Ground-truth Reference Dataset of **1001 Rocket Launches for Space Missions and their Infrasonic Signatures**

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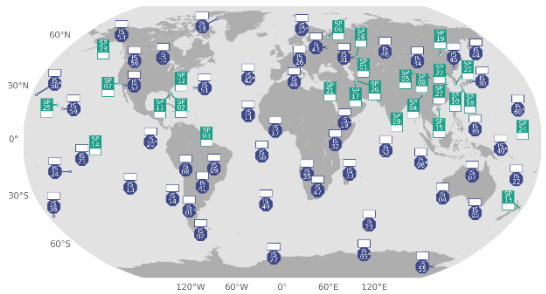
EGU21-8474, NH8.6

vPICO

1001 Rocket Launches for Space Missions and their Infrasonic Signatures

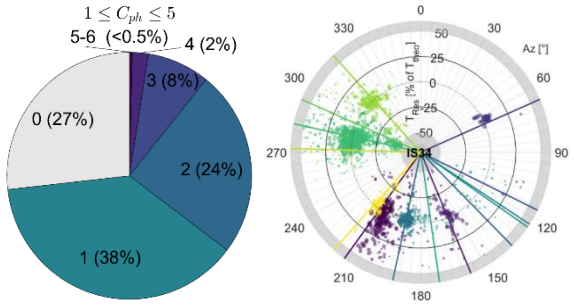
Data & methods

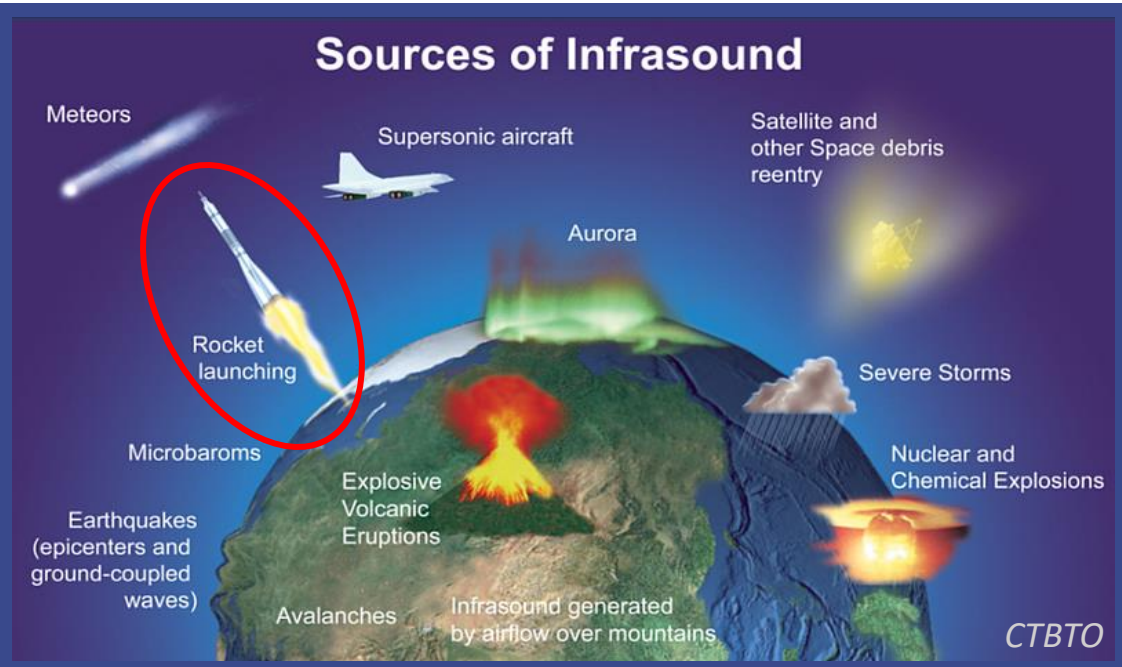
Launches, spaceports, infrasound: automated processing and new quality criteria for event selection



Detectability at IMS stations

Global detection statistics for IMS infrasound network & station IS34 detecting the most events

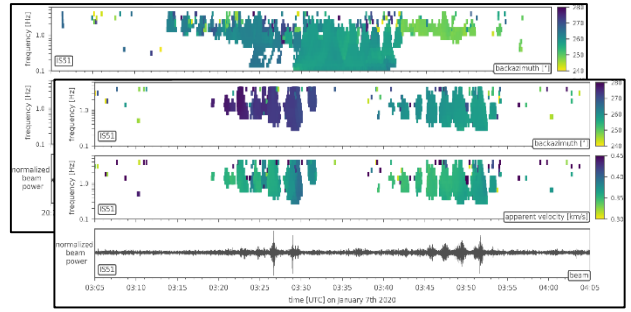




- Rockets: vessels with thrusts up to thousands of kilonewton
- Acceleration by reactive mass expulsion of burned fuel to overcome the Earth's gravitational influence
- Potential infrasound generation during launches: ignition, burning, re-entry, supersonic velocities (Mach cone)
- Earlier studies: focus on single or specific rocket types
- ➢ Here: 1001 launches (2009-2020), global infrasound system
- ➢ Event signatures provided as open-access data product

