Infrasound signatures from powerful rocket launches for space missions

Christoph Pilger and Patrick Hupe

Federal Institute for Geosciences and Natural Resources (BGR), B4.3, Hannover, Germany

SLS sending Artemis 1 to the moon

Infrasound Technology Workshop, 07 November 2024

Abstract

Rocket launches are a source of infrasound detectable at infrasound arrays in thousands of kilometers distance. Recorded signatures originate from the ignition, launch, supersonic movement, stage separation and reentry of rockets within the first about 100 kilometers of altitude in the atmosphere. We use IMS infrasound data to localize and characterize rocket launches all over the world.

During the last 20 years, an increasing number of annual space missions was conducted from various globally distributed space ports. These missions were mainly launched to inject satellites in Earth's orbit, but also for space station flights and the exploration of the Moon and other bodies in the solar system.

We investigate and present infrasound detections of interest, including NASA's Artemis 1 Moon mission using the Space Launch System in 2022, SpaceX's orbital flight tests of Starship in 2023 and 2024 and ESA's first launch of the new Ariane 6 rocket in 2024. Furthermore, we highlight a systematic analysis of infrasound recorded from multiple, regularly launched vehicles like Ariane 5, Falcon 9, and various Soyuz and Long March rocket types.

Overview

Introduction

- Motivation: Infrasound from rocket launches
- IMS infrasound data and array signal processing
- Rocket launches and reentries as ground truth data

Specific Launch Events

- Artemis: NASA's renewed moon exploration, 2022
- Ariane: ESA's last Ariane5, 2023, first Ariane6, 2024
- Starship: SpaceX's integrated flight tests, 2023/2024

Systematic Launch Study

- A study on 1001 rocket launches for space missions
- Rocket launches at IS34 from multiple spaceports
- Estimate of an energy vs. amplitude relation

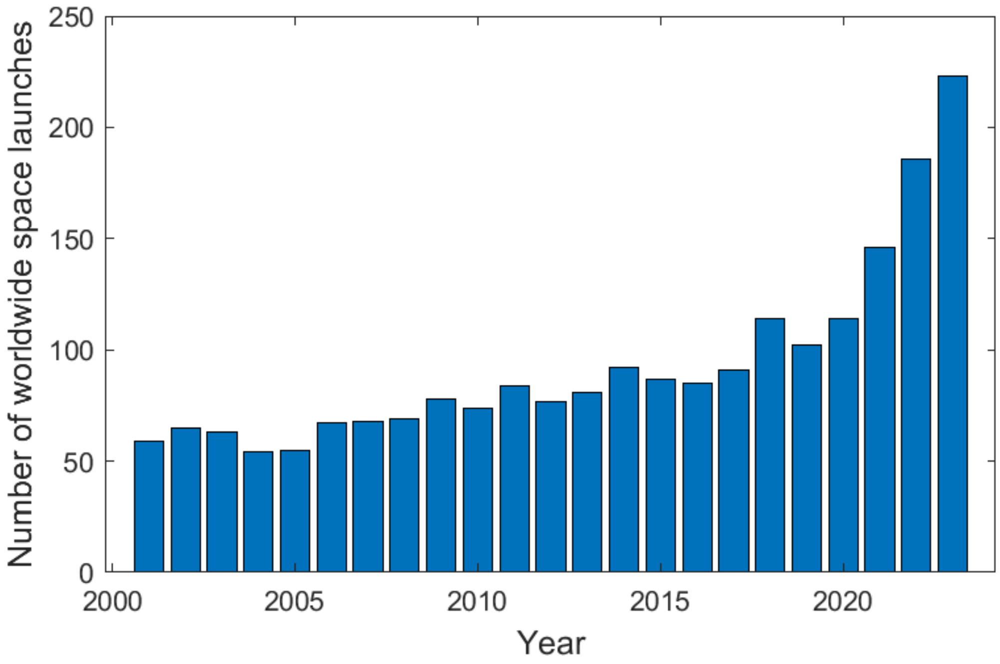
Reentries

- OSIRIS-REx: Utah Test and Training Range, USA, 2023
- Starlink-30167: near Puerto Rico, Caribbean, 2023
- Polaris Dawn: Dry Tortugas, Florida, USA, 2024
- Starship IFT 3,4,5: Reentries over the Indian Ocean, 2024

...and Conclusions

Motivation: Infrasound from rocket launches

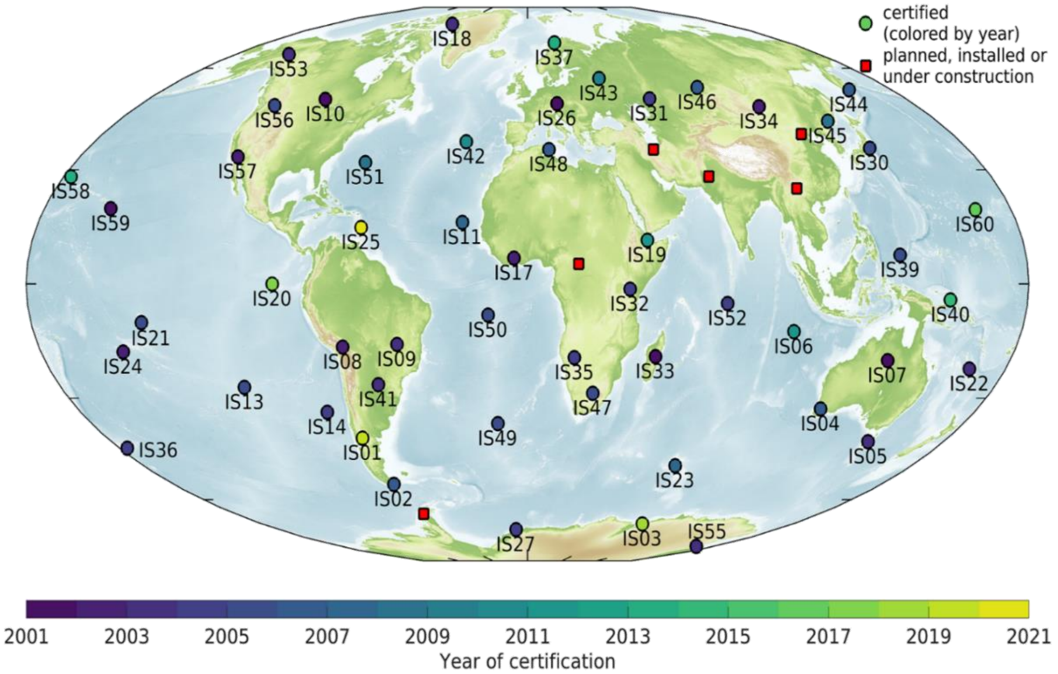
- **Rocket launches** use propulsion engines and boosters having thrusts of hundreds to tens of thousands of kilonewton. They accelerate the rockets to supersonic velocities and produce a lot of audible and **infrasound noise (or signal)**
- During the recent years/decade, a largely **increasing number of** rocket launches is conducted for various **space missions**
- Rocket launches are comparable to large **atmospheric explosions** (up to kilotons of TNT yields) and are therefore useful as ground-truth sources for estimating the **detection capability of the IMS** infrasound network



