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LEVERAGING MULTI-STATION INFRASOUND DETECTIONS FOR CHARACTERIZATION OF HIGH-ALTITUDE FIREBALLS

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LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

WHERE INNOVATION BEGINS

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U.S. DEPARTMENT OF ENERGY

NNSA

BACKGROUND

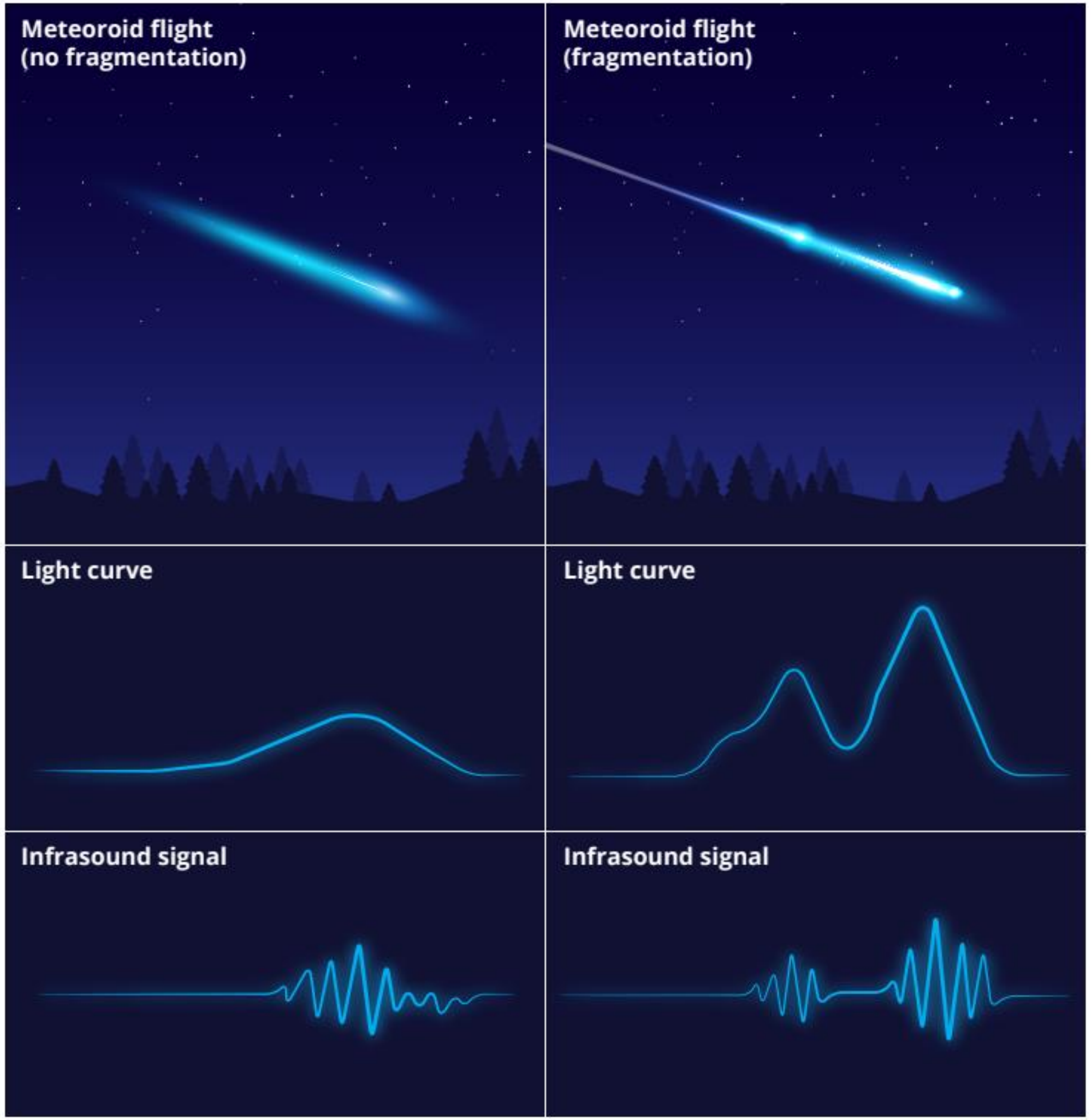


Figure adapted from Silber (2024)