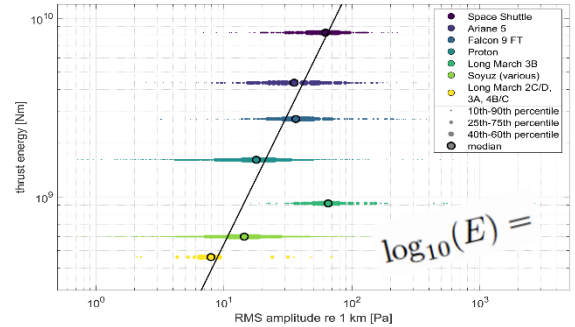
Infrasound signatures

Processing examples of Space Shuttle and Falcon 9 launches: identifying multiple launch phases



Amplitude–energy relation

Robust relation estimate between infrasonic amplitude and energy released during lift-off



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1001 Rocket Launches for Space Missions and their Infrasonic Signatures

The infrasound technique is applied to monitor atmospheric explosions in the context of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) and, among other purposes, to characterize large meteoroids entering Earth's atmosphere. Anyhow, for both types of sources, the exact location and time are initially unknown and sometimes difficult to precisely estimate. In contrast, rocket launches are well-defined ground-truth events generating strong infrasonic signatures. In this study, we analyse infrasound signatures of 1001 rocket launches for space missions recorded at stations of the International Monitoring System (IMS) between 2009 and mid-2020. We include all surface- or ocean-based launches within this period with known launch time, location, rocket type, and mission name; whereas launches of sounding rockets and ballistic missiles for scientific and military purposes, respectively, are excluded from our study. We characterize the infrasonic signatures of over 70 different types of rockets launched at 27 different globally distributed spaceports and are able to identify infrasound signatures from up to 73% of the launches considered. We use this unique dataset to estimate the global detectability of such events and to characterize rocket infrasound. We provide the results as a DOI-assigned ground-truth reference dataset for supporting its further use in geophysical and atmospheric research.

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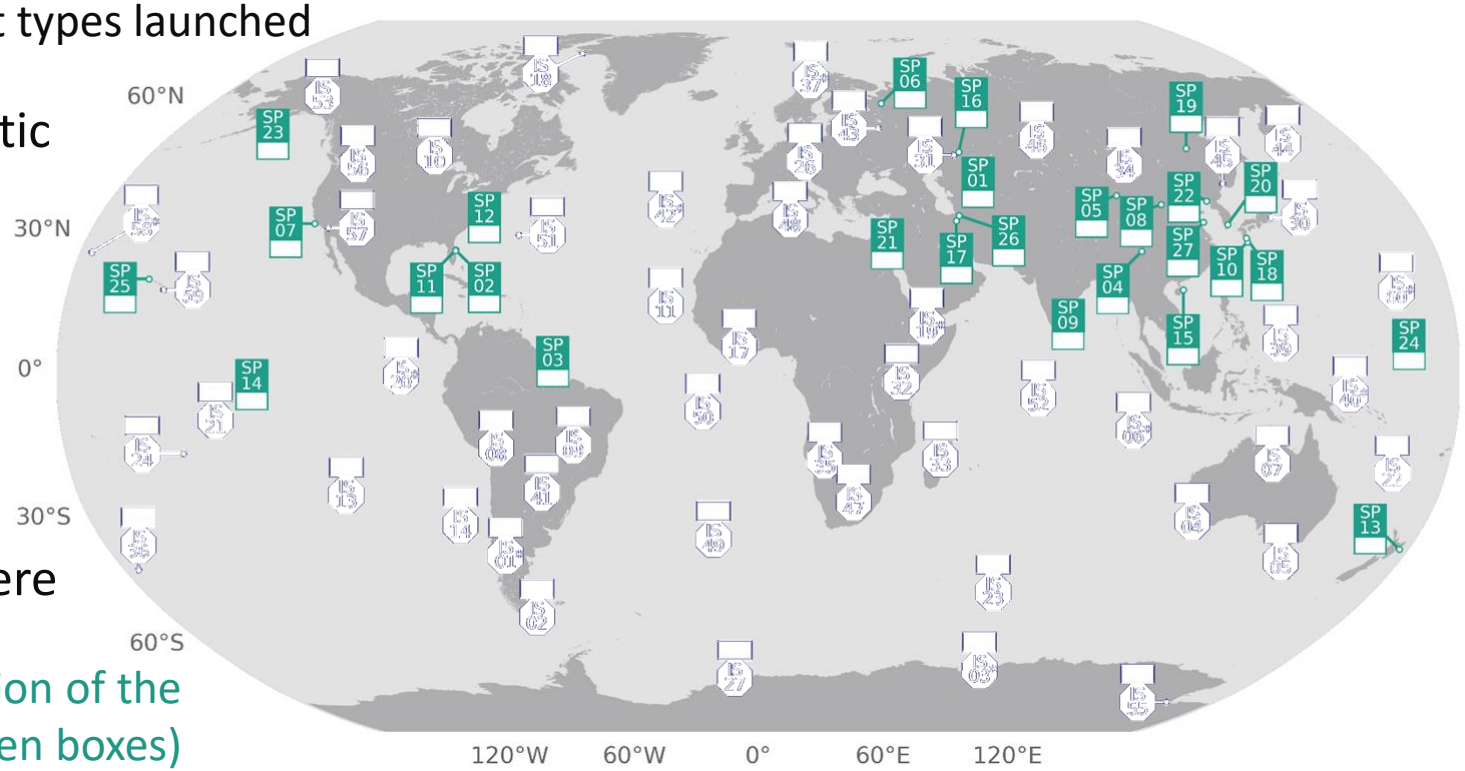
Database: rocket & spaceport information

