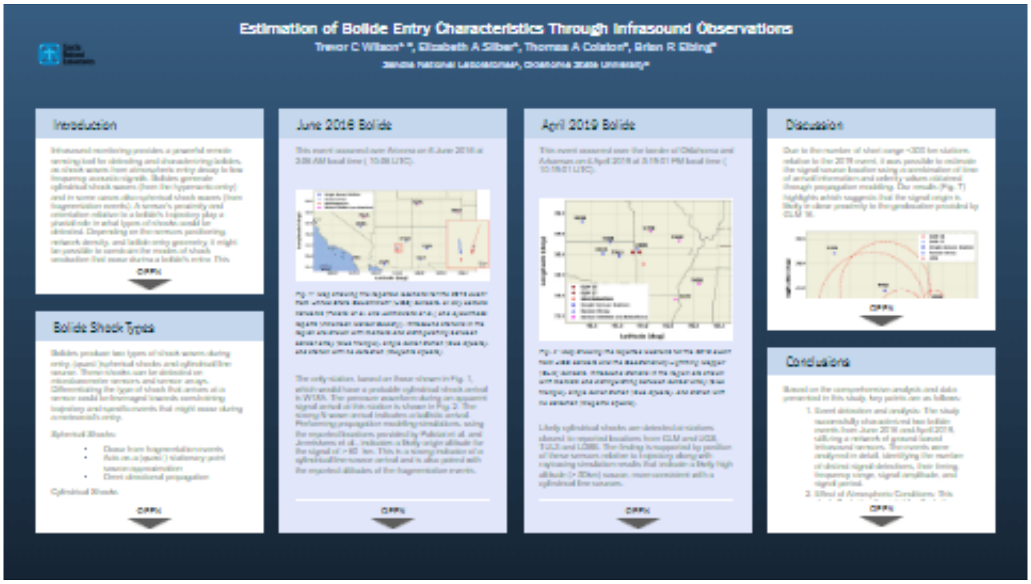
Estimation of Bolide Entry Characteristics Through Infrasound Observations



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INTRODUCTION

Infrasound monitoring provides a powerful remote sensing tool for detecting and characterizing bolides, as shock waves from atmospheric entry decay to low frequency acoustic signals. Bolides generate cylindrical shock waves (from the hypersonic entry) and in some cases also spherical shock waves (from fragmentation events). A sensor's proximity and orientation relative to a bolide’s trajectory play a pivotal role in what types of shocks could be detected. Depending on the sensors positioning, network density, and bolide entry geometry, it might be possible to constrain the modes of shock production that occur during a bolide’s entry. This study focuses on two bolides, a June 2016 event over Arizona and an April 2019 event over Arkansas. Arriving waveforms were analyzed and used to compliment other sensing modalities in helping to constrain the entry trajectory along with other entry characteristics.

BOLIDE SHOCK TYPES

Bolides produce two types of shock waves during entry, (quasi-)spherical shocks and cylindrical line source. These shocks can be detected on microbarometer sensors and sensor arrays. Differentiating the type of shock that arrives at a sensor could be leveraged towards constraining trajectory and specific events that might occur during a meteoroid's entry.

Spherical Shocks:

- Occur from fragmentation events
- Acts as a (quasi-) stationary point source approximation
- Omni-directional propagation

Cylindrical Shocks

- Produced from hypersonic passage through atmosphere (M>25)
- Can be approximated as cylindrical line source
- Shocks propagate perpendicular to trajectory

JUNE 2016 BOLIDE

This event occurred over Arizona on 6 June 2016 at 3:56 AM local time (10:56 UTC).