- Ongoing effort to better characterize fireballs and bolides
- Events recorded and documented through various means of observation
  - US Government sensors
  - GLM
  - All-sky cameras (still and video)
  - Radar
  - Casual witnesses
  - Infrasound & seismic
- Fireballs can vary in composition, velocity, size, and entry angle
- Can produce infrasound through a cylindrical line source and fragmentation (discrete, continuous, airburst)
- Infrasound signal should carry some information about the source

INTRODUCTION

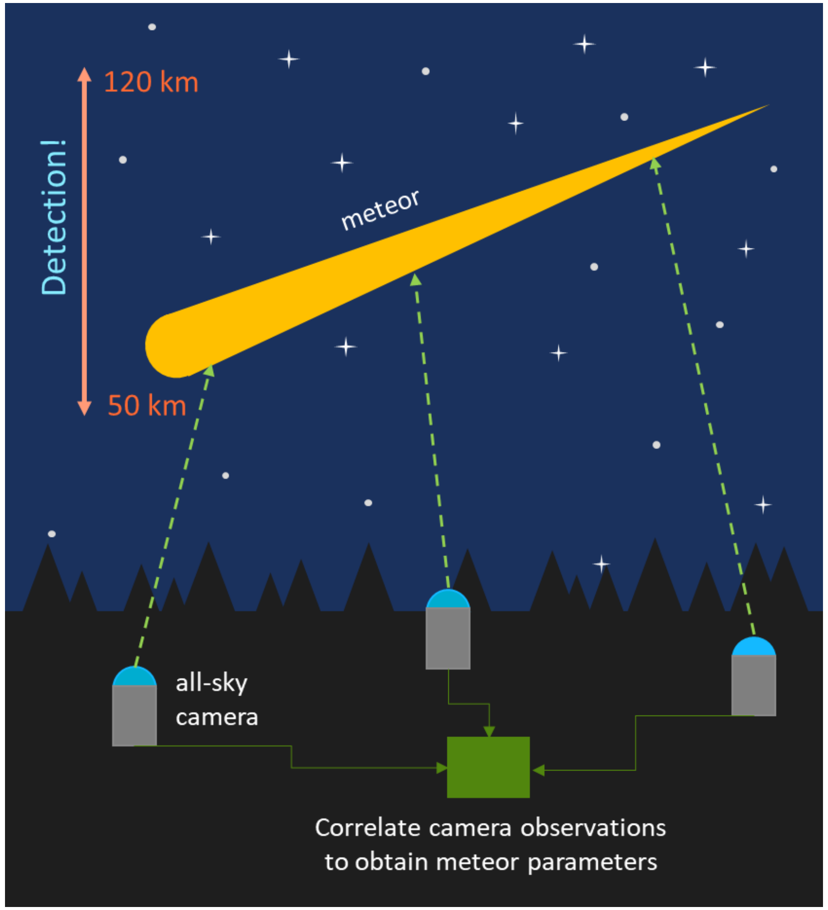
- Well-documented observations of ***earthgrazing meteoroids*** are exceptionally rare [1]. These objects are unique in that they enter the Earth’s atmosphere at an extremely shallow angle relative to the horizon.
- While interacting with the denser regions of the atmosphere, an earthgrazing meteoroid might undergo ablation and produce a luminous path that could span as much as several hundreds of kilometers [2]. Earthgrazers generally do not penetrate deep into the atmosphere; documented cases had their minimum altitude between ~70 km and ~100 km [1].
- During their passage through the atmosphere, sufficiently large and fast meteoroids produce shockwaves that can decay to very low frequency acoustic waves, also known as infrasound [3].
- Theoretically, earthgrazers falling within the category of sufficiently fast and large objects should also generate infrasound. However, documented infrasound detections of earthgrazers are nearly non-existent.
- Here we report an infrasound detection of a rare earthgrazing fireball.

EARTHGRAZER OVER EUROPE

- A rare horizon-to-horizon earthgrazer event occurred over northern Europe on 22 September 2020 at 03:53:40 UTC, capturing attention of many eyewitnesses and numerous ground-based cameras aimed at the skies [4].
- As per the analysis released by the Global Meteor Network [6], the luminous path of the earthgrazing fireball started over Germany and ended over the UK, at the altitude of 101 km and 107 km, respectively.
- The point of the closest approach was at ~90 km. The object's velocity upon the entry was ~34 km/s, and only slightly less, ~30 km/s, when it exited [4,5].
- All-sky cameras observed the event from multiple angles, which allowed for accurate trajectory derivation.