- ✓ 1001 rocket launches for space missions between January 2009 and June 2020 (11.5 years) with known start time, location, rocket type, and mission name
  - conducted at 27 different spaceports (25 land-based, 2 open-sea platforms)
  - 76 different rocket types launched
- X Not included: ballistic missiles, sounding rockets
- Many spaceports located in Asia
- Only one SP in the Southern Hemisphere



Global distribution of the 27 spaceports (green boxes)

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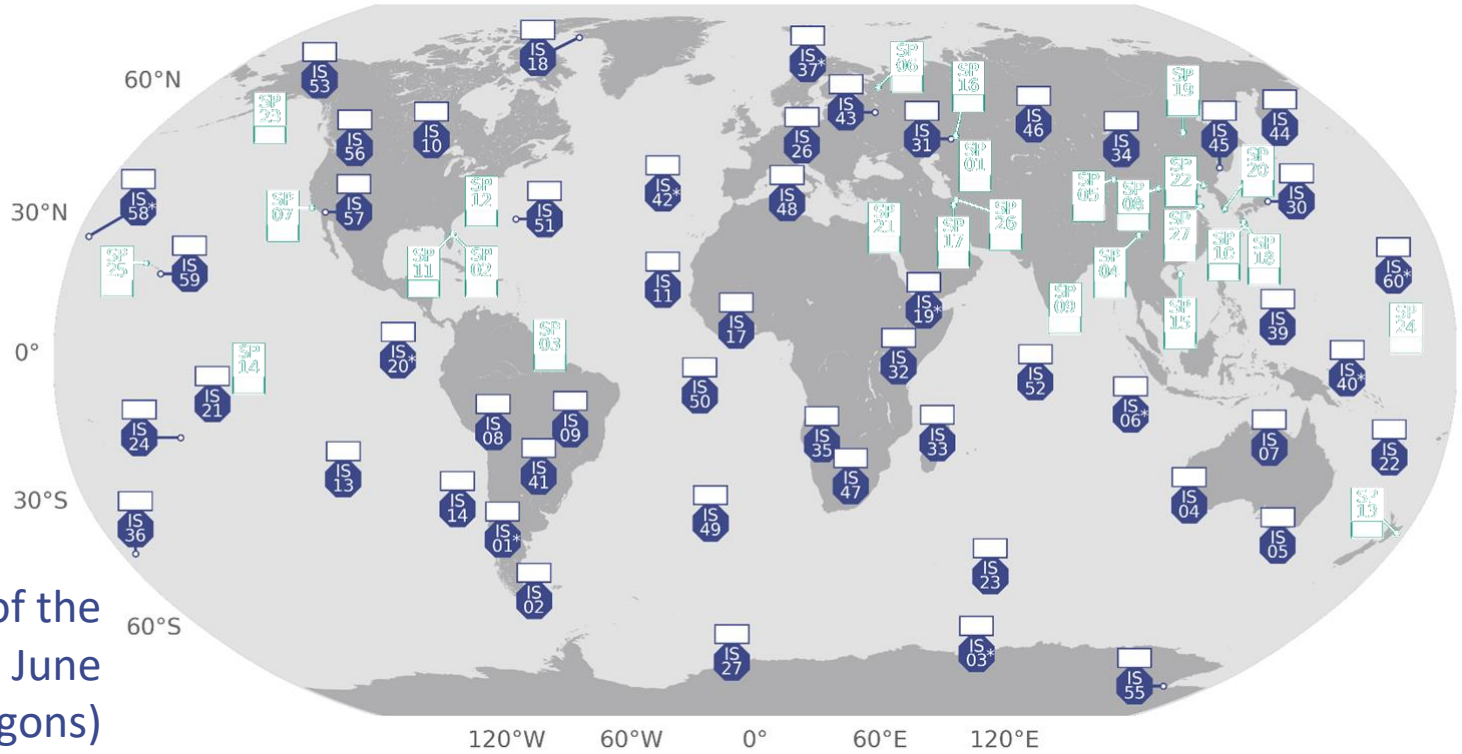
Database: infrasound

- Differential pressure data of IMS infrasound arrays
- Infrasound data are regularly reprocessed at BGR using the Progressive Multi-Channel Correlation (PMCC) algorithm [Cansi, 1995; Cansi & Le Pichon, 2008]
- Only certified stations: number increasing from 42 in early 2009 to 52 in early 2020



52 infrasound stations of the IMS, certified before June 2020 (blue octagons)