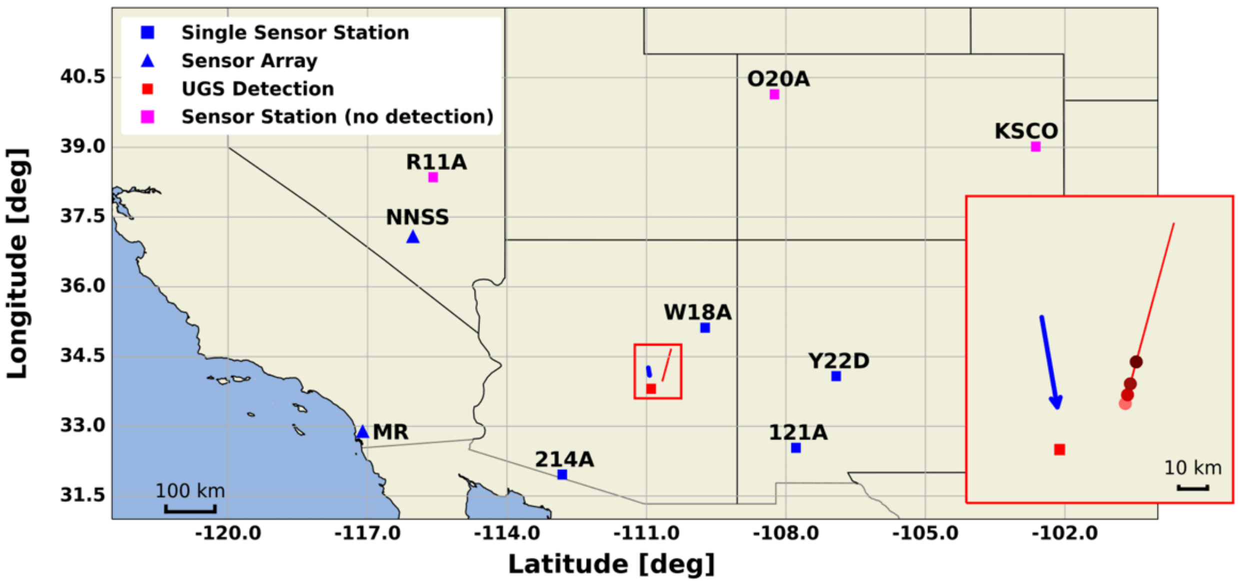

Fig. 1: Map showing the reported locations for the 2016 event from United State Government (UGS) sensors, all sky camera networks (Palotai et al. and Jenniskens et al.) and eyewitness reports (American Meteor Society). Infrasound stations in the region are shown with markers and distinguishing between sensor array (blue triangle), single senor station (blue square), and station with no detection (magenta square).

The only station, based on those shown in Fig. 1, which would have a probable cylindrical shock arrival is W18A. The pressure waveform during an apparent signal arrival at this station is shown in Fig. 2. The strong N-wave arrival indicates a ballistic arrival. Performing propagation modeling simulations, using the reported locations provided by Palotai et al. and Jenniskens et al., indicates a likely origin altitude for the signal of > 60 km. This is a strong indicator of a cylindrical line source arrival and is also paired with the reported altitudes of the fragmentation events.