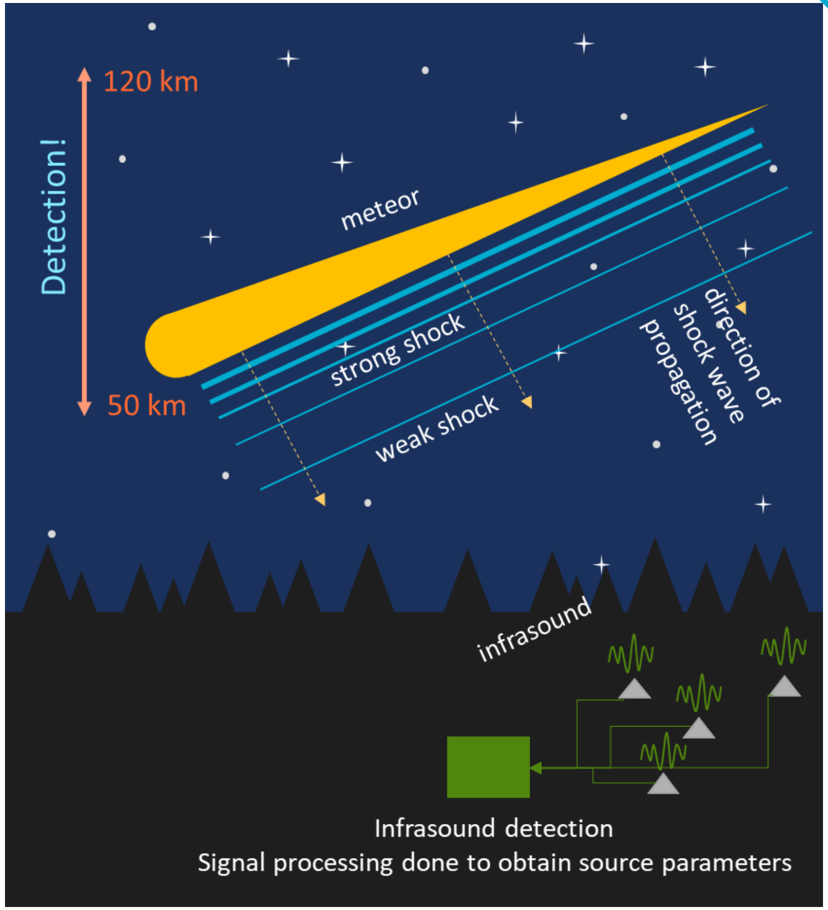
All-sky camera image of the earthgrazer.
Image credit: Cees Bassa [5].