IMS infrasound data and array signal processing

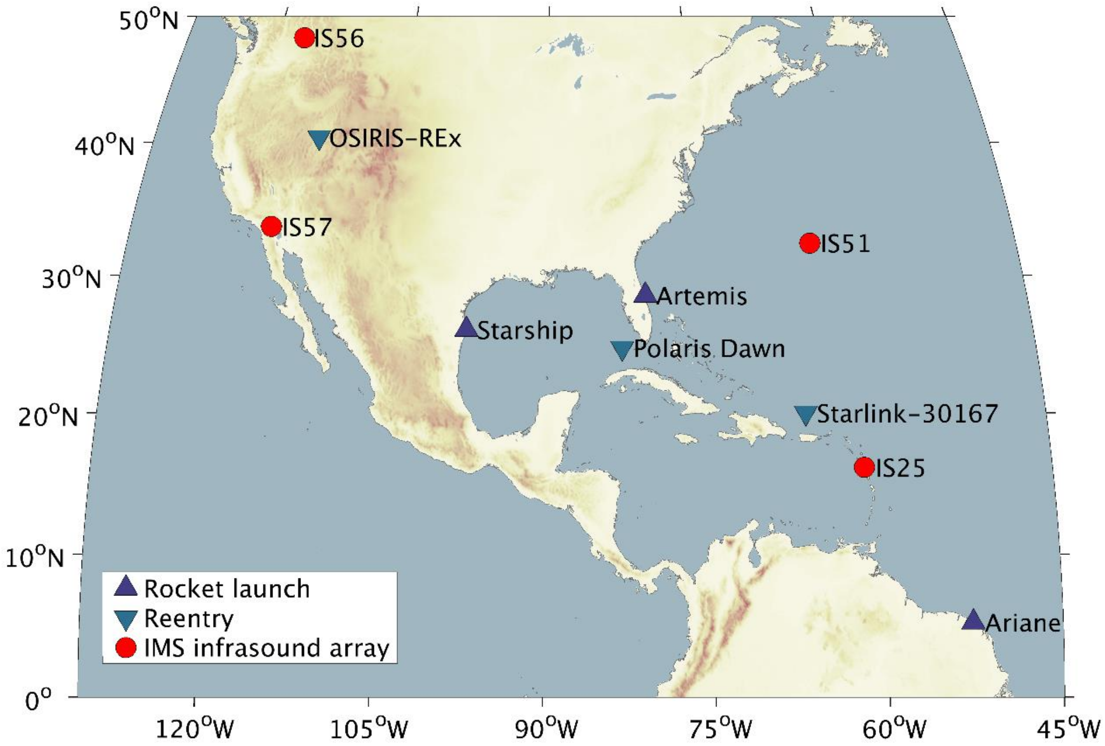
- Differential pressure data from a globally distributed network of currently **53 IMS infrasound arrays** is used to individually highlight and systematically investigate rocket launch cases

- **DTK-GPMCC software** developed by CEA is used for the array signal processing, data analysis and visualization of results hereafter

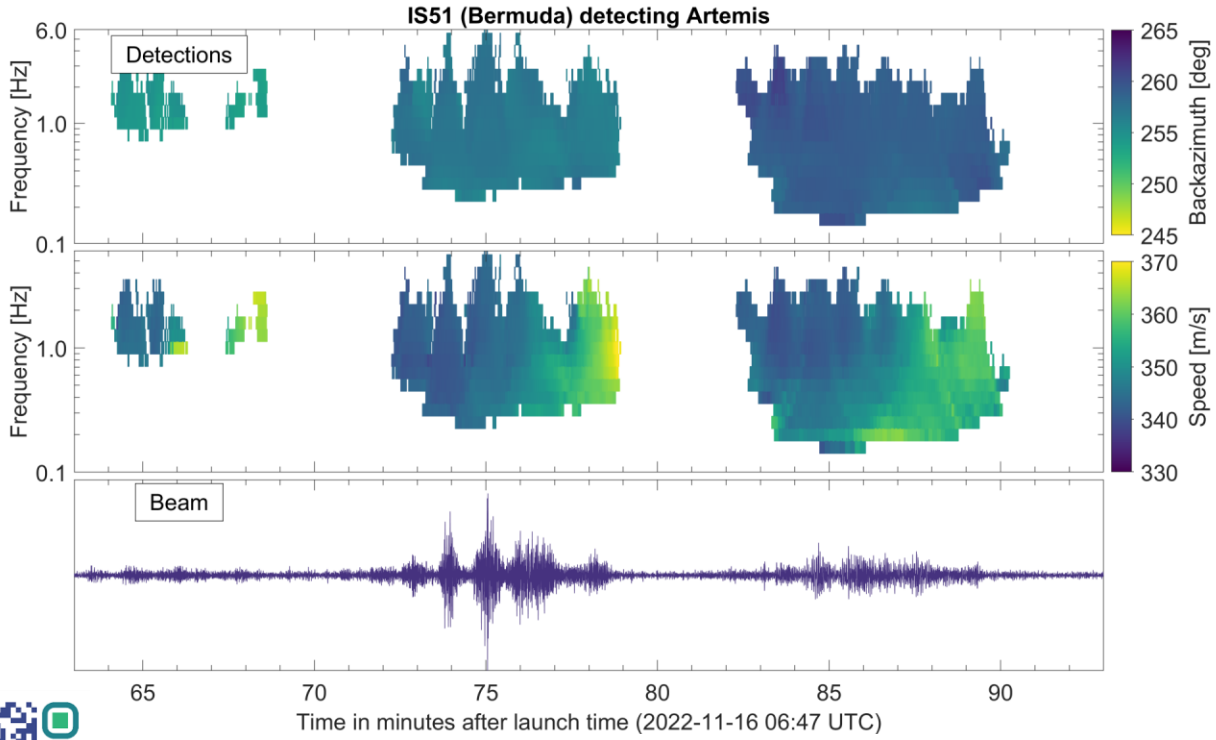


Rocket launches and reentries as ground truth data

- The **launch time** and **launch location**, normally a spaceport facility, of the according space mission is well known, as in normal cases is also the trajectory of the flight and the schedule for stage separations, engine ignitions and flight maneuvers
- Same holds true for the trajectories of many **reentries** of landing capsules (with crew or cargo) or space debris
- **Infrasound is generated by** the ignition, fuel burning, stage separation, re-entry and booster landing, but also by explosions from failures and by objects traveling at supersonic to hypersonic velocities (Mach cone -> sonic boom)