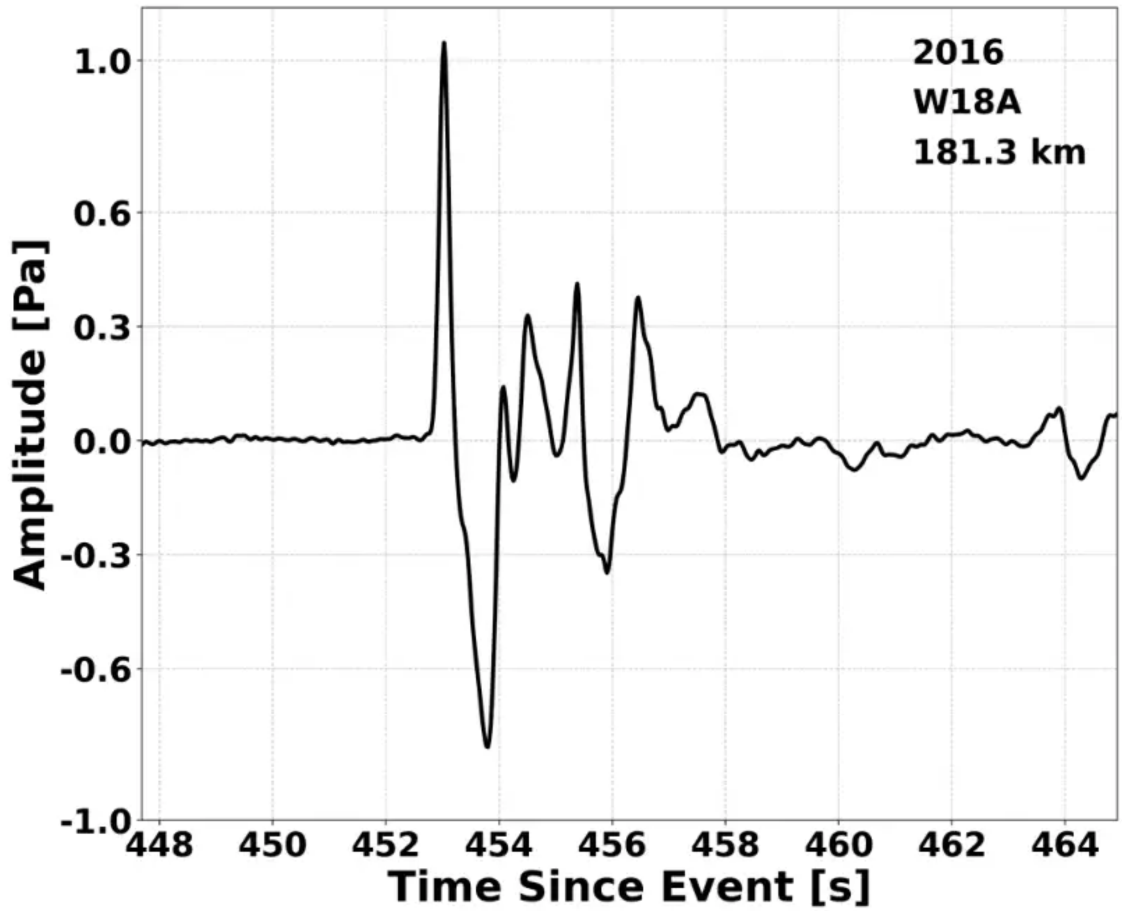

Fig. 2: Single sensor station W18A pressure time trace during presumed arrival of a cylindrical shock from the meteoroid entry.

Spherical shocks are recorded at many other stations up to 600 km. The figure below shows a wavelet scalogram that highlights distinct arrivals from the fragmentation events. The time separated arrivals are likely caused by multi-pathing in the atmopshere rather than originating from different parts of the trajectory. This is due to the minimal time delay induced along the trajectory by such a fast moving object, over a relatively small distance ~10 km, when compared to event-sensor distance 600 km.

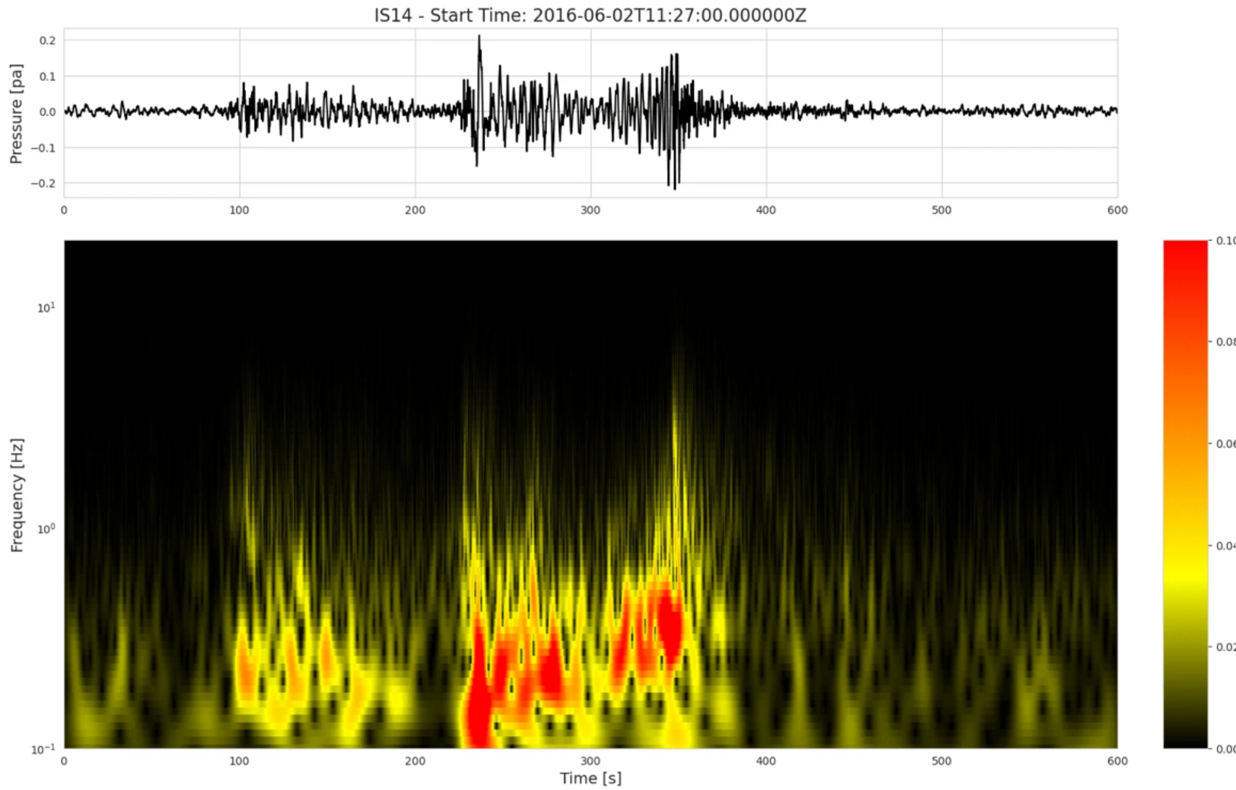

Fig. 3: The top panel depicts the best beam of station IS1 located at the Nevada National Security Site. The bottom panel includes the morlet wavelet scalogram showing the frequency content of the arriving waveform.