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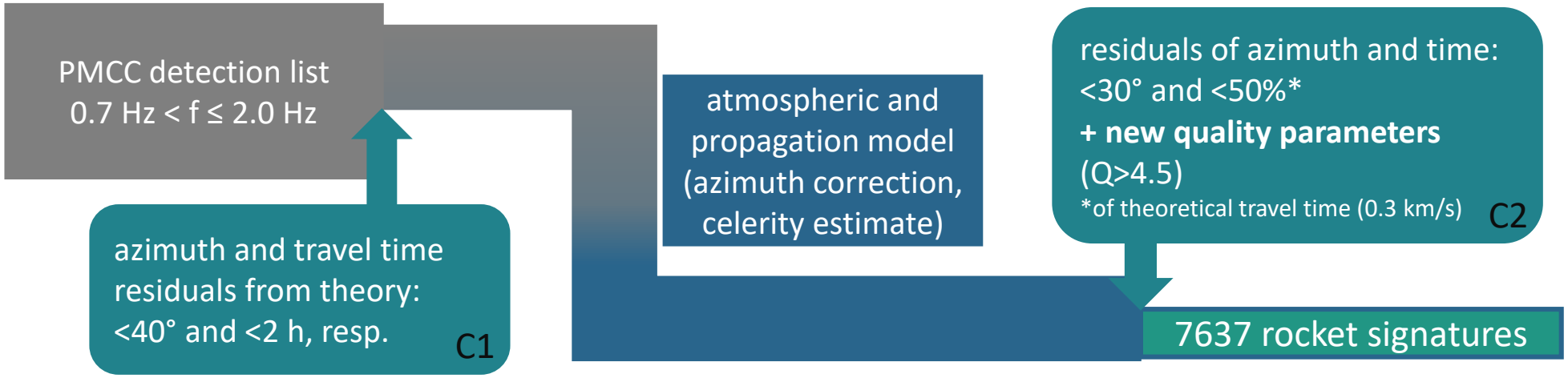
Data processing: automatic selection of potential rocket launch signatures

- PMCC configuration: one-third-octave frequency bands between 0.01 and around 5 Hz, overlapping time windows, decreasing windows lengths from 600 to 30 sec
- Event detection lists:
  - focus on center frequencies of between 0.7 and 2.0 Hz (avoiding overlap with dominant microbarom frequencies, i.e. 0.1-0.6 Hz)
  - only stations at maximum distances up to 5000 km from a spaceport
- Two criteria sets applied to the detection parameters for subsequent event selection:



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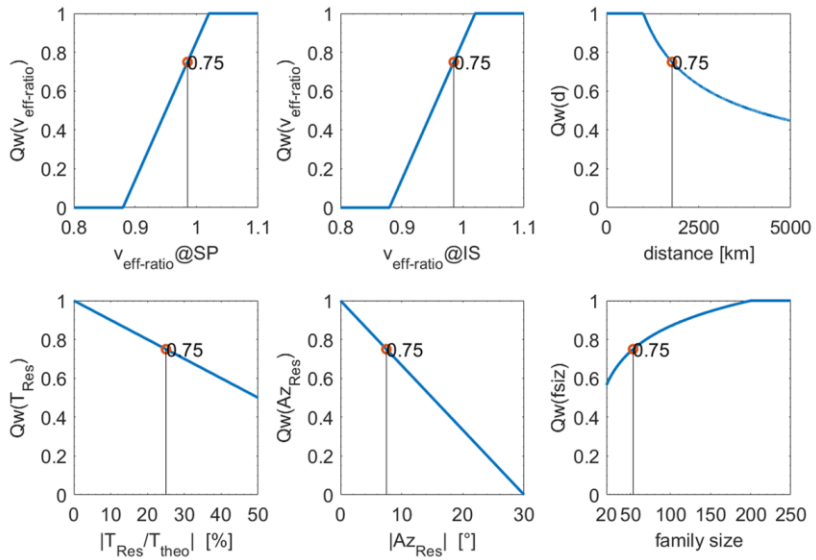
Infrasound quality parameters

Objective: sensitive data set – a **low false-association rate**, disregarding as few true detections as possible

- **Q:** quality indicator ranging from 0 (low) to 6 (high)
  - sum of weighting functions (0-1) for propagation quantities (e.g., eff. sound speed ratios) and detection parameters (e.g., time & azimuth residuals)
  - Q>4.5 represents top-25% quality
- **N_{az}:** indicator for repetitive signals in terms of other sources (based on all infrasound detections between 2009 and 2020, 0.7-2.0 Hz)
- **C_{ph}:** index ranging from 1 to 6 classifying the potential launch phase, depending on Q, N_{az}, Az, T
  - allows to **focus on the lift-off phase**
  - events with C_{ph} = 6 finally sorted out



- C_{ph} *= 1* – very likely related to the lift-off phase
- C_{ph} *= 4* – a potential post-lift-off phase (e.g., re-entry or remote landing)
- C_{ph} *= 6* – very likely another repeating source (e.g., industrial noise in the same direction)

