for Lunar Transient Phenomena (LTPs) in Grimaldi Crater. Note that similar analyses are not possible for Flash 1 (for which we do not have an exact location as it was below Mattingly's local horizon) or Flash 3 (reported in Mare Orientale, which is almost invisible as seen from the Earth and was only recognised as a distinct lunar area around 100 years ago).

LTPs are reported changes in the Moon's appearance in a certain area at a certain time, and could potentially be caused by a variety of phenomena including impact processes (Srnka, 1977; Freeman & Benson, 1977). Whilst this review does not have a direct bearing on our analysis as conducted in this paper, it nonetheless offers useful context.

Cameron (1978) lists 1,468 LTP of which 23 pertain to Grimaldi crater (including one entry corresponding to Flash 2 reported by HJS). This appears to be a disproportionately large number for a single crater. Of these, approximately half refer to 'brightening', 'streaks', or 'flashes'. Most of the remainder refer to 'smoke' or various colours. If the clustering of LTPs in Grimaldi can be relied upon (i.e. is not spurious or the result of confirmation bias), we consider that there are two possibilities.

Firstly, it is possible that some other non-impact phenomena is occurring in the crater which routinely produces a noticeable brightening, and is local to said crater. Outgassing events have been proposed as one plausible mechanism (Crotts, 2008; Nardini, 2022), but there is little direct evidence for this hypothesis.

Another possibility is that there is some local geology within the crater which makes flashes especially noticeable (e.g. hard bedrock which converts a larger percentage of the incoming kinetic energy to light). This is the only plausible reason that flashes are more common in a certain area, as impacts on the lunar surface are expected to be randomly distributed. We see no indication from geological maps that there is anything unusual about Grimaldi which would cause this, so do not consider it a particularly likely explanation. Nonetheless, a preponderance of LTPs have been recorded in Grimaldi going back to at least the year 1789, which future flash and seismic observations will be able to investigate.

### 4.1.3 Non-detections

In theory, the non-detection of the seismic signals on most stations could be used to estimate the maximum momentum of the incoming meteoroid. This procedure would involve using the seismic noise floor as the upper bound on the amplitude of the impact-generated seismic waves, and accounting for the effects of attenuation (intrinsic, scattering, and geometric) to place an upper bound on the momentum of the incoming meteoroid. Such a procedure has been carried out on Mars as part of NASA's InSight mission and enabled the placement of an upper bound on the seismic efficiency (the ratio of impactor kinetic energy to seismic energy) for an artificial impact (Fernando et al., 2022).

Undertaking such a process would require full-waveform modelling to account for energy loss during the propagation of seismic waves and is non-unique (due to a strong dependence on impact angle and impact azimuth as well as other bulk lunar seismic properties). Furthermore, given that there are many positively identified meteoroid impacts

in the PSE catalogue, the additional insight offered by this analysis would be slight, and hence we do not undertake it here. Nonetheless, further details about these pipeline for such measurements setups may be found in Fernando, Wójcicka, Froment, et al. (2021) and Fernando, Wójcicka, Han, et al. (2021). Combined constraints derived e

### 4.2 Lessons learned for Artemis and beyond

#### 4.2.1 Timing associations

Although not necessary for the Apollo flashes (as there were no candidates within 10 minutes of the flash report), seismic modelling can be used as evidence of an association between a flash and a recorded seismic signal. This is highly likely to be relevant for Artemis III and beyond, where flash observations will occur whilst seismometers are active on the surface.

The simplest way to do this is via ray-based modelling, for example via the TauP method Crotwell et al. (1999) and the standard lunar interior model of Weber et al. (2011). Ray-based modelling tracks the propagation of seismic wavefronts through the lunar interior and yields predicted travel times for a given combination of source-receiver distance and source depth (which in this case is zero). A genuine seismic detection of an impact flash would hence be expected to have a travel time from the reported location to the receiving station which matches that predicted by modelling.

Should a match in arrival times be found, more detailed waveform modelling can be used to inform source or structural inversions or compare waveform shapes, with the effects of topography and scattering accounted for. Such functionality for lunar impacts in this context has already been demonstrated (Nunn et al., 2024; Fernando et al., 2024).