APRIL 2019 BOLIDE

This event occurred over the border of Oklahoma and Arkansas on 4 April 2019 at 5:19:01 PM local time (10:19:01 UTC).

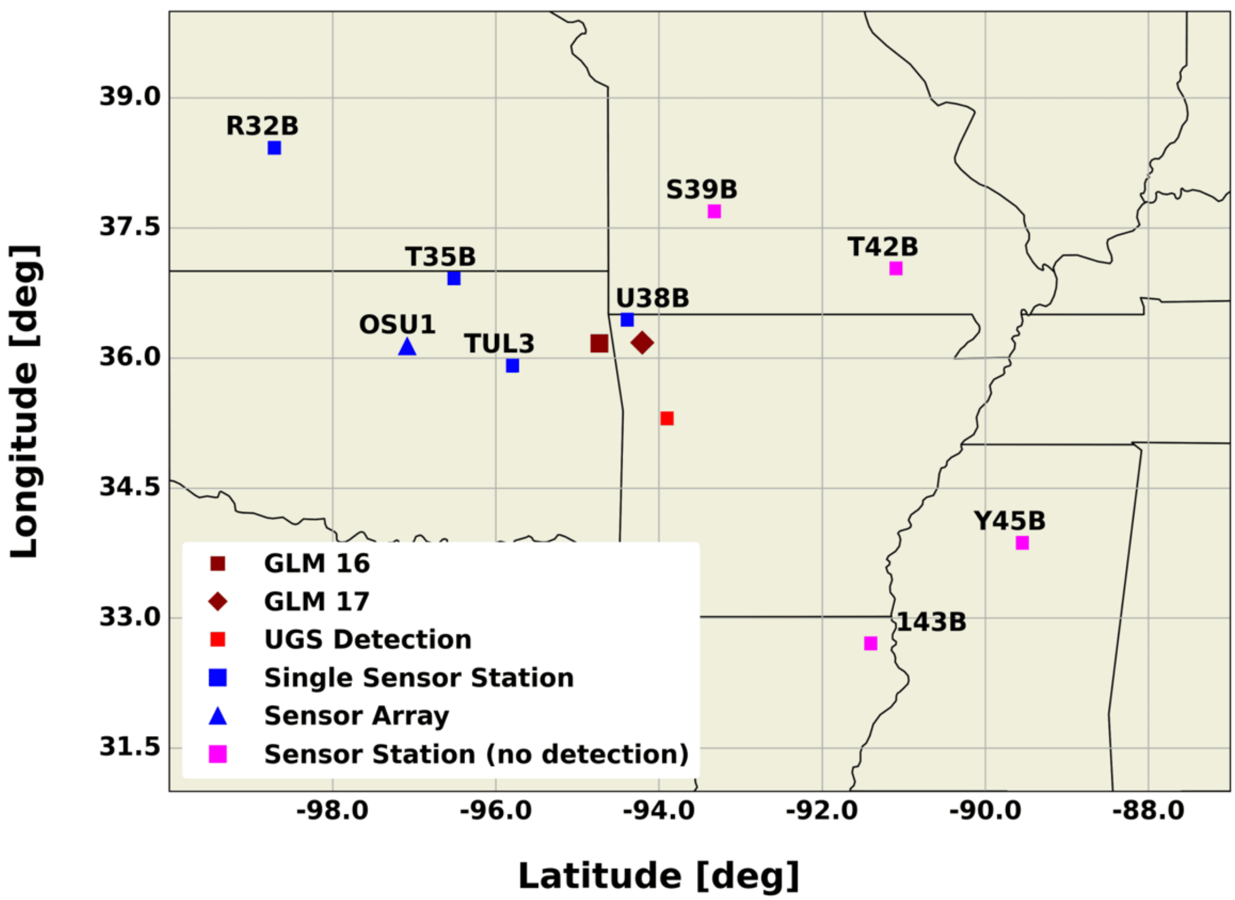

Fig. 4: Map showing the reported locations for the 2019 event from UGS sensors and the Geostationary Lightning Mapper (GLM) sensors. Infrasound stations in the region are shown with markers and distinguishing between sensor array (blue triangle), single senor station (blue square), and station with no detection (magenta square).