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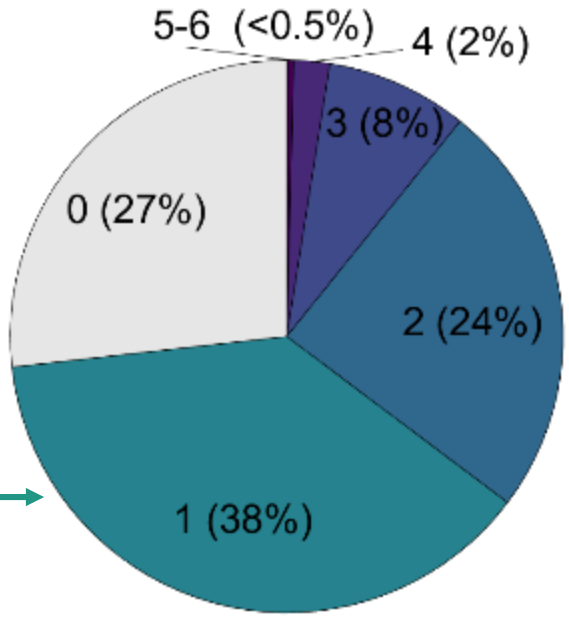
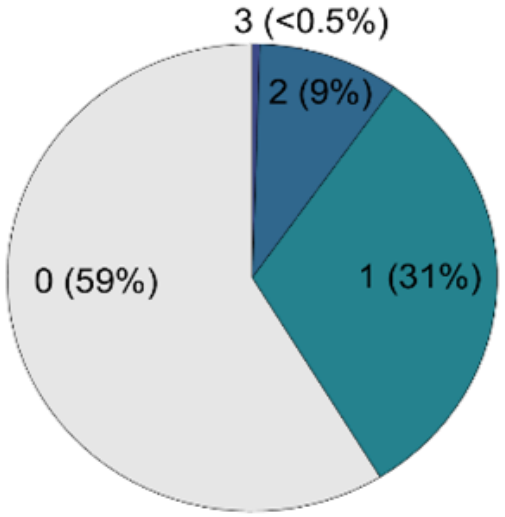
Detectability at IMS stations: global statistics

- 7637 signatures cover 73% of the 1001 rocket launches, detected at 37 IMS infrasound arrays (within 5000 km radius)
  - 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

All ($C_{ph} \leq 5$)



initial phase(s) ($C_{ph} \leq 3$)



- Initial start phase(s), i.e. $C_{ph} \leq 3$: 41% of the launches detected at 25 IMS arrays
- very likely lift-off phase ($C_{ph} = 1$): 1394 signatures (10 IMS arrays)

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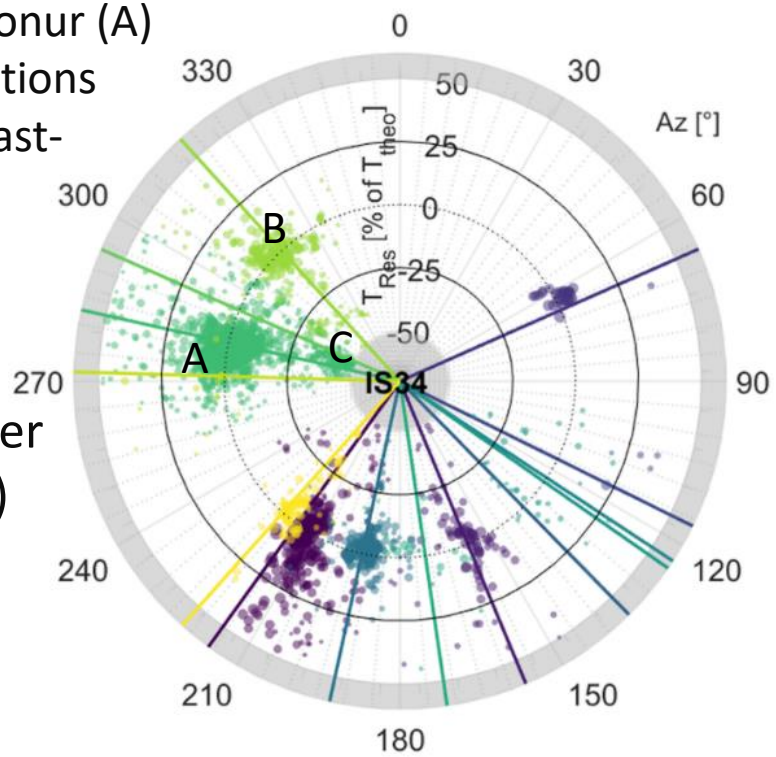
Detectability at IMS stations: IS34, Mongolia

- Most infrasound detections at IS34 – 2253 signatures from 206 launches at 14 different spaceports
- Seasonal propagation effects
  - e.g. signals from Baikonur (A) and Plesetsk (B) directions only during winter (east-ward propagation)
- Accumulations at larger time residuals (e.g., C) are mostly classified as $C_{ph} = 4$