Artemis 1: NASA's renewed moon exploration, 2022, *IS51*

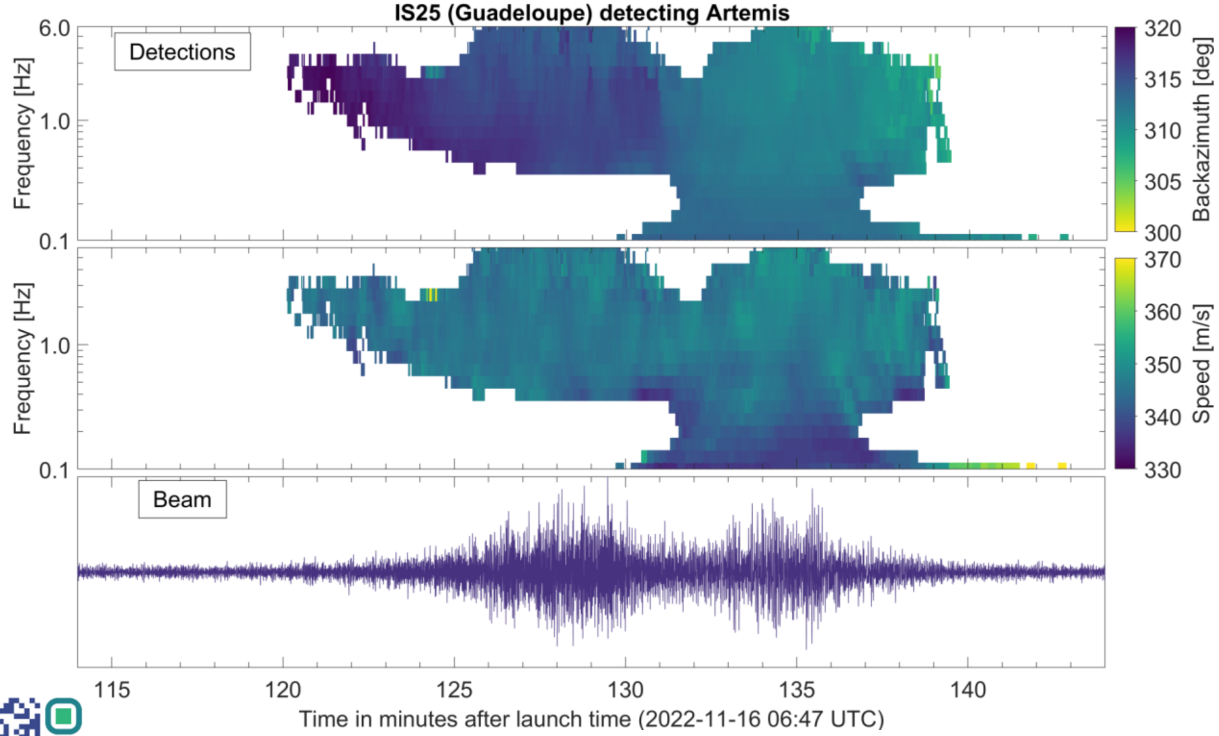


(Figure from: Pilger and Hupe, 2024, https://doi.org/10.1121/2.0001861)

Noteworthy features:

- Signals are (by design) similar to the space shuttle (also observed until 2011 at IS51): solid fuel booster impulses, high amplitudes, low frequency content
- Rocket approaches station, therefore lift-off signals arrive later than sonic boom and booster separation signals
- Multipath-propagation, repetitive signal groups

Artemis 1: NASA's renewed moon exploration, 2022, *IS25*



(Figure from: Pilger and Hupe, 2024, https://doi.org/10.1121/2.0001861)

Noteworthy features:

- The more distant station IS25 observes the rocket as a compact signature (reduced effect of rocket traveling towards station)
- The very low frequency content (down to 0.03 Hz) indicates the immense power of the rocket at lift-off (39,000 kN, 8.8 million pounds of thrust)
- *...next launch:* ***Artemis 2*** *(with crew), not before September 2025*

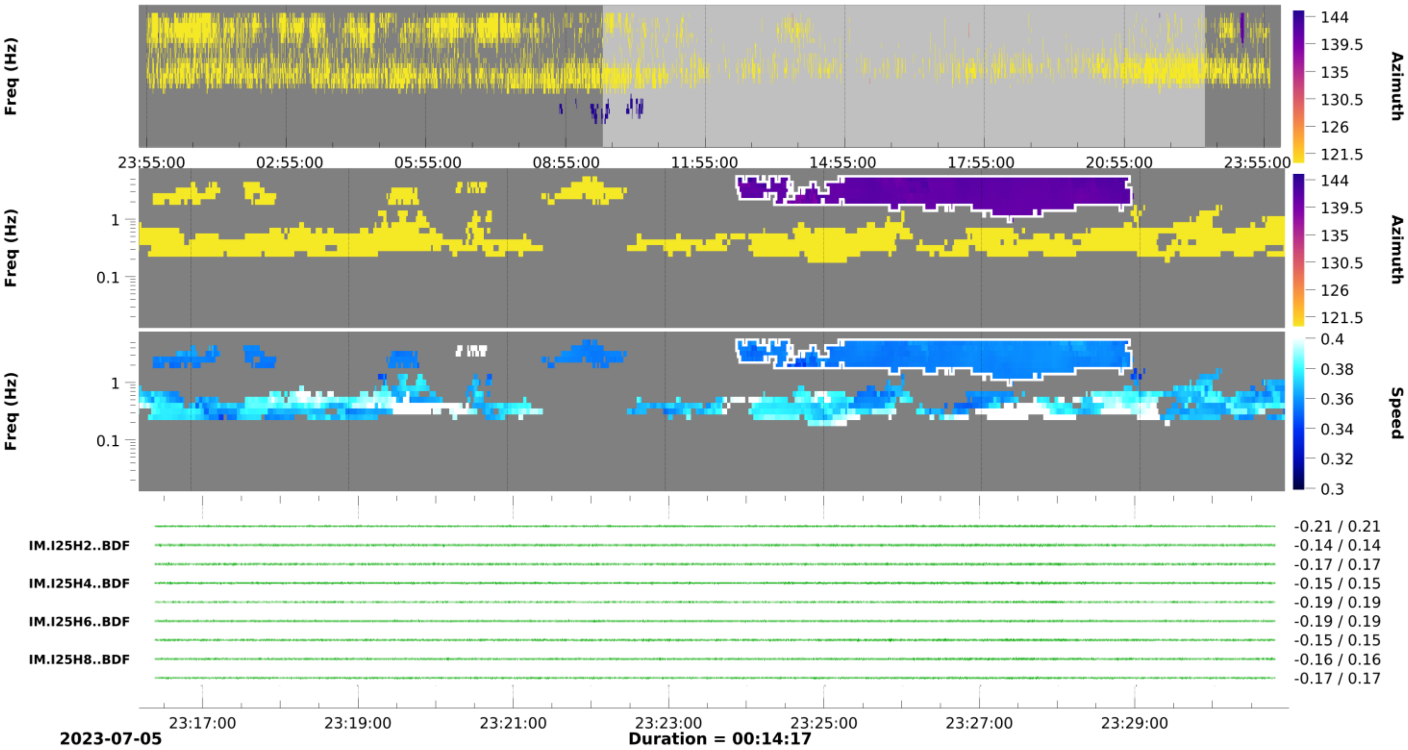
Ariane 5 / Ariane 6 launches

- **All launches** take place at ESA facilities in Kourou, French Guyana. Engine testing is also performed at DLR facilities in Lampoldshausen, 320 km west of the German IMS infrasound array IS26 (e.g. see *Pilger et al., 2022, Pure Appl. Geophys., doi: 10.1007/s00024-022-03055-3*)

- **Ariane 5:** 117 launches from 1996 to 2023 (112 successful, 3 partial successful, 2 failed), mostly transporting satellites to orbit/space, e.g. Envisat in 2002, Rosetta probe in 2004, Herschel/Planck space telescopes in 2009, James-Webb space telescope in 2021.
Last (and final) launch: **05 July 2023**

- **Ariane 6:** first (and only) launch **09 July 2024** (partially successful, last stage & reentry failure)