Likely cylindrical shocks are detected at stations closest to reported locations from GLM and UGS, TUL3 and U38B. The finding is supported by position of these sensors relative to trajectory along with raytracing simulation results that indicate a likely high altitude (> 50km) source, more consistent with a cylindrical line sources.

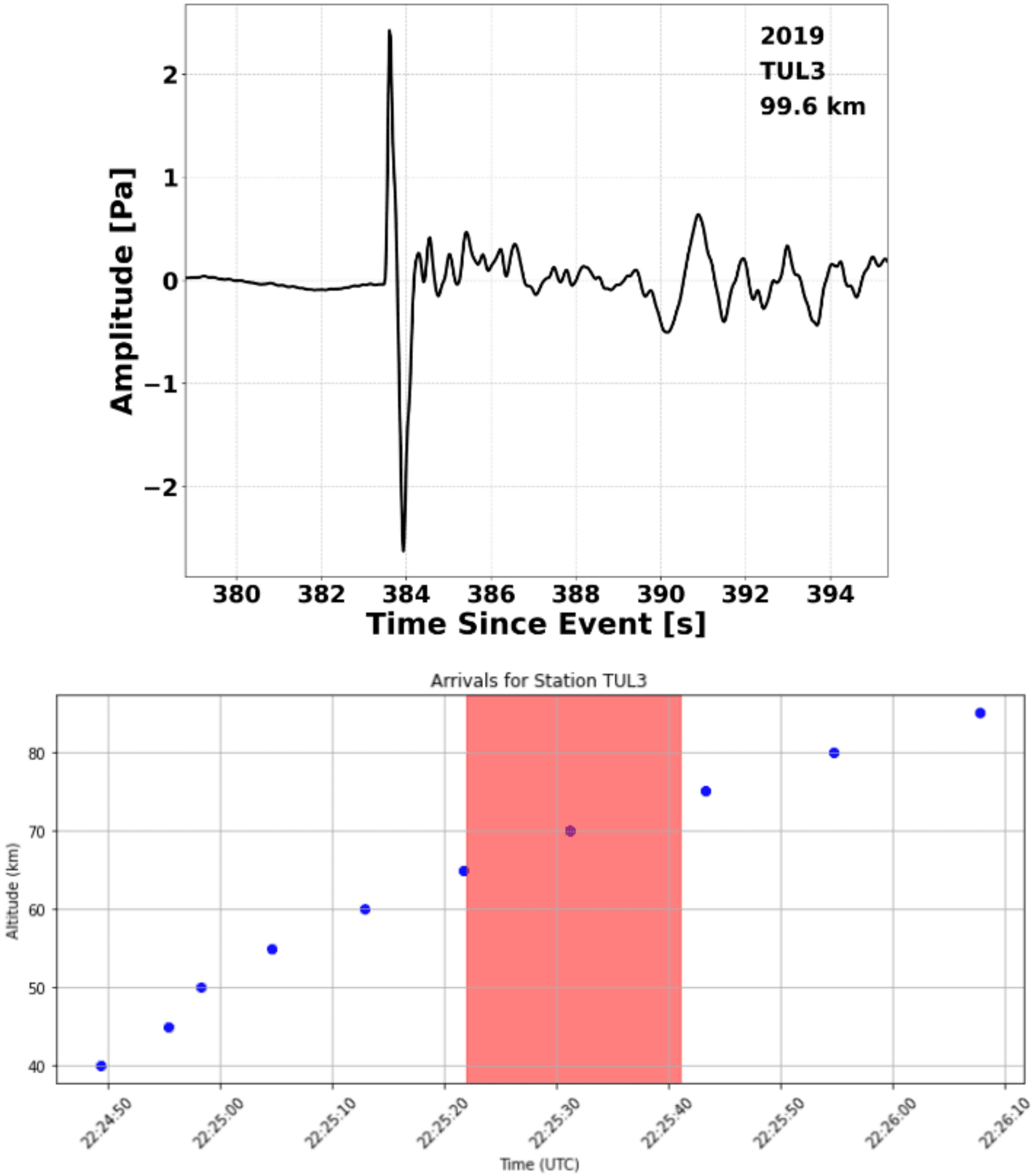

Fig. 5: Top panel shows the classic N-wave signal arrival at the TUL3 station (See Fig. 4). The bottom pannel shows propagation modeling output indicating the most likely source altitude for a signal arriving at the time of the true arrival. The red highlighted region shows the time in which there is signal arrival at the station.

Likely spherical shocks were detected at ranges varying from 180 to 350 km. All of these detections occurred within a similar azimuth from the reported source location and also exhibit similar signal characteristics. The diffuse and extended nature of these signals, along with the propagation modeling results, indicate that these are more than likely lower altitude signals from the two fragmentation episodes.