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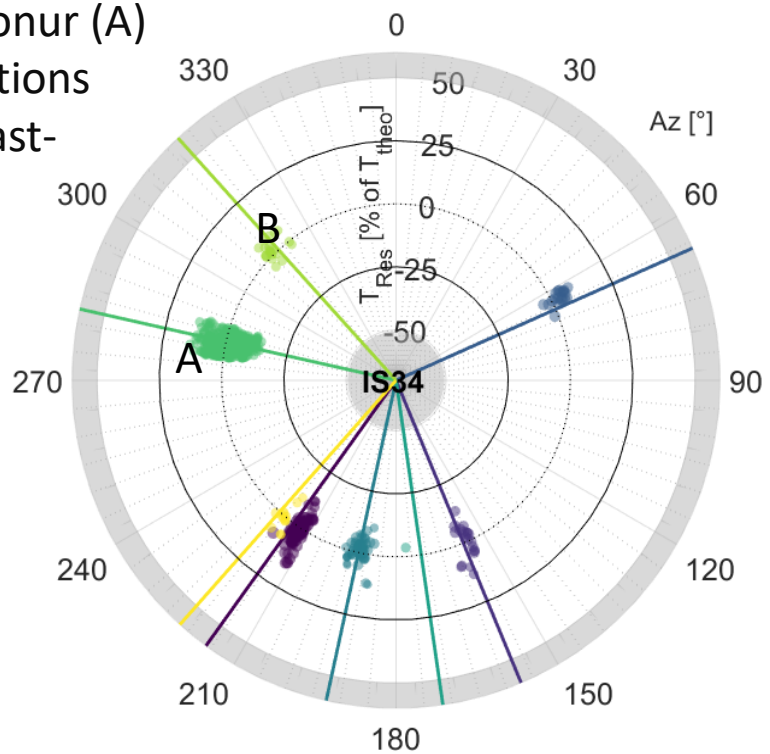
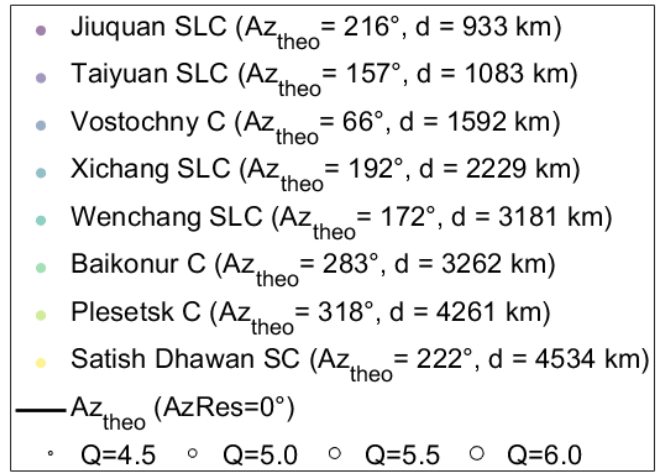
- Seasonal propagation effects
  - e.g. signals from Baikonur (A) and Plesetsk (B) directions only during winter (east-ward propagation)
- Initial launch phases ($C_{ph} \leq 3$) are detected from one half of the spaceports only





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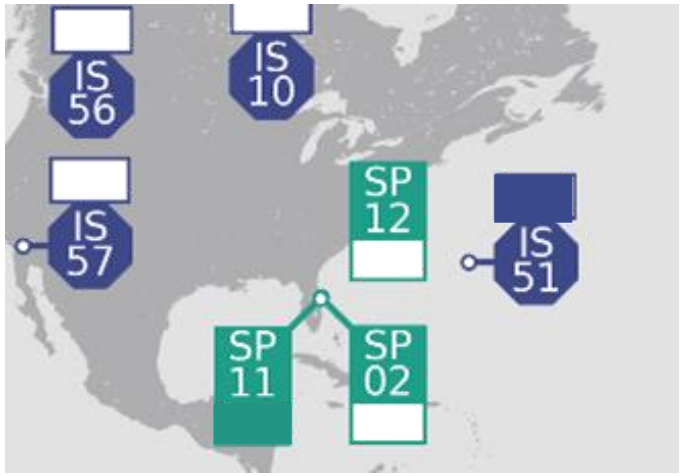
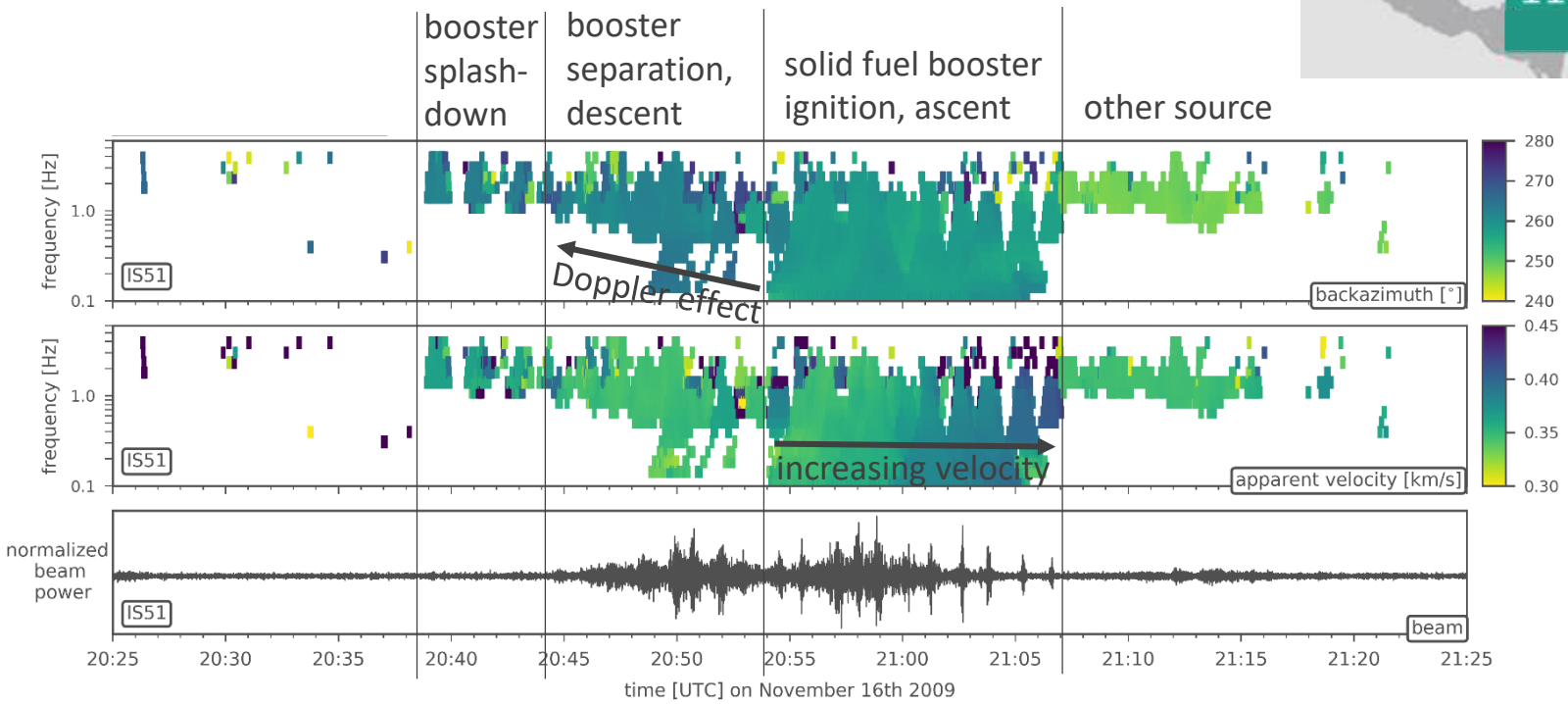
Space Shuttle (2009) detected at IS51 (Bermuda)