#### 4.2.2 Observation suggestions

Based on the above discussion and the experience of co-author HJS in observing Flash 2 whilst orbiting the Moon on Apollo 17, we make the following suggestions:

- **Planning**: For the astronauts to have the maximum probability of observing a flash, their eyes should be dark-adapted (e.g. from wearing a blackout mask for a few minutes beforehand), with stray light inside the spacecraft minimised. A high-quality map (ideally printed) appropriately orientated to the spacecraft's trajectory would also improve location accuracy.
- **Control**: As a control, astronauts should repeat the Apollo experiment wherein the rate and character of cosmic ray flashes (caused by energetic particles striking an astronaut's retina) during times when the spacecraft is dark (or whilst masked) is recorded (Osborne et al., 1975). This comparison will aid in discrimination of impact flashes from cosmic ray phenomena in the event that the purported flash is not recorded by other observers or on spacecraft video.
- **Coordination**: Coordination of multiple viewing modalities will help to localise the timing, location, and approximate magnitude of flashes and enable false positives (e.g. those caused by cosmic rays striking an astronaut's cornea) to be discounted. Ground-based observations may include world-wide networks of amateurs and/or professionals, overcoming limitations to do with weather or local daylight. However, this coordination is only possible when astronaut-based observation campaigns focus on the lunar nearside. Following the launch of ESA's LUMIO flash observer mission (Cervone et al., 2022), triangulation of impact locations from multiple spacecraft will improve localisation accuracy without restriction to the nearside.
- **Timing**: During meteor showers whose sub-radiant point is on the darkened hemisphere of the lunar surface, the flash observation rate is expected to be maximised.

Coordination of observation campaigns around these times is hence most likely to prove fruitful.

- **Follow-up imaging**: Following detection of a flash, imaging campaigns undertaken by spacecraft in lunar orbit (e.g. NASA's Lunar Reconnaissance Orbiter) may be able to identify fresh craters (Robinson et al., 2015). Such an identification would dramatically improve the localisation accuracy of the flash. Because it is much more challenging to determine that a given crater on the Moon is new than it is on Mars (due to the lack of atmospheric weathering), this will likely rely on either before-after image pairs to identify a fresh crater, or evidence of dynamic mass movement (e.g. dust lofting) in the hours to days after the impact. Follow-on observations should prioritise targets that have a brighter flash magnitude as identification of fresh craters and detectable post-impact crater modification will be easier to identify for larger craters.

- **Prompt notification**: Due to data transmission limitations, future lunar seismic missions may store higher sample rate data onboard for a given period of time, downlinking only lower sample-rate data in the first instance. Prompt notification of a flash occurrence will maximise the likelihood of higher-rate data still being available for download.

## 5 Conclusions

Coordinated impact flash observations from the Earth's surface and lunar flyby/orbit will enable more detailed information about the timing, location, and dynamics of flashes to be obtained than is possible from either method alone. We analysed three flashes observed by the Apollo astronauts, none of which appear to have been detected on seismic instruments. Nonetheless, we consider that this analysis pipeline will prove instructive flash observations made by Artemis astronauts, and beyond.

When combined with seismic measurements made from the lunar surface, flash observations can be used to directly reduce the uncertainty associated with both source and structural inversions. This will be relevant for Artemis III onwards. As such, our proposed joint observation campaigns will enable us to both develop more accurate models of the lunar interior and to better constrain the impact flux and hence associated impact hazard on the lunar surface.

## Conflict of Interest declaration

The authors declare no conflicts of interest.

## 6 Data availability

Data from the Apollo Passive Seismic Experiments are available via the Earthscope Data Center (IRISDMC) under network code **XA**. See also G. V. Latham et al. (1970); Nunn et al. (2022). The map in this paper was produced using data from the Lunar Orbiter Laser Altimeter onboard NASA's Lunar Reconnaissance Orbiter (Smith et al., 2010) and Matplotlib's plotting routines (Hunter, 2007).

Transcripts of the Apollo 17 mission for timestamping purposes are available via the Apollo in Real Time website `https://apolloinrealtime.org` with further interpretative details in the mission Preliminary Science Report (?, ?).

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## References

Avdellidou, C., & Vaubaillon, J. (2019). Temperatures of lunar impact flashes: Mass and size distribution of small impactors hitting the Moon. *Monthly Notices of the Royal Astronomical Society*, *484*(4), 5212–5222.

Benna, M., Schmerr, N., Sarantos, M., Bailey, H., Gershman, D., Horanyi, M., . . . Szalay, J. (2020). *The lunar environment monitoring station (LEMS)]* (Tech. Rep.). Copernicus Meetings.

