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Infrasonic Signatures of 1001 Rocket Launches for Space Missions

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Events and Nuclear Test Sites

T2.3 - Seismoacoustic Sources in Theory and Practice

Infrasonic Signatures of 1001 Rocket Launches for Space Missions

In the present study we analyze infrasound signatures of 1001 rocket launches for space missions recorded at stations of the International Monitoring System 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 to estimate the general detectability of rocket infrasound, to evaluate the individual station performance, to quantify propagation and attenuation effects and, finally, to derive a relation between rocket thrust and acoustic energy. Results from the infrasound analysis of the launches will be provided as a DOI referenced dataset for supporting future research on infrasound topics as well as on atmospheric dynamics.

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Infrasonic Signatures of 1001 Rocket Launches for Space Missions

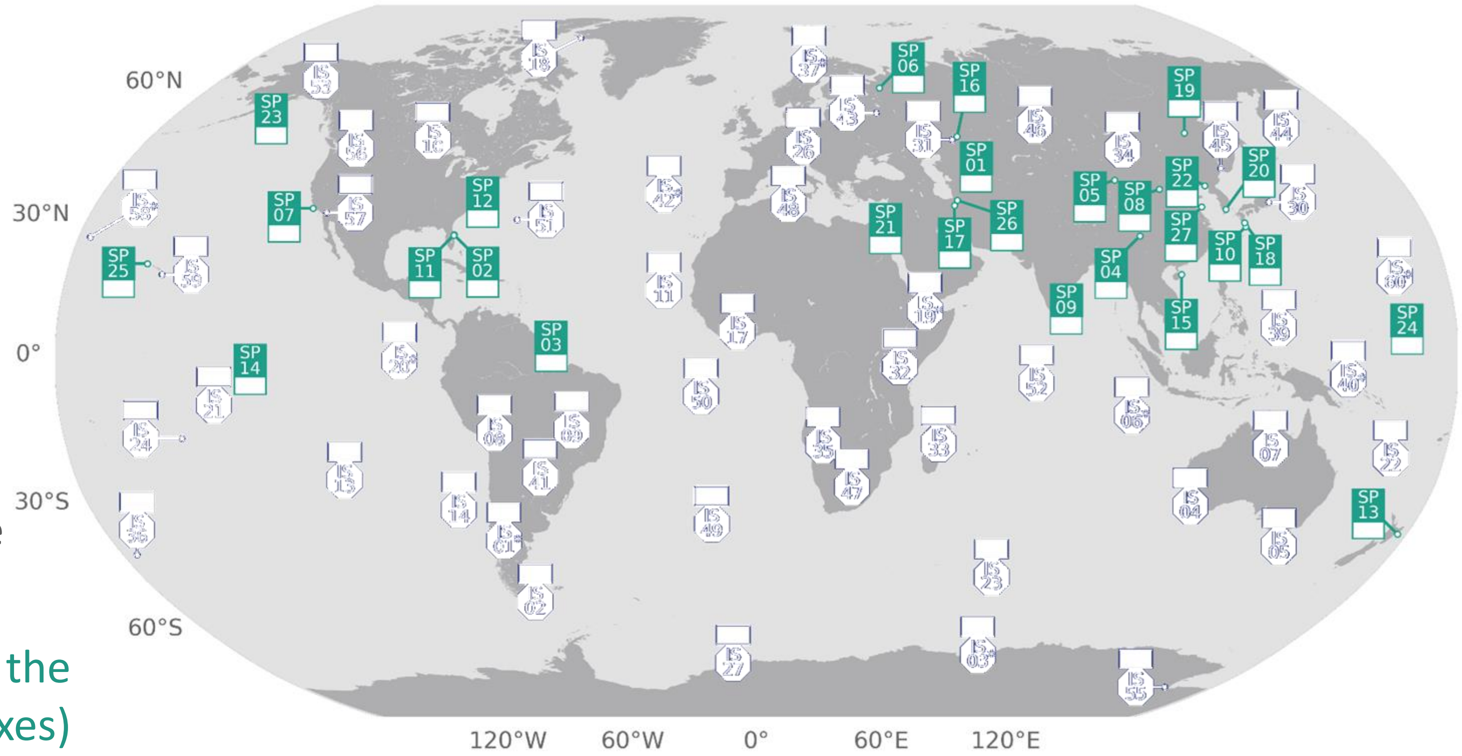
Database: rocket & spaceport information