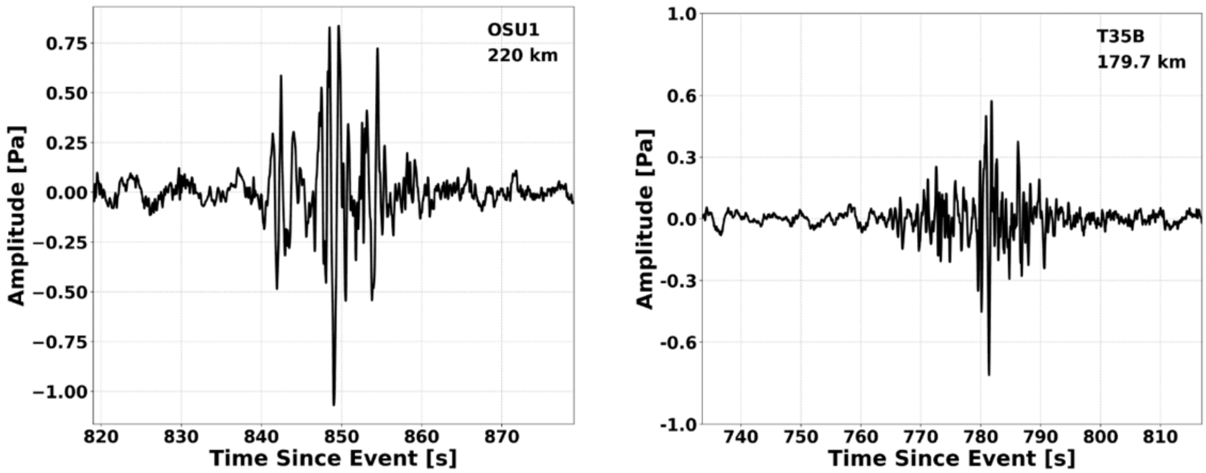

Fig. 6: Left panel shows a more diffuse (when compared to the classic N-Wave) signal arrival at the OSU1 array. The right panel shows a similar signal at a single sensor station, T35B, slightly more north than OSU1 (See Fig. 4).

DISCUSSION

Due to the number of short range <300 km stations relative to the 2019 event, it was possible to estimate the signal source location using a combination of time of arrival information and celerity values obtained through propagation modeling. Our results (Fig. 7) highlights which suggests that the signal origin is likely in close proximity to the geolocation provided by GLM 16.