MULTI-MODAL DETECTIONS: ALL-SKY CAMERAS AND INFRASOUND



Correlate camera observations
to obtain meteor parameters

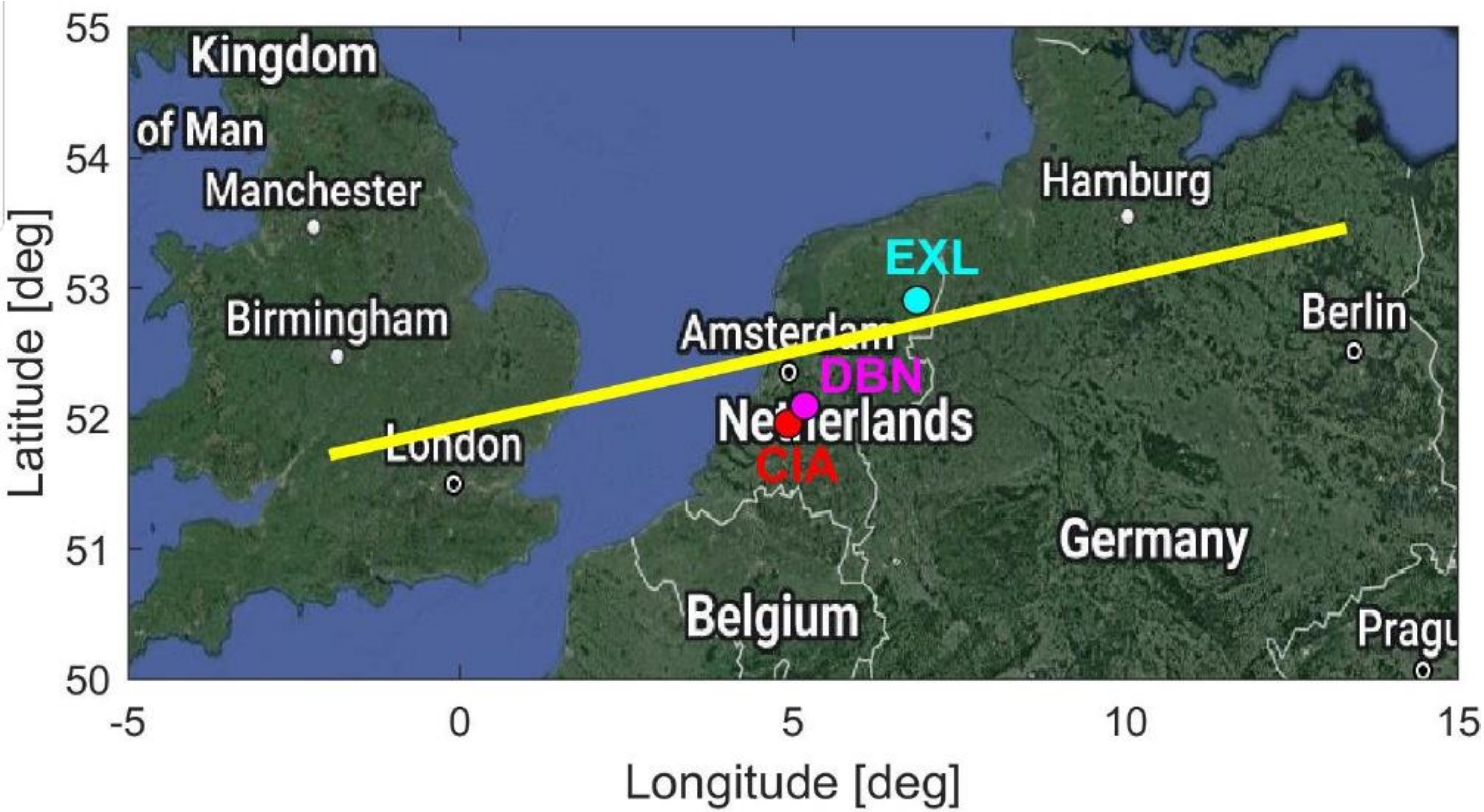
- Optical observations from multiple vantage points can provide valuable ground truth information.
- Accurate trajectory, velocity, entry angle, etc. can be fed into infrasound search algorithm (Silber 2024).
- Infrasound detection provides additional layer of information about the source.
- Detailed studies using multi-modal detections of fireballs can provide information (and model validation and refinement) that can be later used for events with limited ground truth.