✓ 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 – e.g., Space Shuttle, Proton, Soyuz, Long March

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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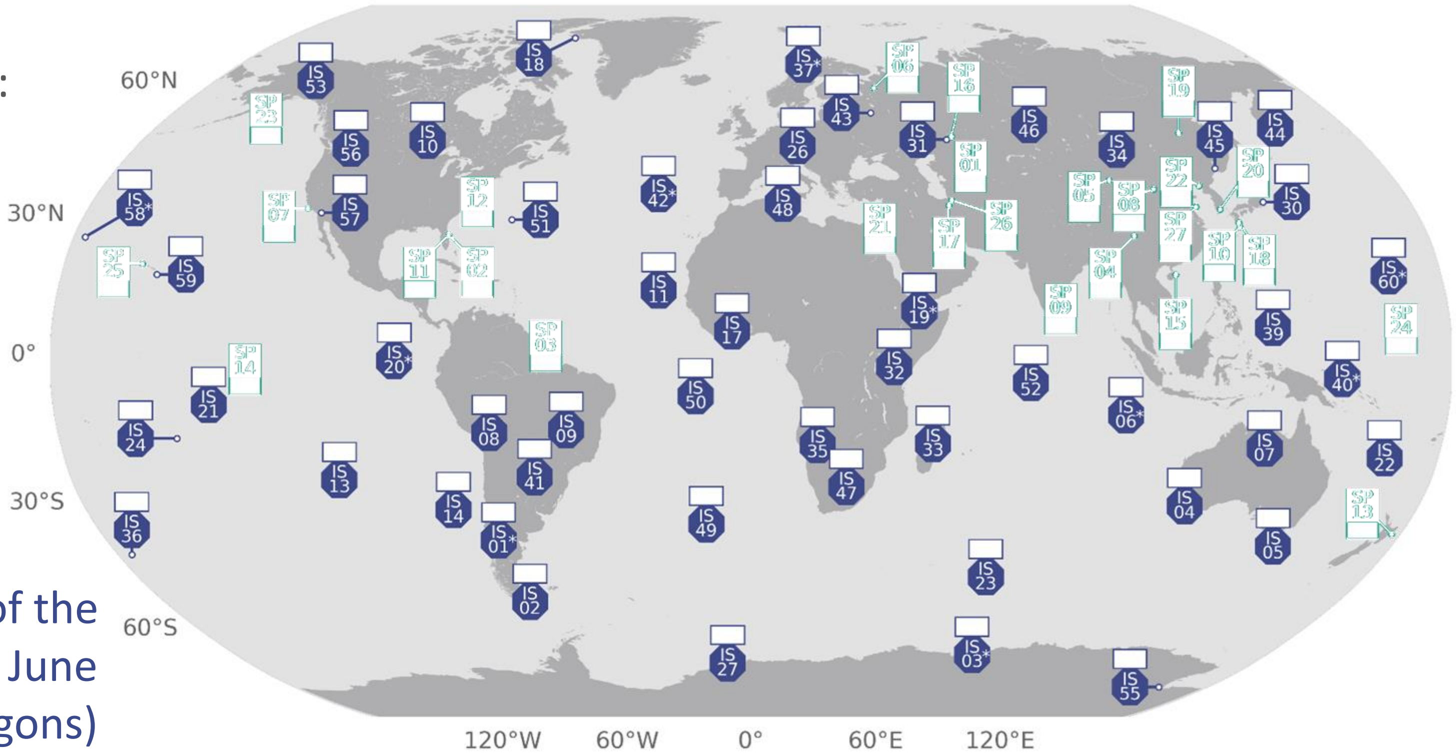
Abstract
Data & methods
Database rockets
Database infrasound
Data processing
Quality parameters
Detectability at IMS
Infrasound signature
Space Shuttle
Falcon 9
Energy vs. amplitude
Summary