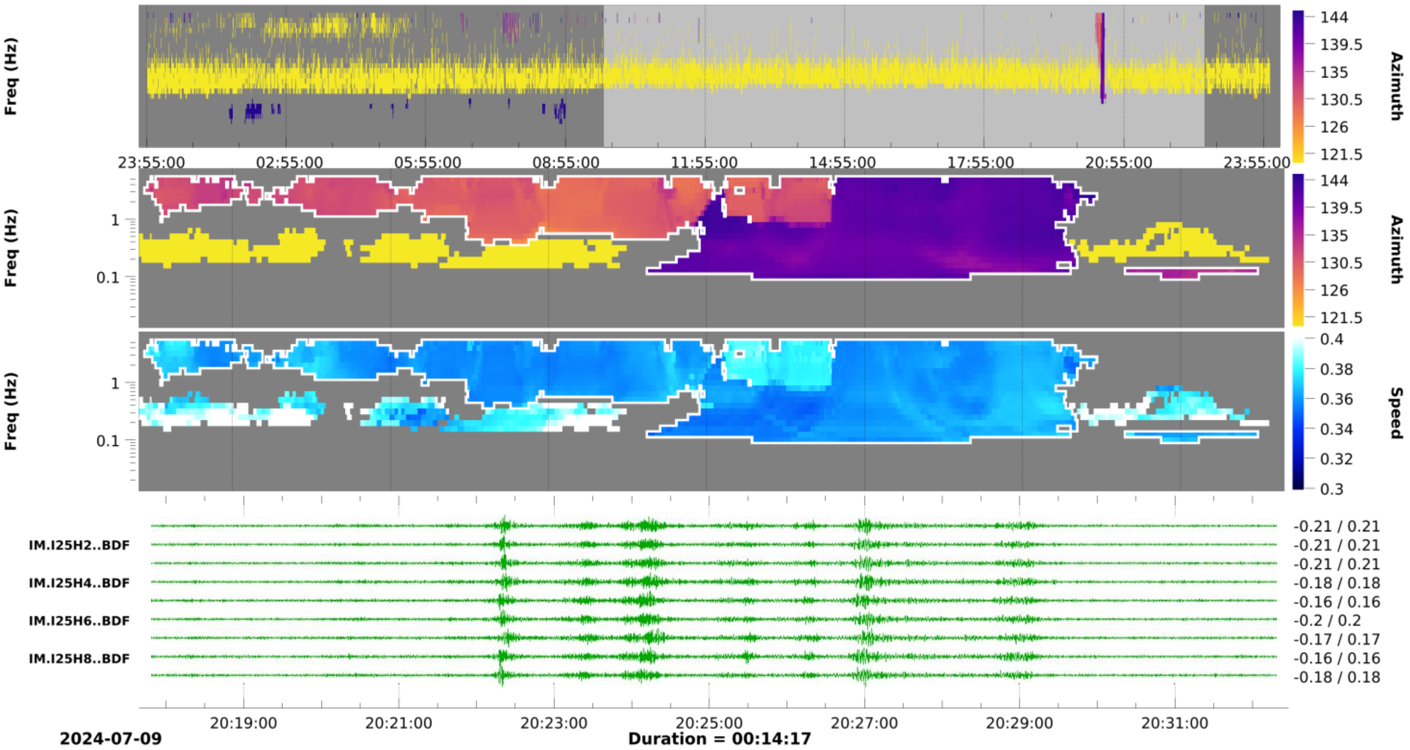
ARIANE 5: ESA‘s “old“ rocket, last launch, 2023, *IS25*



Noteworthy features:

- Signal detection from spaceport direction (~140° azimuth), associated to launch phase, not much more
- Only low-amplitude, high-frequency signal components detected (signals from other directions related to microbaroms and surf)
- Distance ~1550 km, detected at **IS25**, IS09

ARIANE 6: ESA‘s “new“ rocket, first launch, 2024, *IS25*



Noteworthy features:

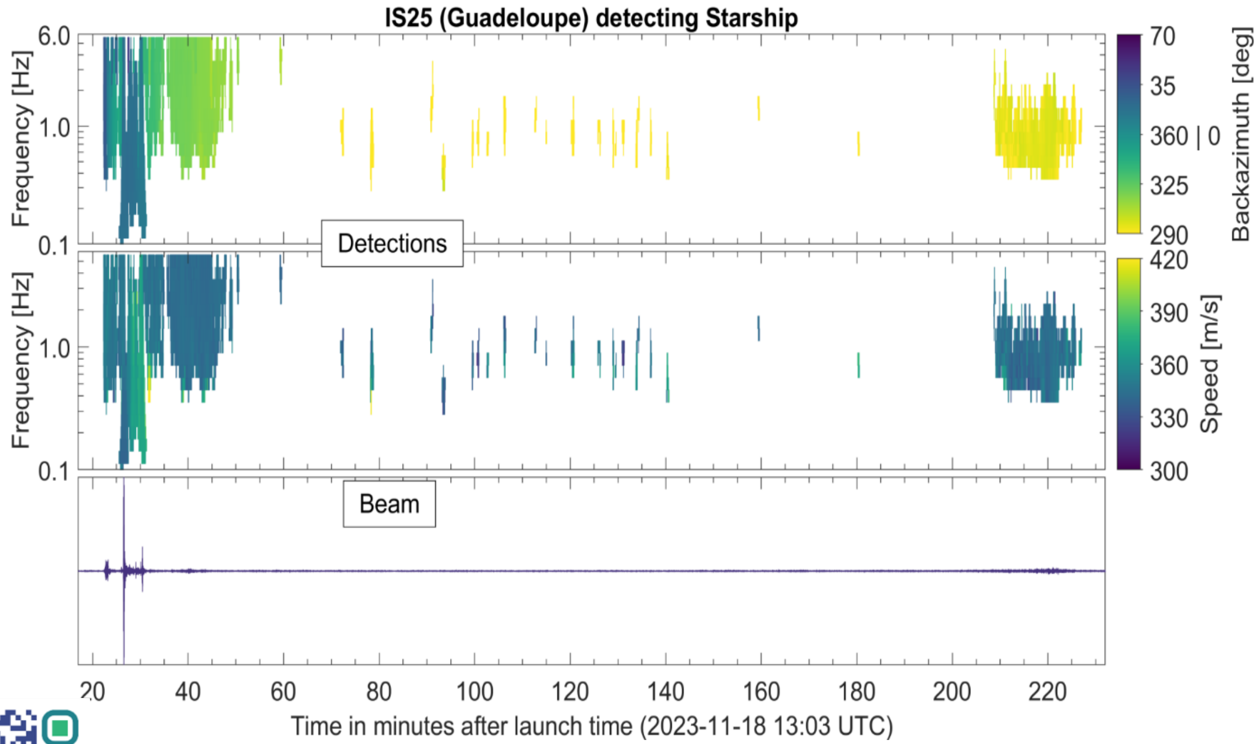
- ➢ Same season (+1yr 4d), similar daytime (-3h), same spaceport, same station…other rocket
- ➢ Signal detection from spaceport direction (~140° azimuth), and from trajectory over Atlantic Ocean (->130°)
- ➢ Higher amplitudes, broader frequencies… more signal power/yield
- ➢ Detected at **IS25** and at IS41, IS51, IS56, IS10

Starship: integrated flight tests 1-5

Integrated Flight Test (IFT) means Super Heavy Booster and Starship Spacecraft fly together. **All launches** are conducted from SpaceX's Starbase in Boca Chica, TX, USA.