Infrasound detection
Signal processing done to obtain source parameters

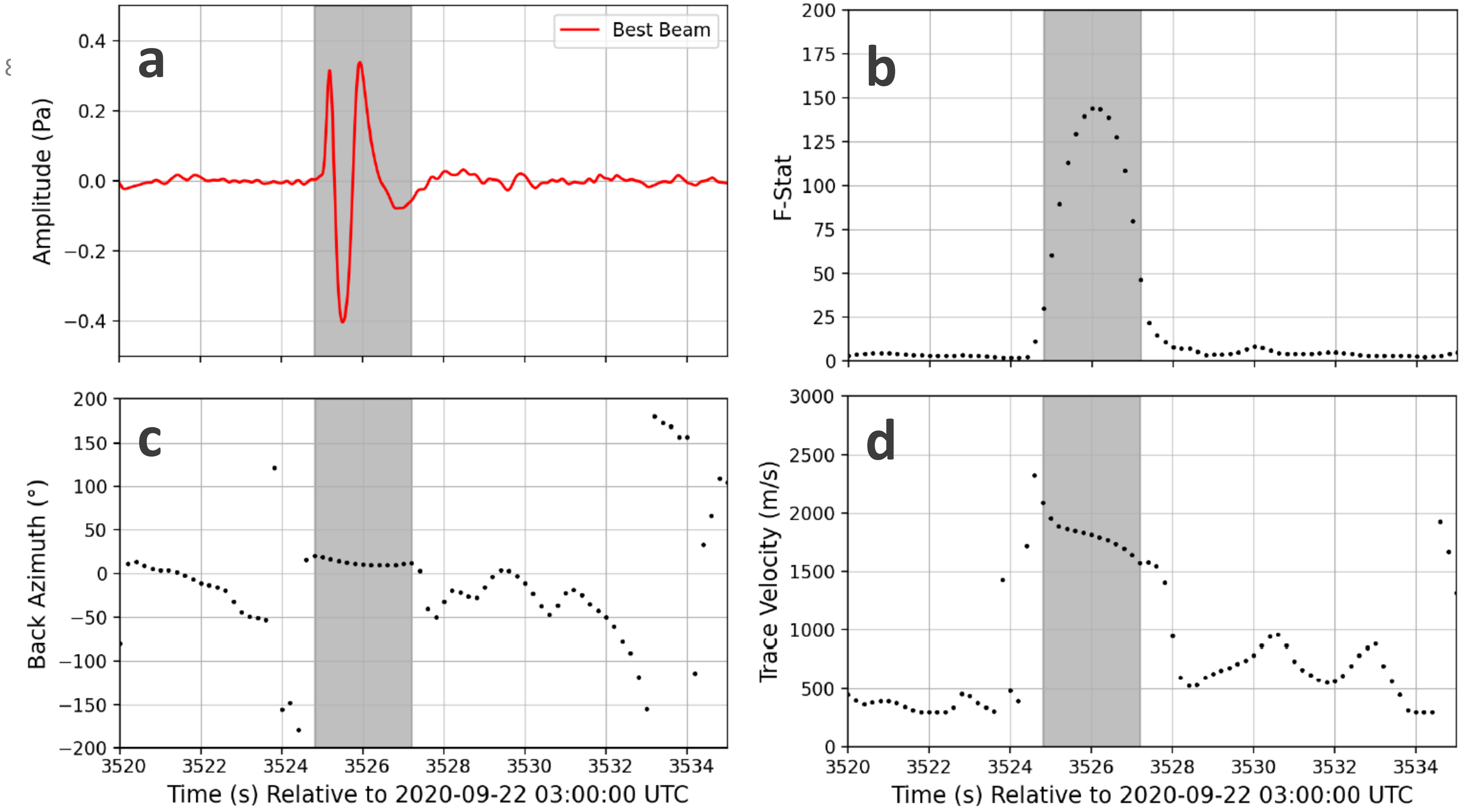
Silber, E. A. (2024). Perspectives and Challenges in Bolide Infrasound Processing and Interpretation: A Focused Review with Case Studies. Remote Sensing

GROUND TRACK OF THE EARTHGRAZING FIREBALL



INFRASOUND DETECTION

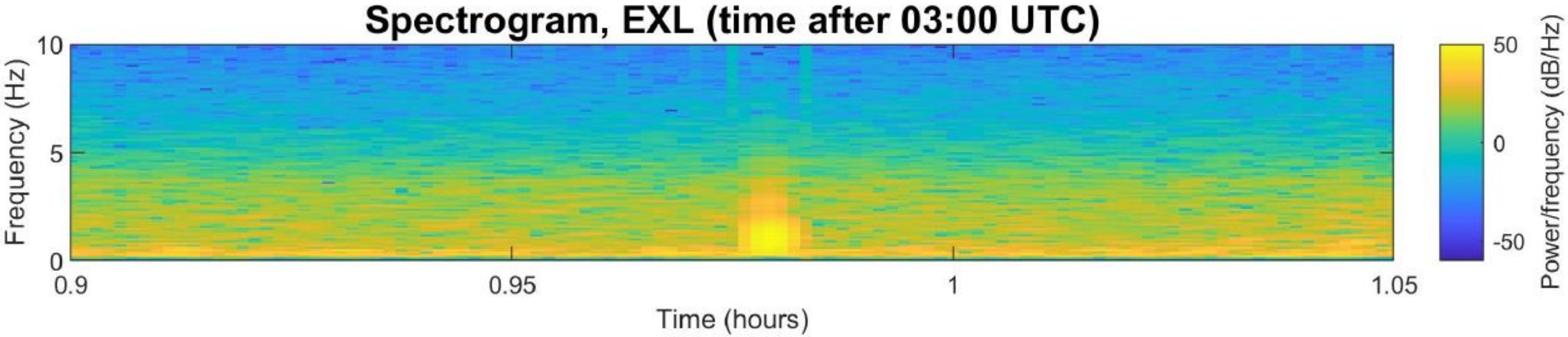
- Despite its high-altitude and apparently silent (to humans) passage, the earthgrazer was detected by infrasound sensors of the Royal Netherlands Meteorological Institute (KNMI) network [6] several minutes after it had entered the atmosphere.
- Three infrasound arrays of the KNMI network detected the signal: EXL, DBN, and CIA. The signal was first detected by the EXL array at 03:58:44 UTC, a few minutes after the onset of the luminous path.
- The infrasound signatures at all three arrays exhibited an N-wave appearance, diagnostic of a ballistic shock [6].
- The signal trace velocity at all stations was high, indicative of a direct arrival from a high-altitude shock produced by the cylindrical line source [6].
- At EXL, which was in the close proximity to the earthgrazer trail, the apparent signal arrival was nearly vertical, consistent with our conclusion that the signal was ballistically generated.
- Implications for detections of high-altitude, shallow entry angle sources