Database: infrasound

- Differential pressure data of IMS infrasound arrays
- Infrasound are data 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

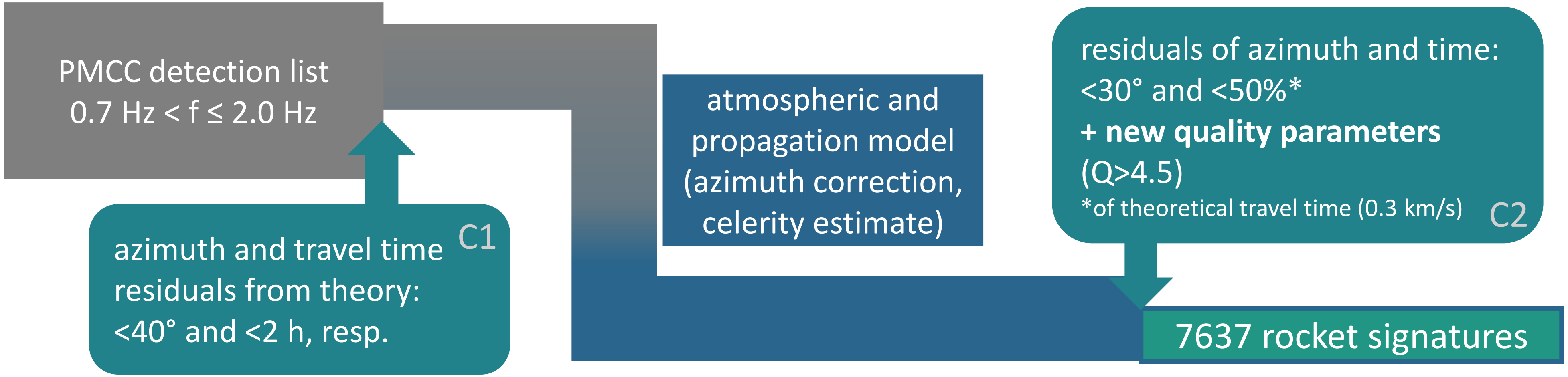


52 infrasound stations of the IMS, certified before June 2020 (blue octagons)

Infrasonic Signatures of 1001 Rocket Launches for Space Missions

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 selection of events:



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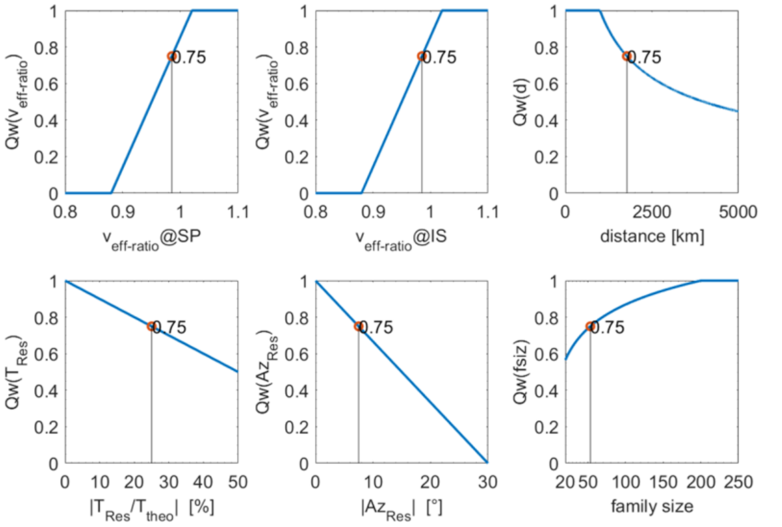
Infrasound quality parameters

Objective: sensitive data set with a **low false-association rate** while 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}, azimuth, and time
  - allows to **focus on the lift-off phase**
  - events with C_{ph} = 6 sorted out