- **IFT-1**: **20 April 2023**, launch pad damaged, vehicle destroyed after 4 min (engine failures, AFTS)
  ➔ REB: IS09, 14, 25, 32, 35, 47, 48, 51, 56, 57, 59
- **IFT-2**: **18 November 2023**, successful hot staging (stage separation), booster exploded during boostback, starship destroyed after 8 min (LOX fire)
  ➔ REB: IS10, 20, 25, 42, 56 (**detections from IS25** along the full trajectory)
- **IFT-3**: **14 March 2024**, successful orbital flight, booster explosion near surface (engine failure), starship break-up during reentry (at 65 km altitude)
  ➔ REB: IS10, 18, 20, 51, 53, 56, (not REB: 09, 25, 41), reentry (not REB): IS52
- **IFT-4**: **06 June 2024**, successful orbital flight and reentry, booster and starship controlled splashdown
  ➔ REB: IS20, 52, 56, 57, 59, **reentry: IS04,** 05, 07, 40
- **IFT-5**: **13 October 2024**, successful orbital flight and reentry, booster caught at tower, starship splashdown
  ➔ REB: IS10, 18, 20, 25, 41, 51, 56, 57, reentry (not REB): IS04, 06

Starship: SpaceX's (2nd) integrated flight test, 2023, *IS25*



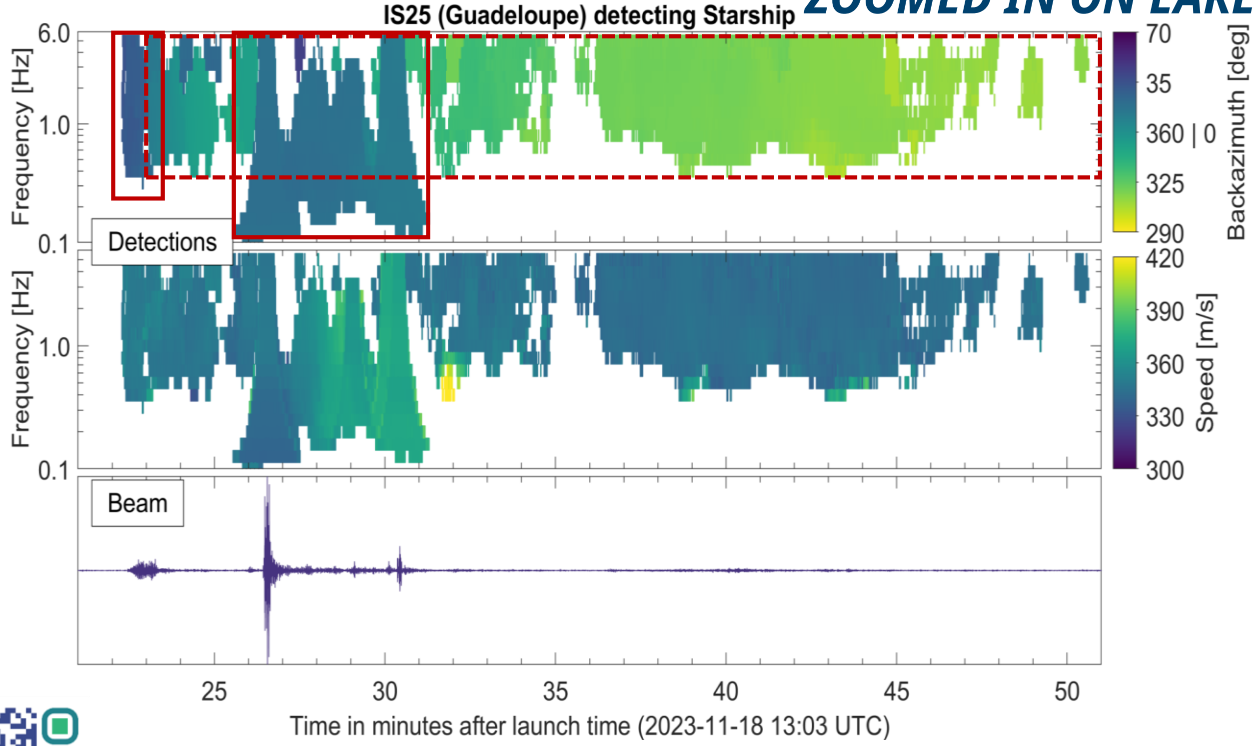
(*Figure from: Pilger and Hupe, 2024, https://doi.org/10.1121/2.0001861*)

Noteworthy features:

- Large time interval (station to spaceport distance is ~ 4000 km) and large backazimuth variation between lift-off (292°) and final flight signals (40°)
- Azimuth variation and reversed timing due to flight path perpendicular and towards the station
- Different signals groups for lift-off, flight, booster separation, explosion(s)

Starship: SpaceX's (2nd) integrated flight test, 2023, *IS25*

ZOOMED IN ON EARLY SIGNALS



(Figure from: Pilger and Hupe, 2024, https://doi.org/10.1121/2.0001861)

Noteworthy features:

Association of known source processes and recorded signals likely associated to them:

- Signal at 23 min: debris reentry after explosion in 150 km altitude of upper stage in ~250 km distance
- Signal at 26-31 min: booster explosion at <90 km altitude, multipathed arrivals
- Signal at 23-50+ min: underlying signal of the rocket as moving source

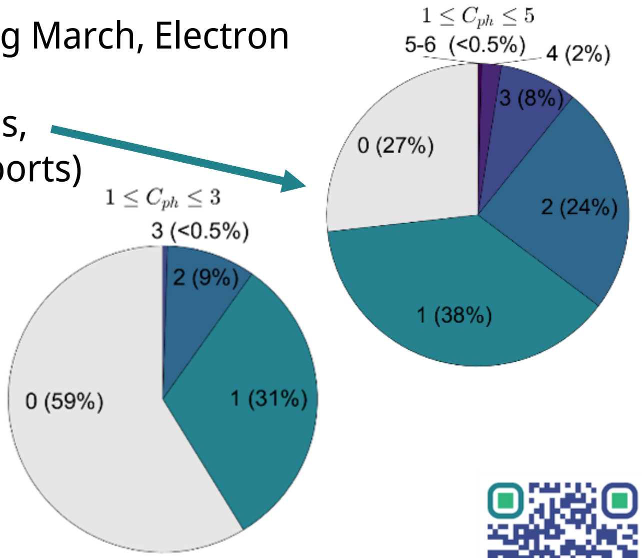
A study on 1001 rocket launches for space missions

Pilger et al., 2021 (*Geophysical Research Letters, doi: 10.1029/2020GL092262*)

- 1001 worldwide space missions from 1 January 2009 to 30 June 2020
- 27 different spaceports (25 land-based, 2 open-sea platforms)
- 76 different rocket types – e.g. Ariane 5, Falcon 9, Soyuz, Long March, Electron

- **7637 infrasound signatures** cover 73% of the 1001 rocket launches, detected at 37 IMS infrasound arrays (within 5000 km of the spaceports)
  - 38% of the launches were detected by one array only
  - one third detected by at least two arrays
  - <3% were detected by 4 or more arrays

- **Initial launch phase signatures**:
  - 41% of the launches detected at 25 IMS arrays,
  - <10% at 2 or more arrays