Bonanos, A., Avdellidou, C., Liakos, A., Xilouris, E., Dapergolas, A., Koschny, D., . . . others (2018). NELIOTA: First temperature measurement of lunar impact flashes. *Astronomy & Astrophysics*, *612*, A76.

Cameron, W. S. (1978). *Lunar transient phenomena catalog* (Tech. Rep.). NASA.

Cervone, A., Topputo, F., Speretta, S., Menicucci, A., Turan, E., Di Lizia, P., . . . others (2022). LUMIO: A CubeSat for observing and characterizing micrometeoroid impacts on the lunar far side. *Acta Astronautica*, *195*, 309–317.

Creech, S., Guidi, J., & Elburn, D. (2022). Artemis: an overview of nasa's activities to return humans to the moon. In *2022 ieee aerospace conference (aero)* (pp. 1–7).

Crotts, A. P. (2008). Lunar outgassing, transient phenomena, and the return to the moon. i. existing data. *The Astrophysical Journal*, *687*(1), 692.

Crotwell, H. P., Owens, T. J., Ritsema, J., et al. (1999). The taup toolkit: Flexible seismic travel-time and ray-path utilities. *Seismological Research Letters*, *70*, 154–160.

Daubar, I. J., Fernando, B. A., Garcia, R. F., Grindrod, P. M., Zenhäusern, G., Wójcicka, N., . . . others (2023). Two seismic events from InSight confirmed as new impacts on Mars. *The Planetary Science Journal*, *4*(9), 175.

Fernando, B., Wójcicka, N., Froment, M., Maguire, R., Stähler, S. C., Rolland, L., . . . others (2021). Listening for the landing: Seismic detections of Perseverance's arrival at Mars with InSight. *Earth and Space Science*, *8*(4), e2020EA001585.

Fernando, B., Wójcicka, N., Han, Z., Stott, A., Ceylan, S., Charalambous, C., . . . others (2021). Questions to heaven. *Astronomy & Geophysics*, *62*(6), 6–22.

Fernando, B., Wójcicka, N., Maguire, R., Stähler, S. C., Stott, A. E., Ceylan, S., . . . others (2022). Seismic constraints from a Mars impact experiment using InSight and Perseverance. *Nature Astronomy*, *6*(1), 59–64.

Fernando, B., Wolf, J., Leng, K., Nissen-Meyer, T., Eaton, W., Styczinski, M., . . . others (2024). Axisem3d-an introduction to using the code and its applications. *EarthArXiv*.

Freeman, J., & Benson, J. (1977). A search for gaseous emissions from the moon. *Physics of the Earth and Planetary Interiors*, *14*(3), 276–281.

Garcia, R. F., Daubar, I. J., Beucler, É., Posiolova, L. V., Collins, G. S., Lognonné, P., . . . others (2022). Newly formed craters on Mars located using seismic and acoustic wave data from InSight. *Nature Geoscience*, *15*(10), 774–780.

Howard, K. A., Wilshire, H. G., Carr, M. H., Elston, D. P., & Milton, D. J. (Eds.). (1972). *Apollo 16 preliminary science report* (No. SP-315). Washington, DC: National Aeronautics and Space Administration. (Prepared by the Apollo 16 Preliminary Science Report Team)

Hunter, J. D. (2007). Matplotlib: A 2d graphics environment. *Computing in Science & Engineering*, *9*(3), 90–95. doi: 10.1109/MCSE.2007.55

Jenniskens, P. (1994, July). Meteor stream activity I. the annual streams. *Astronomy & Astrophysics*, *287*, 990–1013.

Latham, G., Ewing, M., Press, F., & Sutton, G. (1969). The Apollo Passive Seismic Experiment: The first lunar seismic experiment is described. *Science*, *165*(3890), 241–250.

Latham, G. V., Ewing, M., Press, F., Sutton, G., Dorman, J., Nakamura, Y., ... Duennebier, F. (1970). Passive seismic experiment. *Science*, *167*(3918), 455–457.

Madiedo, J. M., Ortiz, J. L., Organero, F., Ana-Hernández, L., Fonseca, F., Morales, N., & Cabrera-Caño, J. (2015). Analysis of Moon impact flashes detected during the 2012 and 2013 Perseids. *Astronomy & Astrophysics*, *577*, A118. (Introduces a statistical criterion (probability parameter) to associate lunar impact flashes with a meteoroid stream versus sporadic background.) doi: 10.1051/0004-6361/201525656

McGarr, A., Latham, G. V., & Gault, D. E. (1969). Meteoroid impacts as sources of seismicity on the Moon. *Journal of Geophysical Research*, *74*(25), 5981–5994.