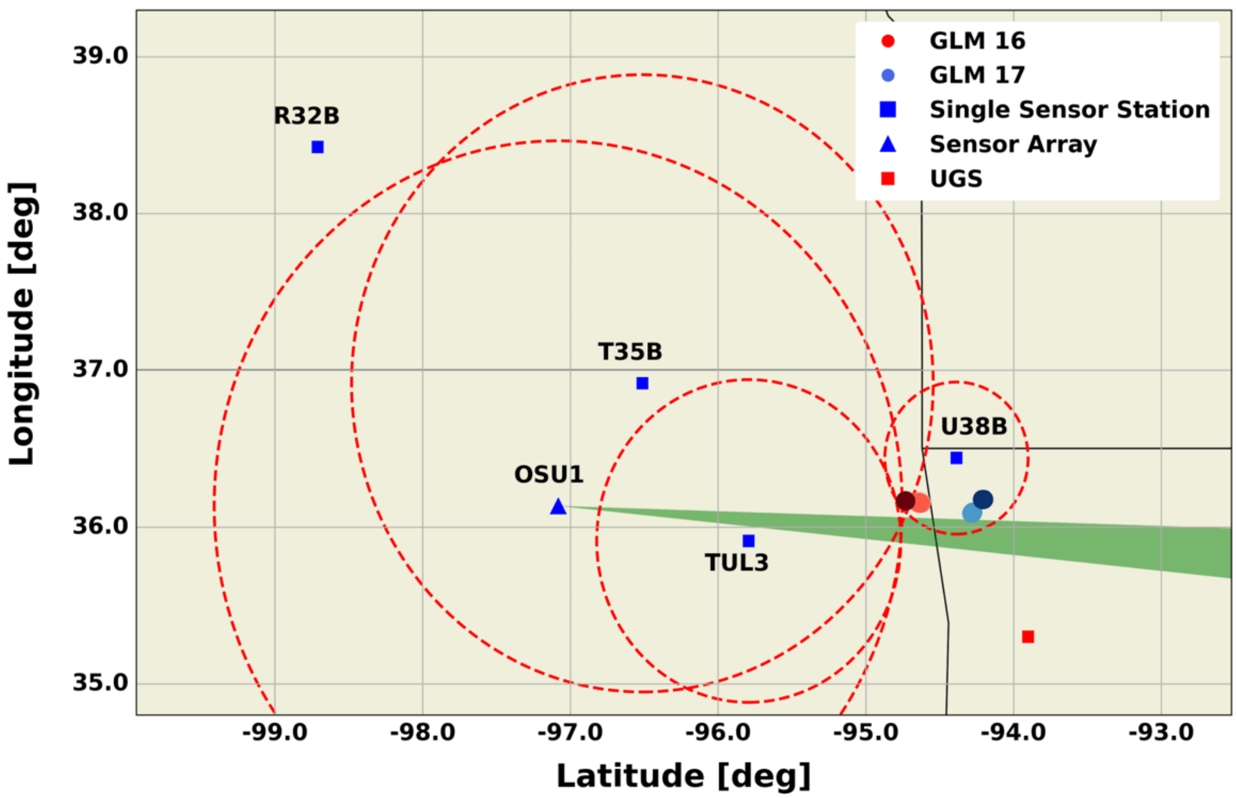

Fig. 7: Map showing the most likely bolide location calculated by infrasonic detections compared against the available ground truth information. Circles, red for GLM 16 and blue for GLM 17, indicate locations of GLM detection and are darkest at the point of maximum brightness and a lighter shade at the final reported location.

Due to the much longer propagation distances between source to station for the 2016 event, an estimated source location was much harder to estimate. While time of arrival estimation and array processing did result in good agreement with ground truth, no additional insights were able to be drawn from the infrasound recordings. However, the long propagation distances did aid in investigating distinct signal arrivals that are estimated to be associated with multipathing in the atmosphere. An example of the raytracing simulation results, along with the waveform of the signal arriving at the MR station, are shown in Fig. 8.