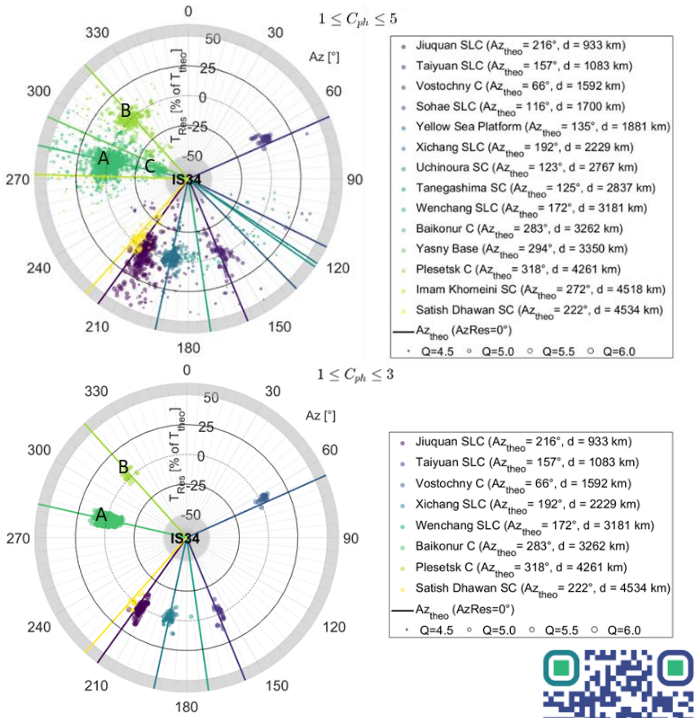
(Figure from: Pilger et al., 2021, https://doi.org/10.1029/2020GL092262*)*

Rocket launches at IS34 from multiple spaceports

Most infrasound detections of rocket launches at IMS station **IS34 (Mongolia)** – **total of 2253 signatures** from 206 launches at 14 different spaceports in
China, India, Kazakhstan, Russia, Iran, South Korea, Japan

- ➢ seasonal propagation effects; e.g. signals from Baikonur (A) and Plesetsk (B) directions only during winter (eastward propagation)
- ➢ accumulations at larger time residuals (C) are mostly associated to later flight stages
- ➢ **Initial launch phases** (filtered using quality and repetitive signal criteria) are only detected from half of the spaceports

➔ Detections of the initial launch phases are more constrained, closer to the ground truth in time and direction, and are used to derive source information (rocket type, thrust, acoustic amplitude)

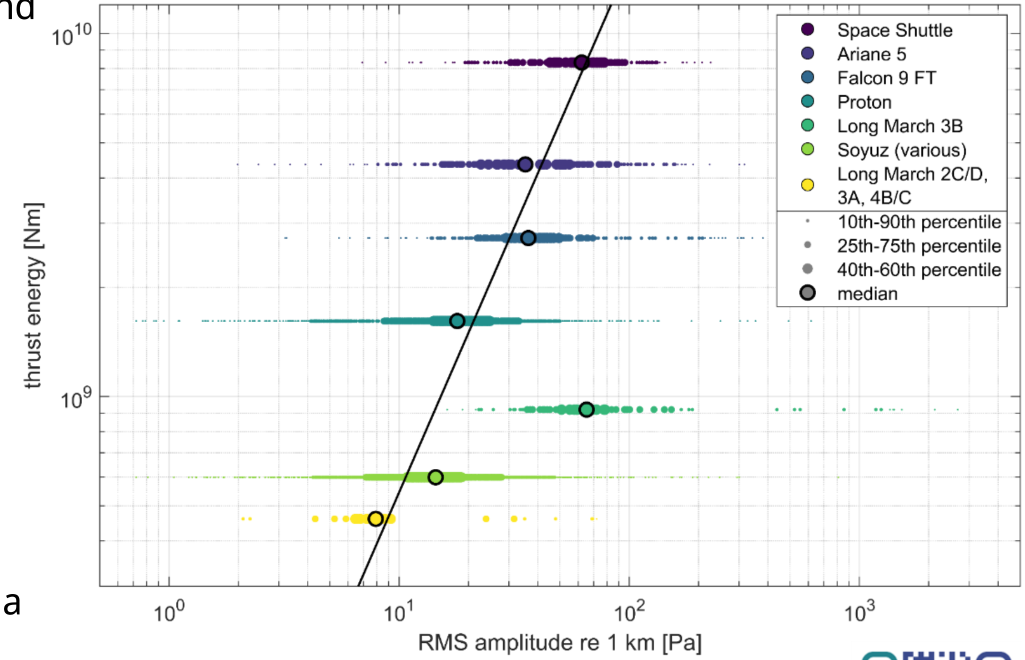


(Figure from: Pilger et al., 2021, https://doi.org/10.1029/2020GL092262)

Estimate of an energy vs. amplitude relation

- Six rocket types launched at least 50 times and eleven Space Shuttle launches (2009-2011)
  - different thrust levels from 3 to 30 MN
  - total of 1146 (initial launch) signatures
- RMS amplitude: **attenuation-corrected**, respective to 1 km distance (Le Pichon et al., 2012, *Journal of Geophysical Research, doi: 10.1029/2011JD016670*)
- Interesting yet not fully understood **outlier**: Long March 3B launches (disregarded)
- Simplified assumptions allow formulation of a first robust **relation of thrust energy and infrasonic amplitude** released during the initial launch phase:

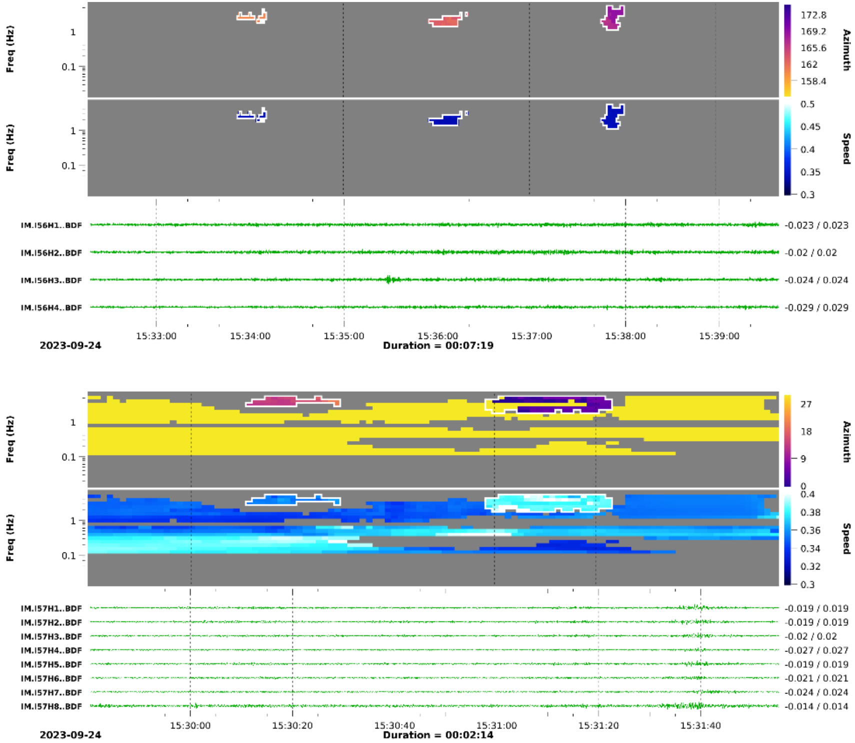
$$\log_{10}(E) = 1.458 \cdot \log_{10}\left(A_{\mathrm{RMS,re\,1\,km}}\right) + 7.278$$