Nakamura, Y., Latham, G. V., & Dorman, H. J. (1980). How we processed Apollo lunar seismic data. *Physics of the Earth and Planetary Interiors*, *21*(2-3), 218–224.

Nakamura, Y., Latham, G. V., & Dorman, H. J. (1982). Apollo lunar seismic experiment—final summary. *Journal of Geophysical Research: Solid Earth*, *87*(S01), A117–A123.

Nardini, C. (2022). *Transient lunar phenomena, outgassing events, and the lunar gravity field: Impacts to sustained human presence on the moon a master's thesis submitted to the faculty of* (Unpublished doctoral dissertation). Doctoral dissertation, American Public University System.

Nunn, C., Fernando, B. A., & Panning, M. P. (2024). Artificial impacts on the moon: Modeling 3d seismic propagation effects with axisem3d. *The Planetary Science Journal*, *5*(11), 246.

Nunn, C., Nakamura, Y., Kedar, S., & Panning, M. P. (2022). A new archive of apollo's lunar seismic data. *The Planetary Science Journal*, *3*(9), 219.

Ortiz, J., Aceituno, F., Quesada, J., Aceituno, J., Fernández, M., Santos-Sanz, P., ... others (2006). Detection of sporadic impact flashes on the Moon: Implications for the luminous efficiency of hypervelocity impacts and derived terrestrial impact rates. *Icarus*, *184*(2), 319–326.

Ortiz, J., Sada, P., Bellot Rubio, L., Aceituno, F., Aceituno, J., Gutierrez, P., & Thiele, U. (2000). Optical detection of meteoroidal impacts on the Moon. *Nature*, *405*(6789), 921–923.

Osborne, W. Z., Pinsky, L. S., & Bailey, J. V. (1975). Apollo light flash investigations. *Biomedical results of Apollo*, *368*, 355.

Panning, M., Kedar, S., Bowles, N., Calcutt, S., Drilleau, M., Garcia, R., ... others (2022). *Farside Seismic Suite (FSS): first-ever seismology on the farside of the moon and a model for long-lived lunar science* (Tech. Rep.). Copernicus Meetings.

Parker, R. A., et al. (Eds.). (1973). *Apollo 17 preliminary science report* (No. SP-330). Washington, DC: National Aeronautics and Space Administration. (Prepared by the Apollo 17 Preliminary Science Report Team)

Posiolova, L., Lognonné, P., Banerdt, W. B., Clinton, J., Collins, G. S., Kawamura, T., ... others (2022). Largest recent impact craters on Mars: Orbital imaging and surface seismic co-investigation. *Science*, *378*(6618), 412–417.

Robinson, M. S., Boyd, A. K., Denevi, B. W., Lawrence, S. J., McEwen, A. S., Moser, D. E., ... others (2015). New crater on the moon and a swarm of secondaries. *Icarus*, *252*, 229–235.

Sheward, D., Delbo, M., Avdellidou, C., Cook, A., Lognonné, P., Munaibari, E., . . . Tanga, P. (2024). Extending lunar impact flash observations into the daytime with short-wave infrared. *Monthly Notices of the Royal Astronomical Society*, *529*(4), 3828–3837.

Smith, D. E., Zuber, M. T., Jackson, G. B., Cavanaugh, J. F., Neumann, G. A., Riris, H., . . . others (2010). The lunar orbiter laser altimeter investigation on the Lunar Reconnaissance Orbiter mission. *Space science reviews*, *150*(1), 209–241.

Solomon, S. C., Anderson, D. L., Banerdt, W. B., Butler, R. G., Davis, P. M., Duennebier, F. K., . . . Phillips, R. J. (1991). *Scientific rationale and requirements for a global seismic network on mars* (Tech. Rep.). NASA.

Srnka, L. (1977). Critical velocity phenomena and the ltp. *Physics of the Earth and Planetary Interiors*, *14*(3), 321–329.

Weber, R. C., Lin, P.-Y., Garnero, E. J., Williams, Q., & Lognonné, P. (2011). Seismic detection of the lunar core. *science*, *331*(6015), 309–312.

Wick, G. L. (1972). Cosmic rays: Detection with the eye. *Science*, *175*(4022), 615–616.