Filtered time series [0.4 – 4.1 Hz] recorded by the EXL array. The maximum and peak-to-peak amplitude is 0.12 Pa and 0.26 Pa, respectively. Also are included the F-stat, back azimuth and trace velocity plots.

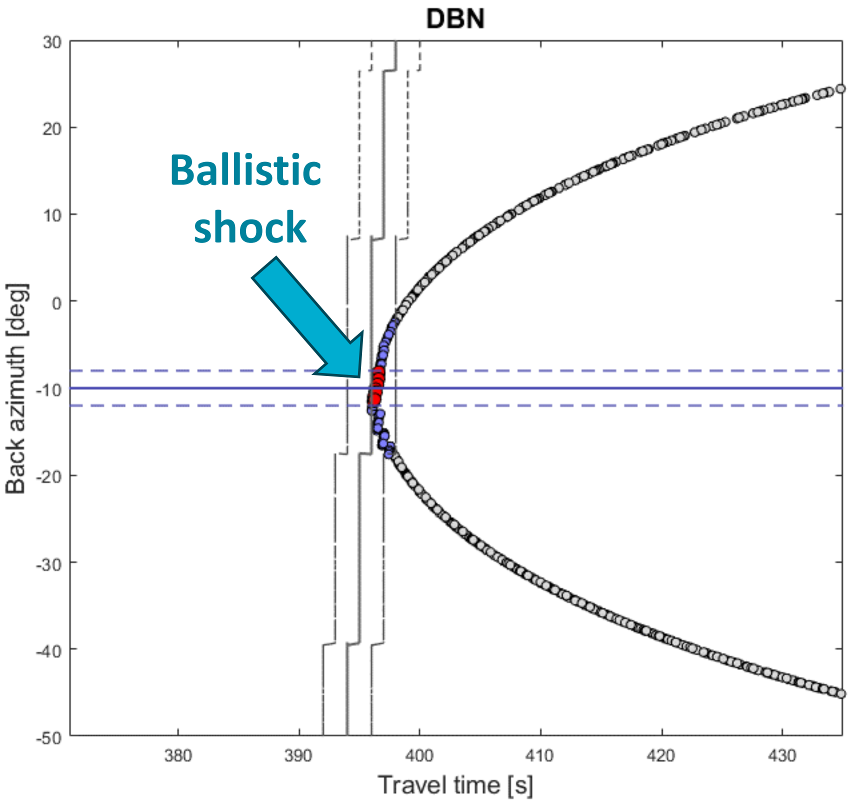
INFRASOUND DETECTION CONT'D

- The frequency content was below 4 Hz.
- The average dominant signal period across the three stations was 1.2 seconds. Using the AFTAC energy relations adapted to bolides [7,8], the energy release was estimated at 7-10 tons of TNT equivalent across the three stations.
- We originally hypothesized that the signal detected at EXL came from a different part of the trail compared to that detected by DBN and CIA. Modeling was done to better understand arrivals at different stations [8].



PROPAGATION MODELING

- We performed propagation modeling using the trajectory derived through all-sky camera observations, which provided accurate timing and location of the fireball along its flight path.
- Propagation modeling was done using InfraGA [9], from discrete points along the fireball trail down to each infrasound station.
- Signal travel times and back azimuths were then compared to the observations to derive the point of signal origin.
- The results show that the signal origin was different for each station, with purely ballistic arrivals.
- Only a handful of studies found infrasound from very high altitudes, especially from relatively small fireballs (< 1 m).