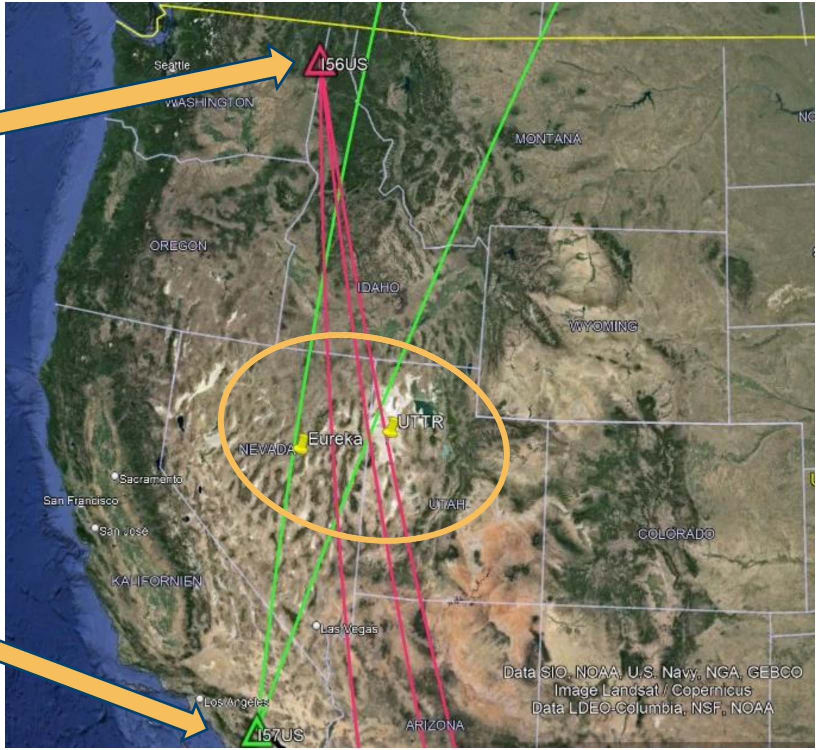


(Figure from: Pilger et al., 2021, [*https://doi.org/10.1029/2020GL092262*](https://doi.org/10.1029/2020GL092262)*)*

Reentry: OSIRIS-Rex, September 2023, *IS56 ? & IS57 ?*

Sample return capsule… planned return at the Utah Test and Training Range, UT, USA

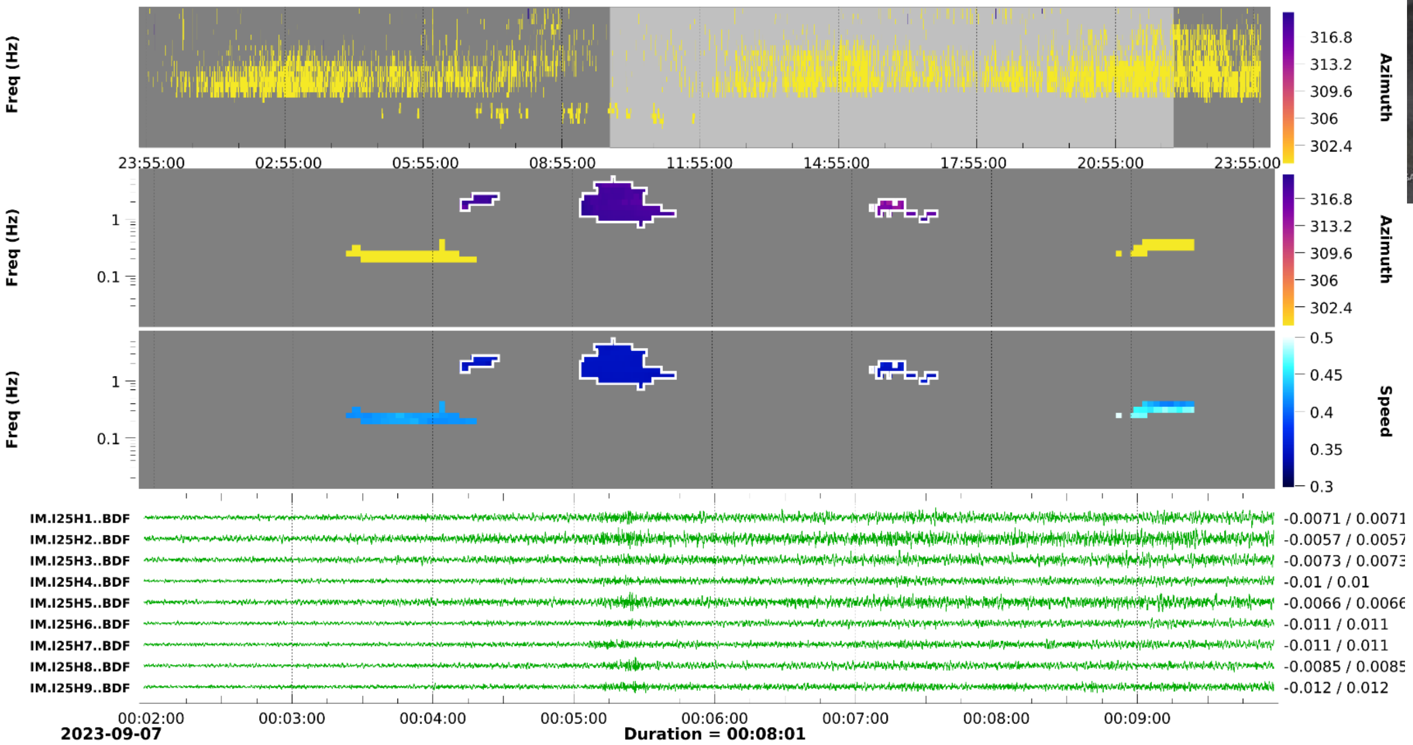




➢ Weak signals but (back projected) location and (back propagated) origin time fit well …