Yanagisawa, M., & Kisaichi, N. (2002). Lightcurves of 1999 Leonid impact flashes on the Moon. *Icarus*, *159*(1), 31–38.

Zou, Y., Liu, Y., & Jia, Y. (2020). Overview of China's upcoming Chang'E series and the scientific objectives and payloads for Chang'E 7 mission. In *51st annual lunar and planetary science conference* (p. 1755).

# Supplement to: Cross-referencing astronaut-observed lunar impact flashes with seismic data - lessons from Apollo for Artemis

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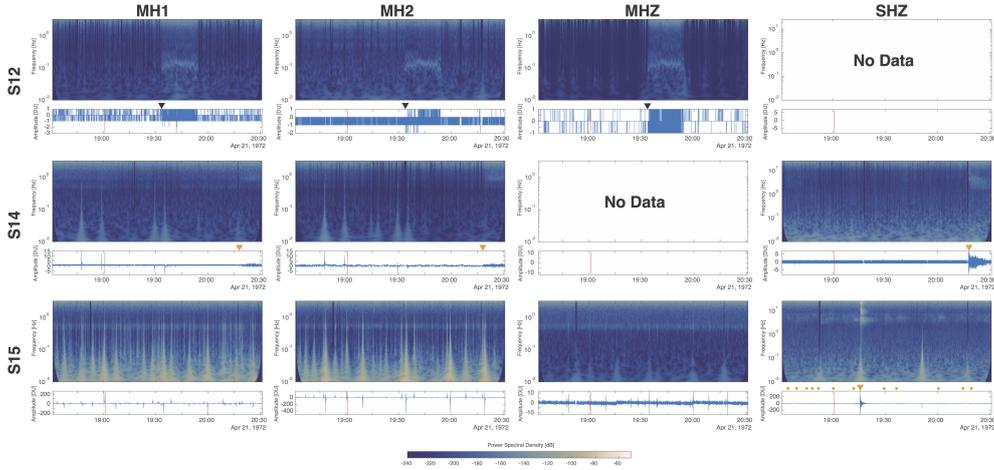Corresponding author: Benjamin Fernando, `bfernan9@jh.edu`

**Figure S1.** All available data for Flash 1, for stations S12-S15.

**Contents**:

- Figs. S1-S3, showing all seismic data available for each impact flash.
- Fig. S4, showing the TauP path for Flash 3 to Station A16, where a candidate signal is recorded.

**Figs S1-S3**

Each row in the figures below corresponds to the data available from one of the Apollo PSE stations. In turn, columns show (from left to right) the two long-period horizontals, the long-period vertical, and short-period vertical components. In each panel, a spectrogram is shown above the corresponding seismogram. The red line indicates the time of the impact flash.

**Fig. S4**

Fig. S4 shows the TauP paths for the P-waves at station S16 from a source located in Mare Orientale. Multiple paths (triplications) are apparent due to the internal velocity structure of the Moon in this model (Weber et al, 2011).