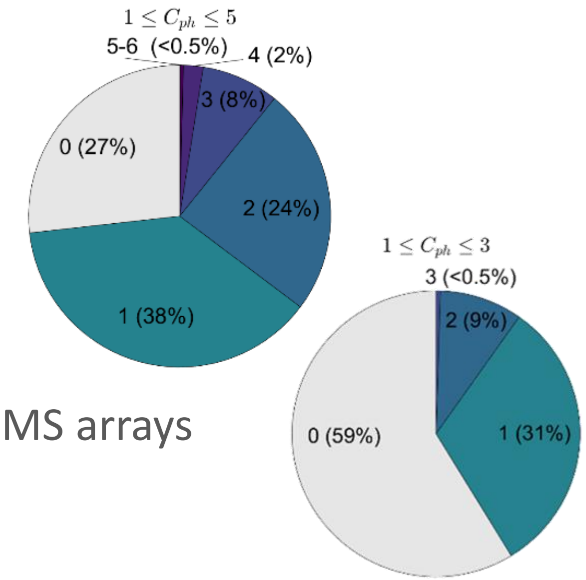


- C_{ph} = *1* – very likely related to the lift-off phase
- C_{ph} = *4* – a potential post-lift-off phase (e.g., re-entry or remote landing)
- C_{ph} = *6* – very likely another repeating source (e.g., industrial noise in the same direction)

Infrasonic Signatures of 1001 Rocket Launches for Space Missions

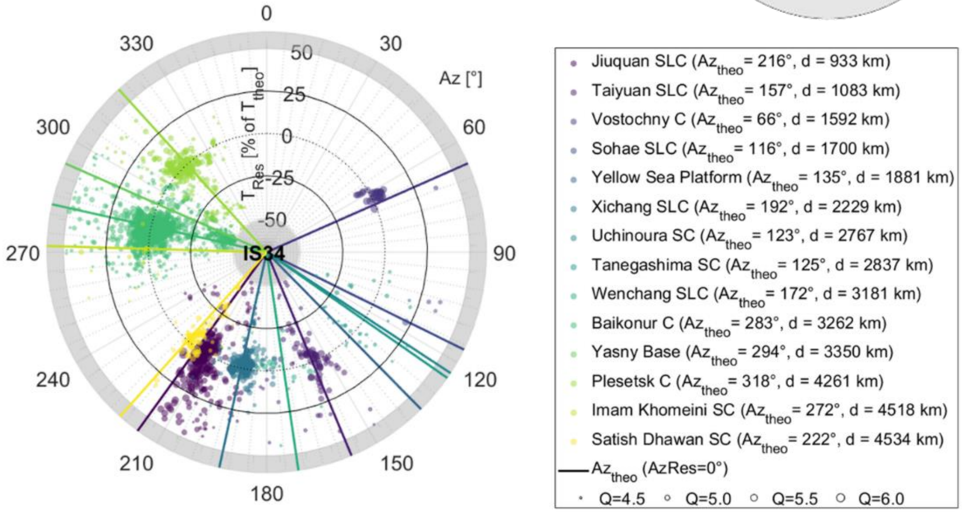
Detectability at IMS stations

- 7637 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 start phase(s), i.e. $C_{ph} < 4$: 41% of the launches detected at 25 IMS arrays
- Very likely lift-off phase ($C_{ph} = 1$): 1394 signatures (10 IMS arrays)

- Most infrasound detections at IS34 (Mongolia) – 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 (eastward propagation)
  - accumulations at larger time residuals (C) are mostly classified as $C_{ph} = 4$
  - Initial launch phases $C_{ph} < 4$ only detected from one half of the spaceports



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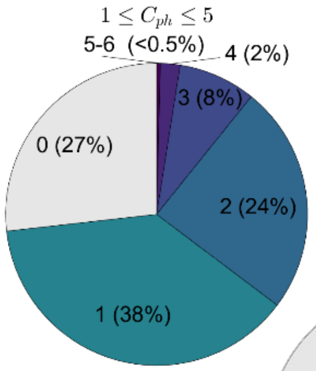