- Space ascent into northeastern direction from Kennedy SC
  - Trajectory towards infrasound array at supersonic flight velocities
- Ejected booster: landing between the US coast and Bermuda





- Landing signals detected earlier than initial phases
- Frequency increase (Doppler)
- Increase of apparent velocity: signal returns from increasing altitudes

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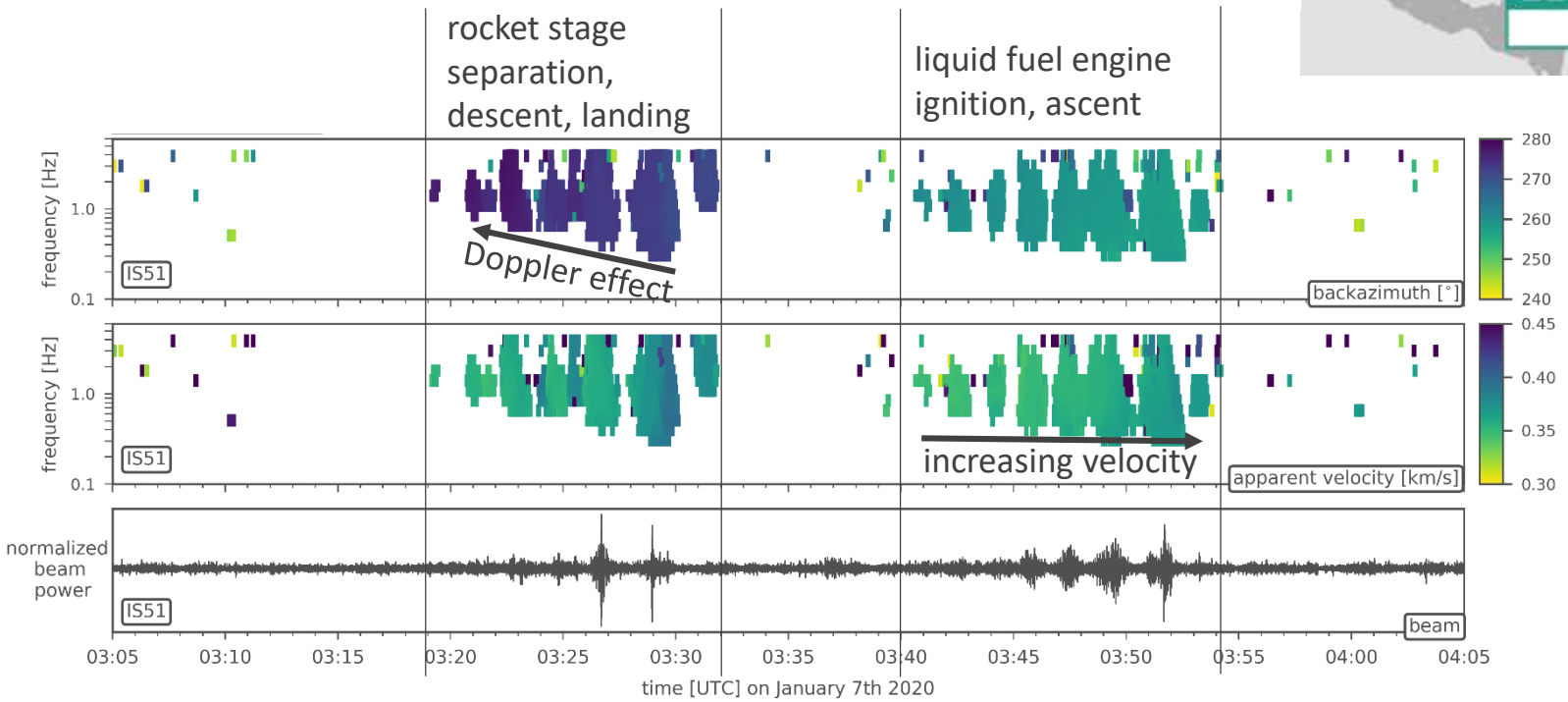
Falcon 9 (2020) detected at IS51 (Bermuda)