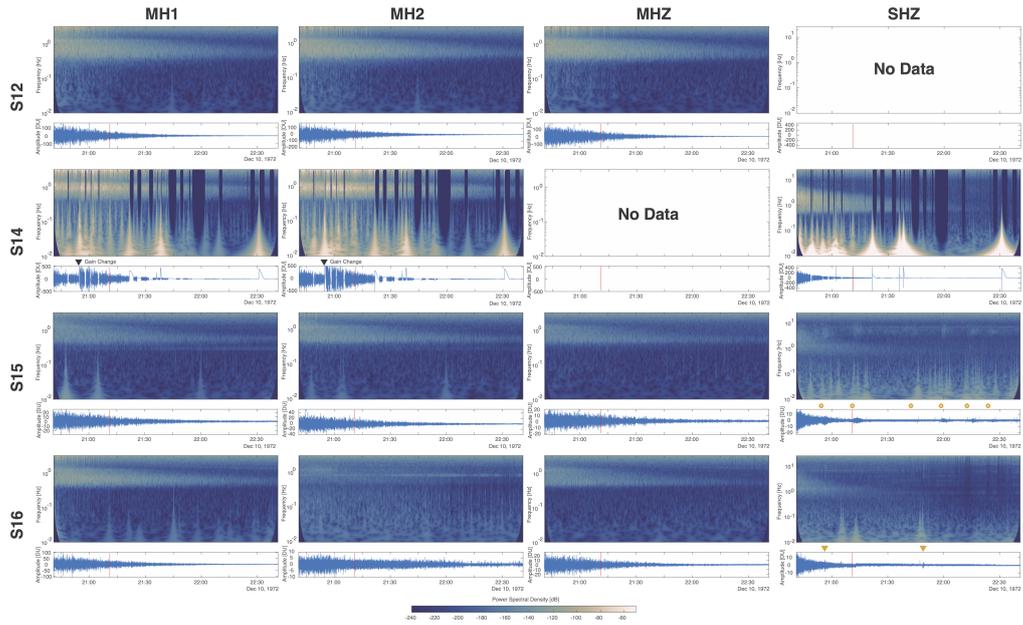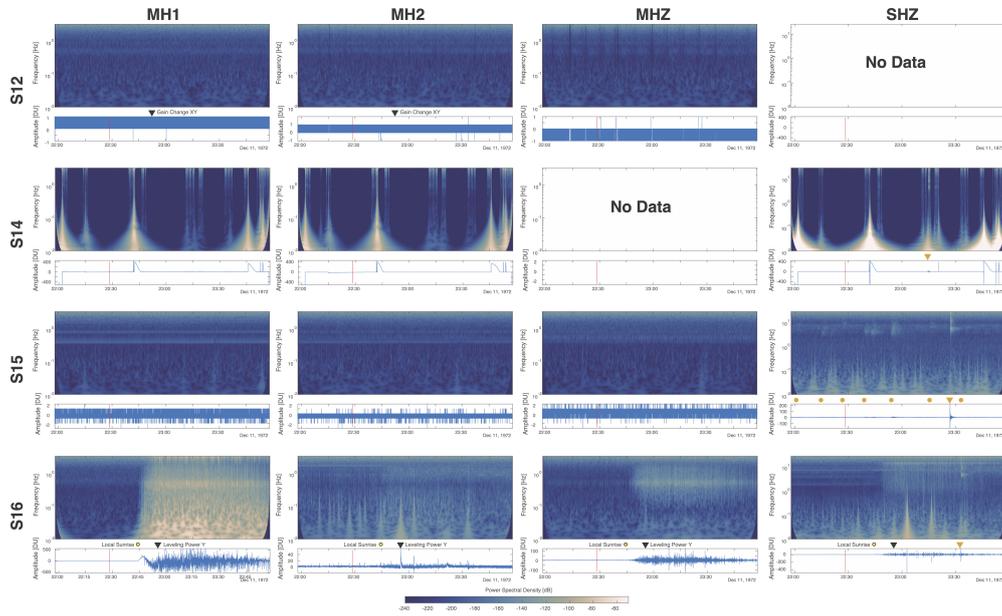**Figure S2.** All available data for Flash 2, for stations S12-S16.



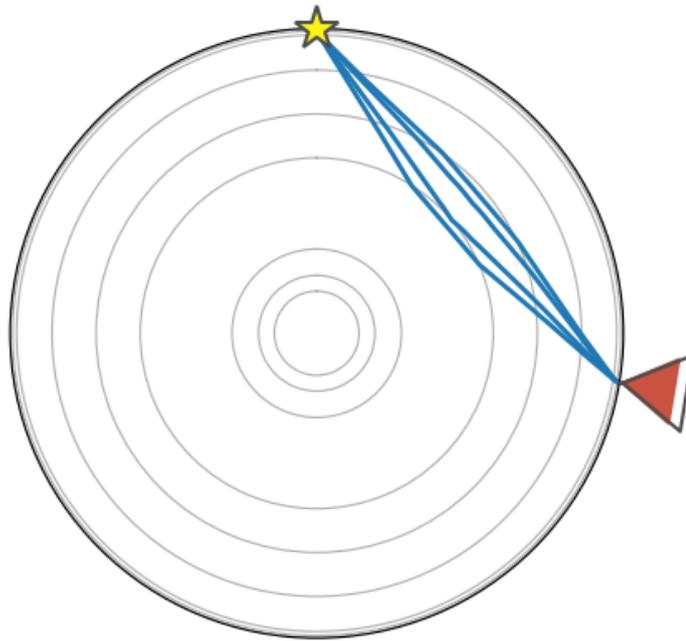**Figure S3.** All available data for Flash 2, for stations S12-S16.

**Figure S4.** TauP paths for Flash 3, with triplications apparent. As is appropriate for an impact source, a depth of 0 is assumed.