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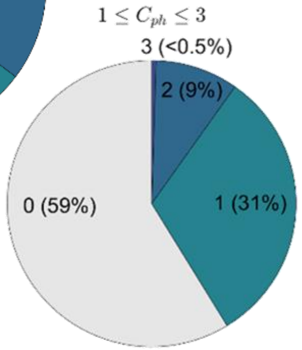

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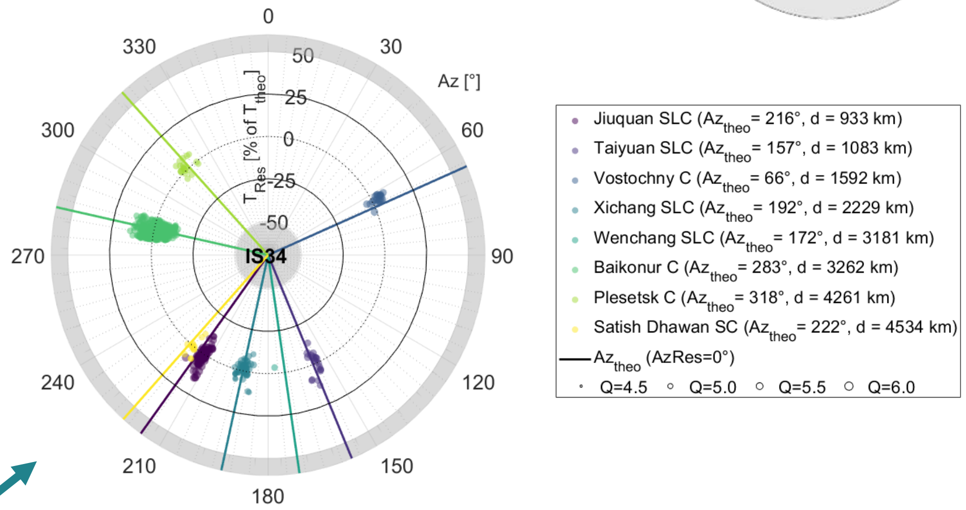

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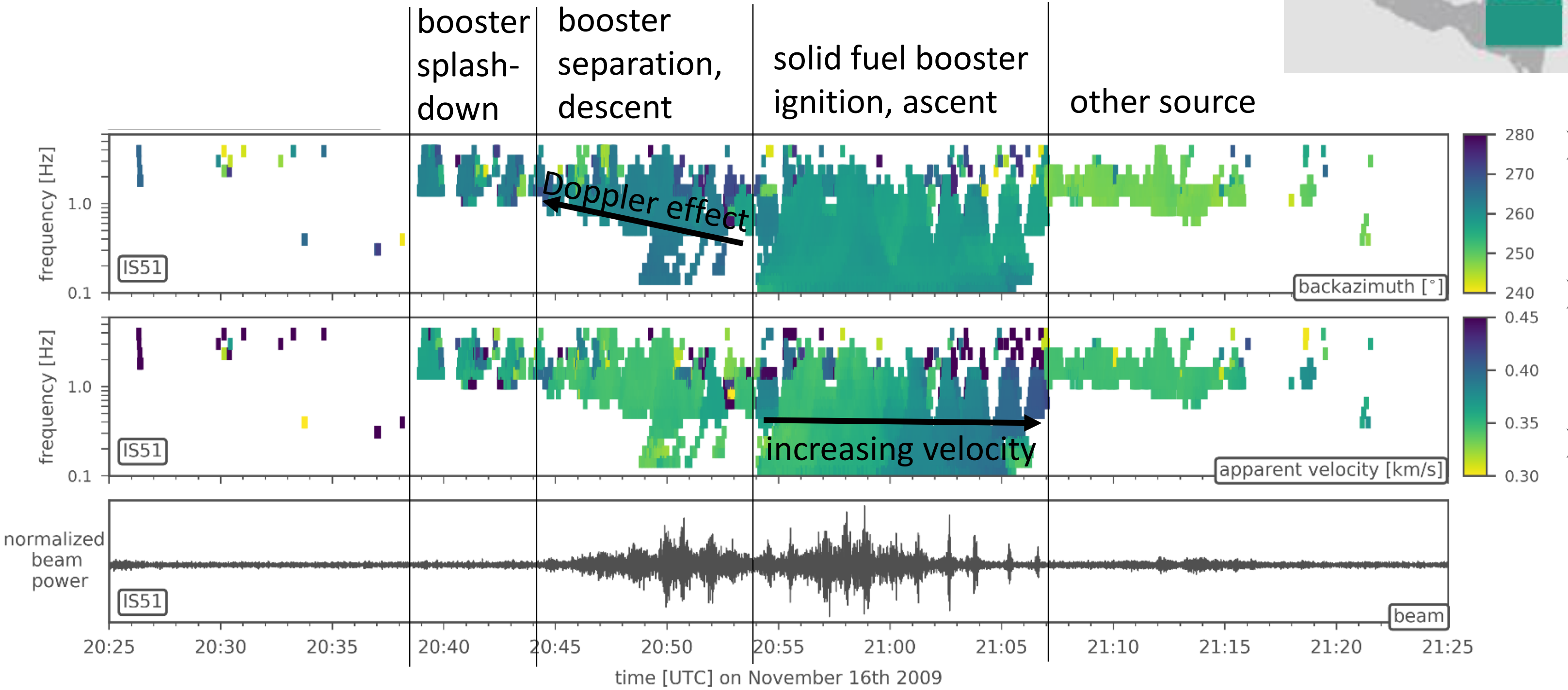
Infrasonic Signatures of 1001 Rocket Launches for Space Missions