Reentry: SpaceX Starlink-30167, September 2023, *IS25*

satellite (debris, breakup)… splashdown north of Puerto Rico, Carribbean Sea

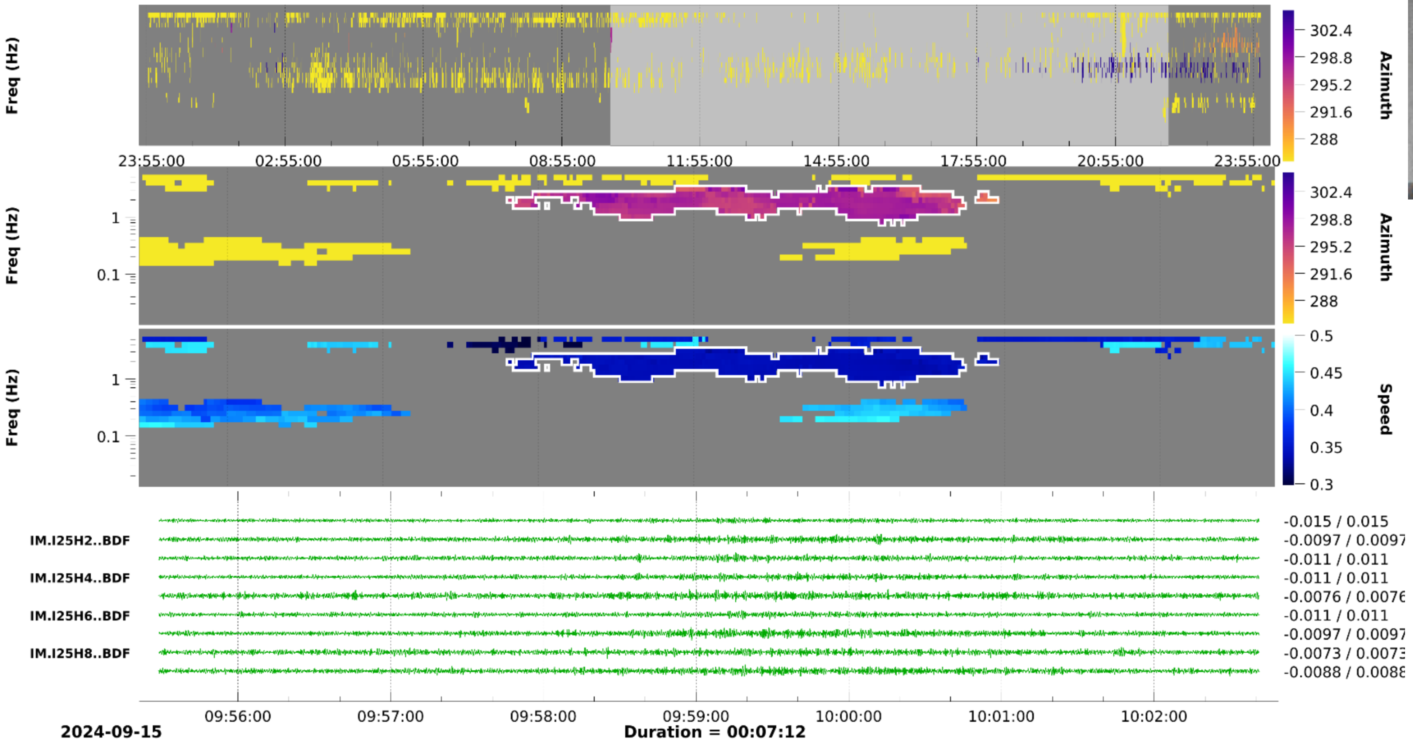


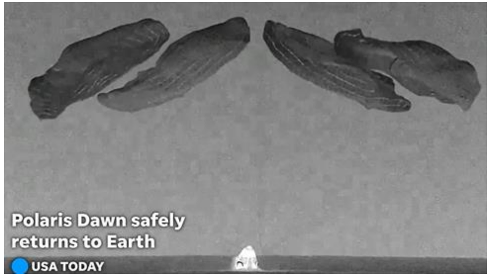
Noteworthy features:

- One station detection only, direction towards source region, but large uncertainty, weak signal
- Multiple signal parts (fragmentation? Multi-path propagation? Incoherent signal?)

Reentry: SpaceX Polaris Dawn, September 2024, *IS25*

crewed space capsule… splashdown in the Dry Tortugas, west of Florida Keys, USA



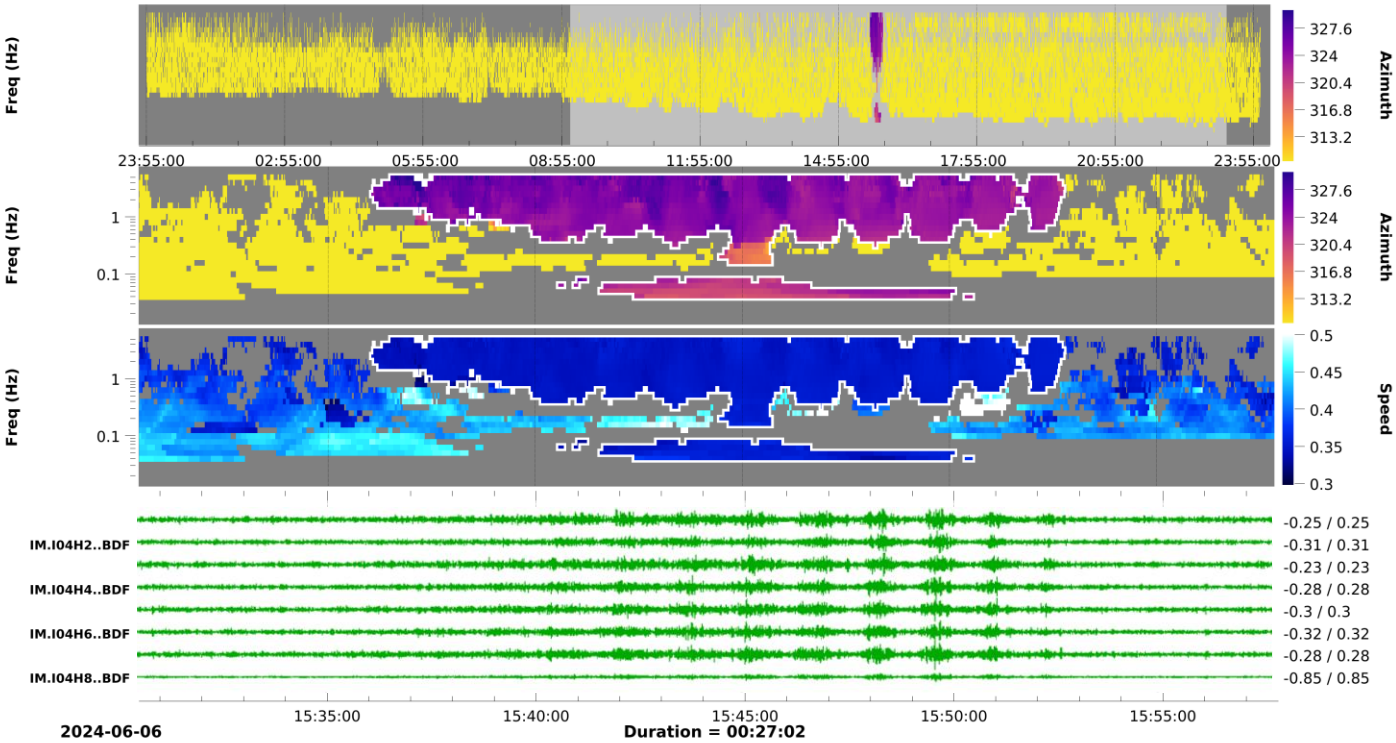


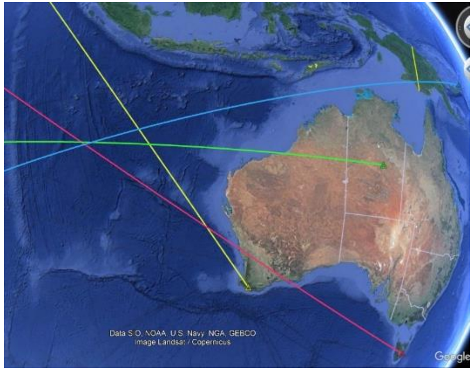
Noteworthy features:

- One year later, same station, same season, nearly same direction
- One station detection only, direction towards landing zone, weak signal
- Single signal (connected, no fragmentation!)

Reentry: SpaceX Starship (IFT-4), June 2024, *IS04*

splashdown in the Indian Ocean west of Australia (detected at **IS04**, IS05, IS07, IS40)





Noteworthy features:

- Extended, multi-pathed pressure signals at **IS04**, detections at distances from 2000 to 6000 km
- High amplitude, broad frequency signal content

Conclusions

- **Rocket Launches and Reentries** are an ideal object for the large-distance, remote study of (ground-truth) surface and (moving source) atmospheric **infrasound (noise),** they can be identified, analyzed and characterized by array localizing and processing methods

- These studies provide insights on infrasound propagation, attenuation and on the **detection capability** of the IMS infrasound network dedicated to monitor and verify nuclear explosions

- The presented **energy-amplitude relation** and the utilized attenuation relation **will be revisited** in the coming year(s), taking into account new model developments and additional rocket launch cases

- **A new systematic study will be prepared** in the coming year(s) and is planned to cover at least 15 years and 1500 to probably 2000 rocket launches, including most recent launches of new rocket types like Artemis, Ariane 6, Starship and others

We appreciate your comments and feedback (please contact: christoph.pilger@bgr.de, patrick.hupe@bgr.de)

Thank you!