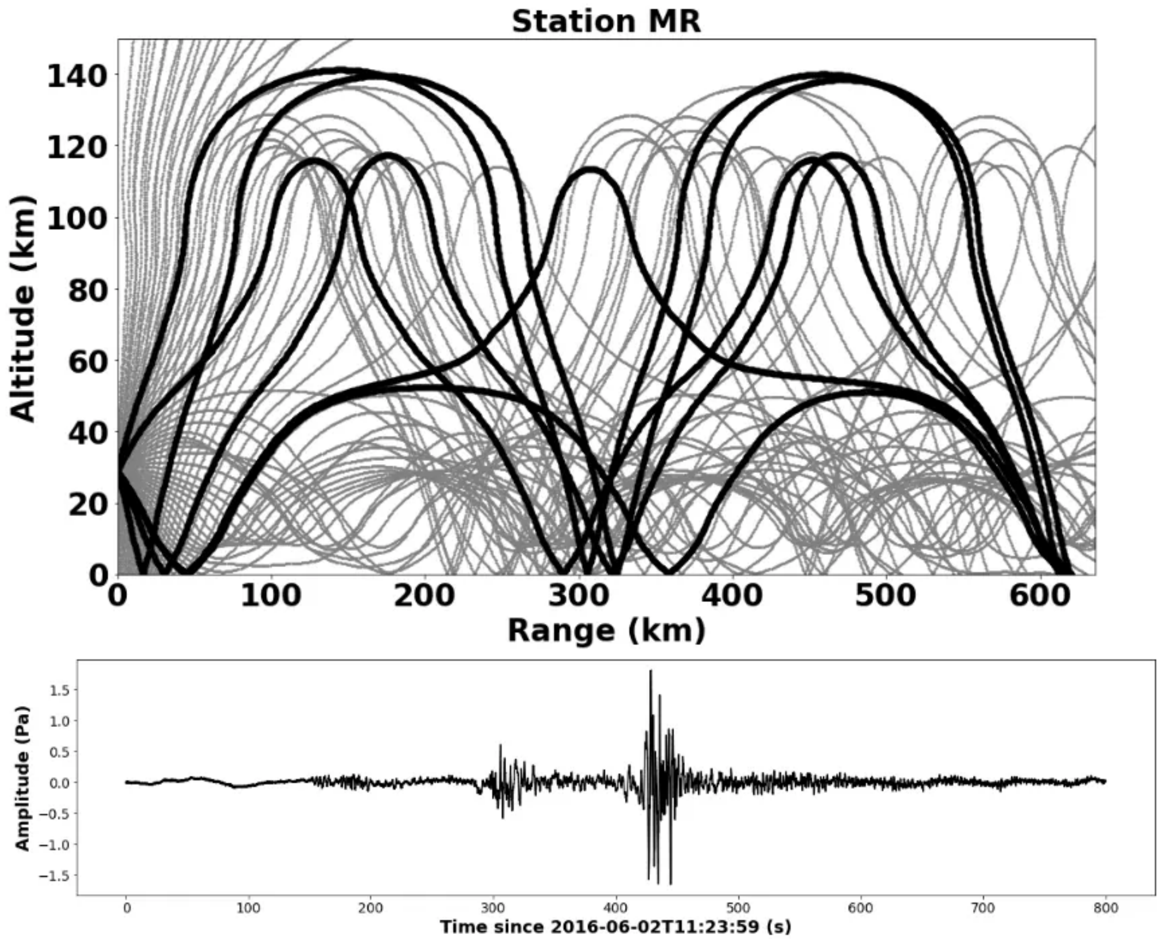

Fig. 7:Top panel is propagation modeling results with a source altitude of 30 km. The Black lines are eigen rays that propagate directly to the reciever location while the gray lines are other propgation paths that do not result in a signal arrial. The bottom panel is the wavefrom at the MR station and three distinct signal arrivals, of varying length and amplitude, can be seen.

CONCLUSIONS

Based on the comprehensive analysis and data presented in this study, key points are as follows:

1. Event detection and analysis: The study successfully characterized two bolide events from June 2016 and April 2019, utilizing a network of ground-based infrasound sensors. The events were analyzed in detail, identifying the number of distinct signal detections, their timing, frequency range, signal amplitude, and signal period.
2. Effect of Atmospheric Conditions: This study illustrates the notable effect of atmospheric conditions, particularly stratospheric winds, on the propagation of infrasound signals. This was evident in the favoring of westerly propagation for both events, demonstrating how wind patterns can affect the detection and consequently, analysis of infrasound data.
3. Shock Identification: Range-dependent ray tracing simulations were instrumental in evaluating source altitudes and possible propagation paths. These simulations provided clues about the likely source altitudes for arriving signals at the selected stations. However, the 2019 event exemplified the limitations of this methodology as simulations failed to capture arrivals seen at the more distant stations that did not receive ballistic arrivals. A significant aspect of this study was distinguishing the mode of shock production (spherical shocks versus cylindrical line source). Shock types were identified for both events and provided further evidence to the limitations on distance and direction for specific shock arrivals.

DISCLOSURES

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

TRANSCRIPT

ABSTRACT

Infrasound monitoring provides a powerful remote sensing tool for detecting and characterizing bolides, as hypersonic shock waves from atmospheric entry generate low frequency acoustic signals. Bolides generate cylindrical shock waves (from the hypersonic entry) and in some cases also spherical shock waves (from fragmentation events). A sensor's location relative to a bolide's trajectory plays a pivotal role in what types of shocks are detected. Given the arriving waveforms at a sensor, insights can be made regarding the modes of shock production that occur during a bolide's entry. This study focuses on two bolide events, a June 2016 event over Arizona and an April 2019 event over Arkansas. Both produced detectable infrasound at regional distances, while the June 2016 events also produced signals detected as far as 6000 km. A combination of satellite data and ground observations provide insight into both of the events' trajectory, allowing for comparison of anticipated and observed acoustic signals, given the locations of sensors. Signal processing techniques were applied including progressive multi-channel correlation and spectral analyses to determine general characteristics of the events such as location and estimated blast energy given only the acoustic measurements. This presentation will showcase detailed analysis of the infrasound signals, array geometries, and sensor placements, focusing on the ability to discern the type and origin of the shock along the bolide path of the arriving waveforms. This will be done by highlighting which sensors detected signals, their orientation relative to trajectory, and the frequency content of the arriving waveforms. These findings will then be used to further demonstrate the ability to estimate entry characteristics of bolides through acoustic detections, as well as provide insight into preferred infrasound sensor placements for characterizing hypersonic sources.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

REFERENCES

Palotai, C., Sankar, R., Free, D.L., Howell, J.A., Botella, E. and Batcheldor, D., 2019. Analysis of the 2016 June 2 bolide event over Arizona. Monthly Notices of the Royal Astronomical Society, 487(2), pp.2307-2318.

Jenniskens, P., Moskovitz, N., Garvie, L.A., Yin, Q.Z., Howell, J.A., Free, D.L., Albers, J., Samuels, D., Fries, M.D., Mane, P. and Dunlap, D.R., 2020. Orbit and origin of the LL 7 chondrite Dishchii'bikoh (Arizona). Meteoritics & Planetary Science, 55(3), pp.535-557.

EVALUATIONS

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