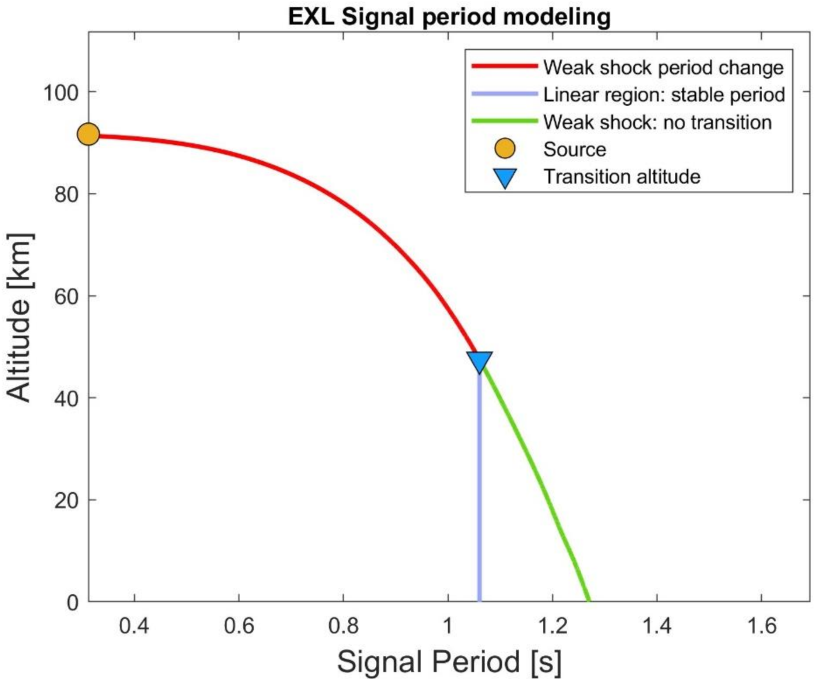


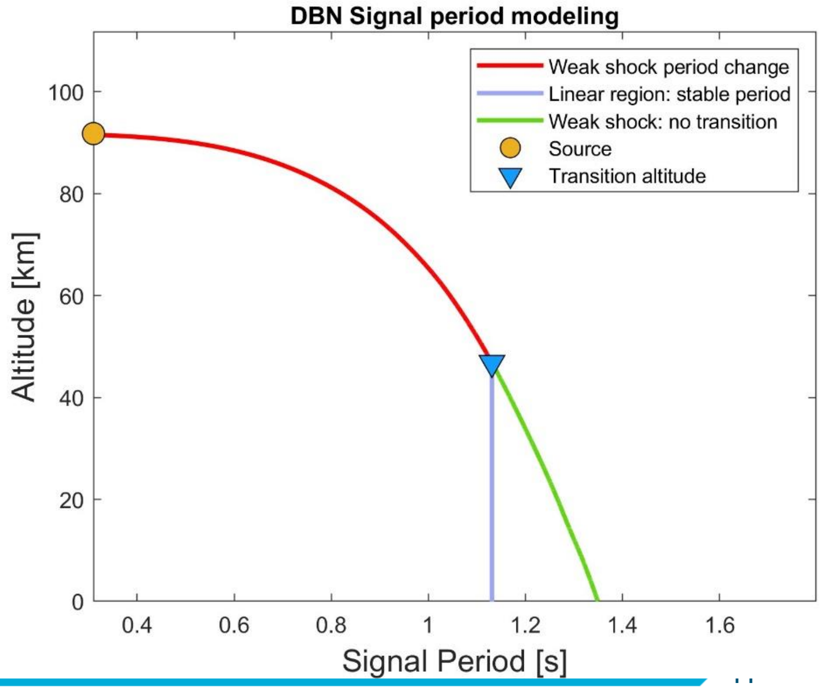
Propagation modeling results	EXL	DBN	CIA
Shock source latitude [deg]	52.979 ± 0.001	52.767 ± 0.004	52.711 ± 0.001
Shock source longitude [deg]	6.853 ± 0.005	4.925 ± 0.031	4.455 ± 0.005
Shock source altitude [km]	91.57 ± 0.01	91.78 ± 0.17	91.81 ± 0.03
Back azimuth [deg]	10.6 ± 2.3	349.7 ± 1.5	341.7 ± 0.2
Ray inclination at source	-84.8	-54.6	-50.1
Fireball velocity [km/s]	33.5 ± 0.3	33.5 ± 0.3	33.6 ± 0.4
Origin time [UTC]	3:53:40	3:53:42	3:53:45