- Similar trajectory as for the Space Shuttle example
- Less impulsive acoustic waveform signatures from lift-off engine ignition (here: liquid fuel)
- Landing area nearer to Bermuda, floating platform



- Larger interval between landing and lift-off signals
- Larger azimuth shift
- Stronger landing signals due to another booster ignition before touchdown

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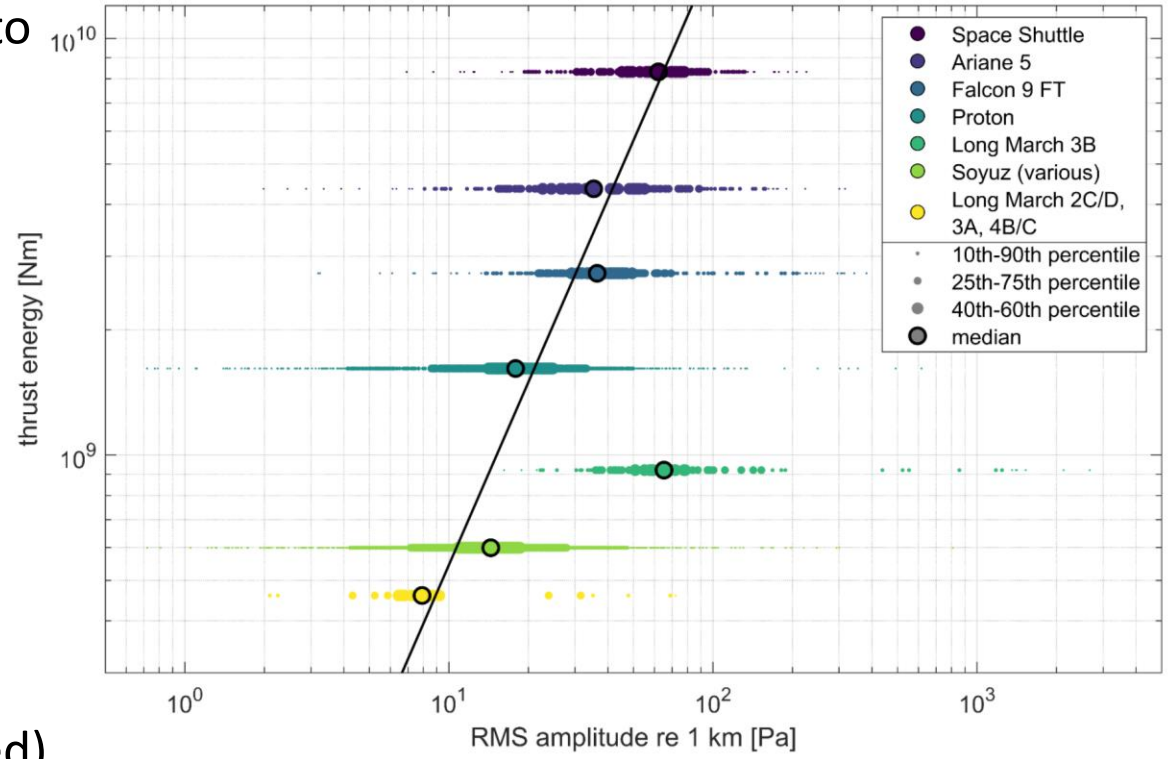
Infrasonic amplitude vs. released energy: a first robust relation estimate

- Only signatures very likely related to the lift-off phase ($C_{ph} = 1$)
- 6 rocket types launched at least 50 times + Space Shuttle (11)
  - different thrust levels
  - 1146 signatures
- Energy: $E = \sum_{t=0}^{t_{boost}} F(t) \cdot v_e(t) \cdot \ln\left(\frac{m_0}{m(t)}\right) \cdot \Delta t$
- RMS amplitude: attenuation-corrected, re 1 km [Le Pichon et al., 2012]
- Outlier: Long March 3B (disregarded)



- Simplified assumptions allow formulation of a first robust amplitude–energy relation:

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

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Summary

- Rocket launches: more complex than infrasound from explosions
  - e.g., different waveform pulses due to different launch phases and different propagation paths
- Data processing using PMCC and automatic post-processing
  - New quality parameters
  - Focus on initial launch phase
- 7367 signatures from up to 733 launches
- Propagation-corrected amplitude–energy relation for rocket launches
- **Open-access** ground-truth **reference data set** for future acoustic & atmospheric studies
  - e.g., detailed investigation towards infrasound magnitude

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