Space Shuttle (2009) detected at IS51 (Bermuda)

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



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

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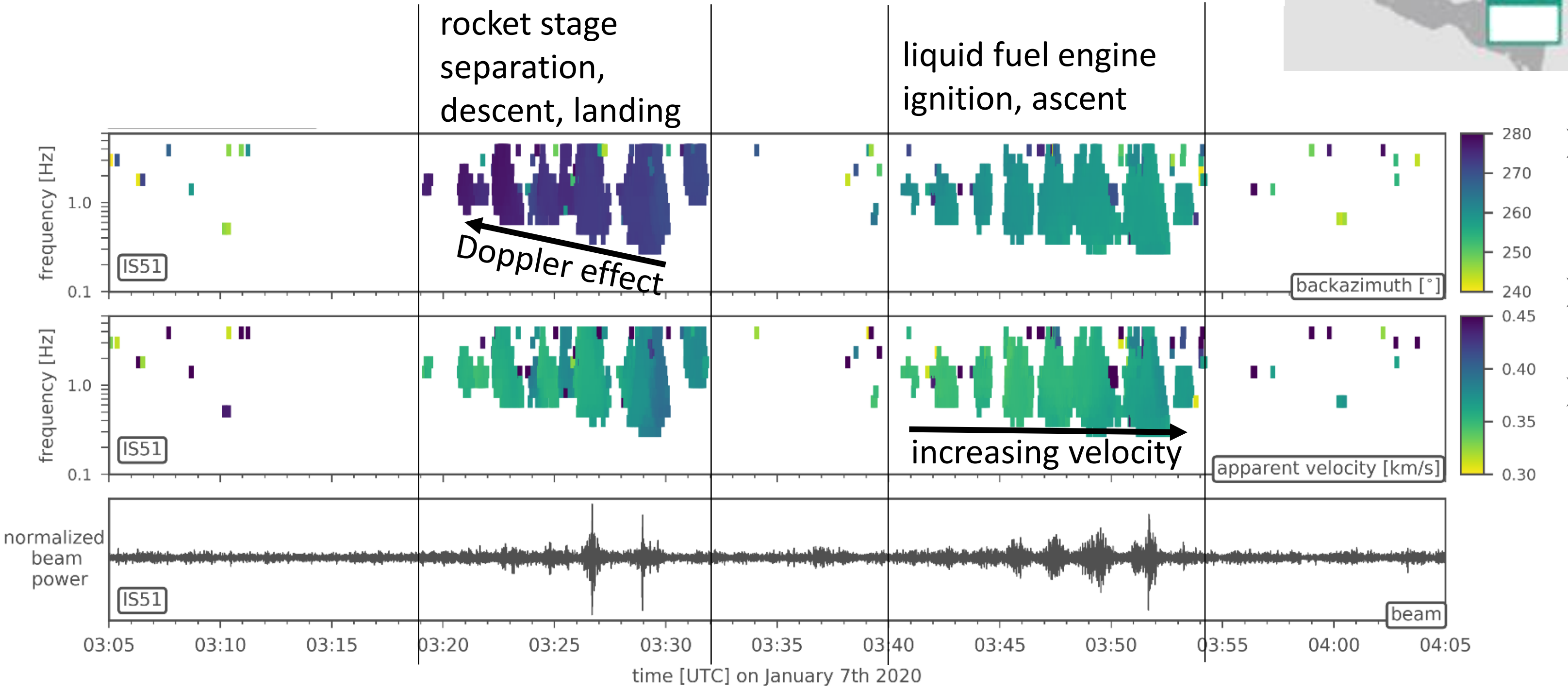
Energy vs. amplitude