WEAK SHOCK MODELING

- Weak shock modeling [8,10] was performed to derive the source function and estimate fireball parameters based on the observed signals. A realistic atmosphere was used to propagate the signal and account for weak shock to linear regime transition.
- The results are consistent across all stations.
- Unusual (but not impossible) for a very small object to generate a shock wave at such altitude.
- Strong ablation can shift the local Knudsen number to the continuum flow regime thereby enabling the formation of the shock wave.

Meteoroid mass	28 kg
Meteoroid diameter	0.251 m
Blast radius [m]	30.8 m
Fundamental frequency	3.2 Hz
Fundamental period	0.31 s
Dominant frequency (weak shock)	0.8 Hz
Dominant frequency (linear)	0.9 Hz





SUMMARY

- This was a very rare event and a detection several interesting observations.
- The extremely shallow entry angle of the fireball enabled the infrasound wave to readily propagate downward, thus assuming a direct path to the receiver.

Image: Cees Bassa
Dwingeloo, the Netherlands
(stack of two images)

- The first documented evidence of capturing ballistic shocks from multiple distinct parts of the trail of a high-altitude fireball using infrasound.
    - First multi-sensor detection from different parts of the trajectory of an artificial event was the observation of NASA’s OSIRIS-REx Sample Return capsule (Silber et al. 2024)
- Shock wave was generated at such a high altitude due to very strong ablation and shift in the local Knudsen number.
- This unique earthgrazing fireball event provides valuable constraints for infrasound detection and characterization of high-altitude meteor events [4,8].
- This event reinforces the potential of infrasound as a tool for monitoring and detecting unconventional high-altitude sources, such as fireballs.

REFERENCES

[1] Shober P. M. et al. (2020) The Astronomical Journal, 159:191.

[2] Moreno A. et al. (2016) LPSC 47, Abstract #1088.

[3] Silber E. A. et al. (2018) Advances in Space Research, 62:3, 489 - 532.

[4] https://sattrackcam.blogspot.com/2020/09/a-very-unusual-fireball-over-nw-europe.html

[5] Vida D. et al. (2020) Global Meteor Network. **[6]** KNMI (1993) Royal Netherlands Meteorological Institute (KNMI). doi: 10.21944/e970fd34-23b9-3411-b366-e4f72877d2c5.

[7] ReVelle, D. O. (1997). Annals of the New York Academy of Sciences, 822(1), 284-302.

[8] Silber, E. A. and P. G. Brown (2014) JASTP, 119, 116-128.

[9] Blom, P. (2014). GeoAc: Numerical tools to model acoustic propagation in the geometric limit. Software Los Alamos National Laboratory, Los Alamos National Laboratory: Seismoacoustic software.

[10] Silber, E. A., & Brown, P. (2019). In A. Le Pichon, E. Blanc, & A. Hauchecorne (Eds.), Infrasound Monitoring for Atmospheric Studies: Challenges in Middle Atmosphere Dynamics and Societal Benefits (pp. 939-986) https://doi.org/10.1007/978-3-319-75140-5_31

Additional references:

Silber, E. A. (2024). The utility of infrasound in global monitoring of extraterrestrial impacts: A case study of the 23 July 2008 Tajikistan bolide. The Astronomical Journal. https://doi.org/10.3847/1538-3881/ad47c3

Silber, E. A., Bowman, D. C., Carr, C. G., Eisenberg, D. P., Elbing, B. R., Fernando, B., Garces, M. A., Haaser, R., Krishnamoorthy, S., Langston, C. A., Nishikawa, Y., Webster, J., Anderson, J. F., Arrowsmith, S., Bazargan, S., Beardslee, L., Beck, B., Bishop, J. W., Blom, P., . . . Zeiler, C. (2024). Geophysical Observations of the 24 September 2023 OSIRIS-REx Sample Return Capsule Re-Entry. The Planetary Science Journal. https://doi.org/10.3847/PSJ/ad5b5e

EXTRA SLIDES