Summary

Falcon 9 (2020) detected at IS51 (Bermuda)

- Similar trajectory as for 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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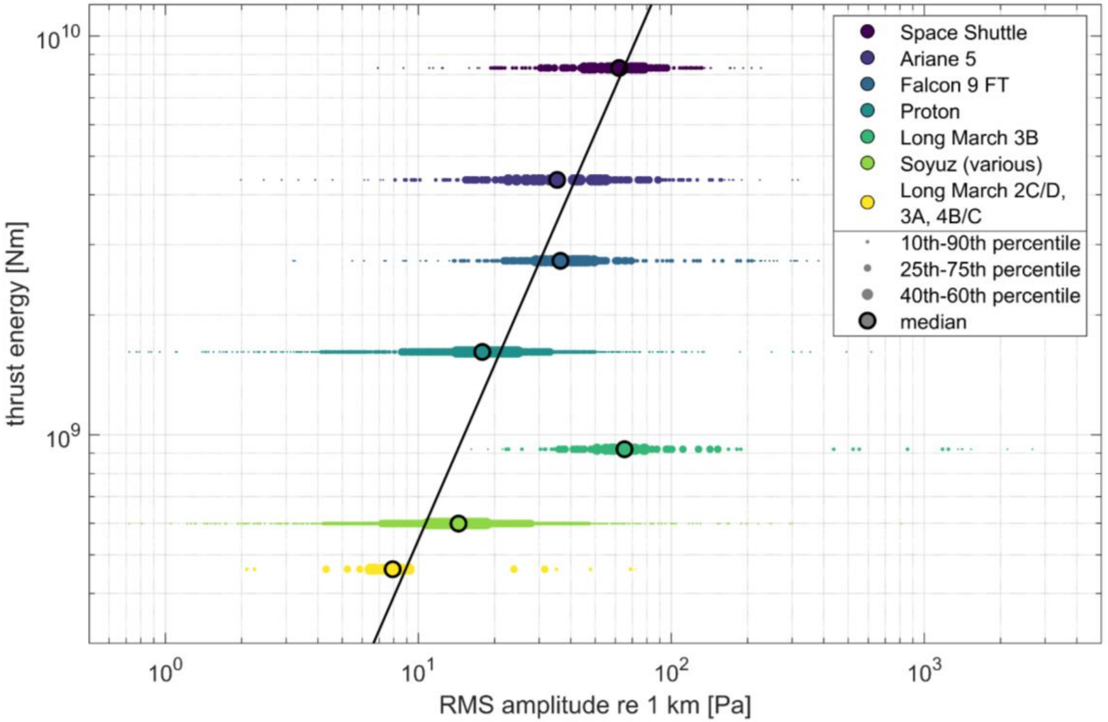
Energy vs. amplitude: a first robust relation estimate

- Signatures with $C_{ph} = 1$
- 6 rocket types launched at least 50 times + Space Shuttle (11)
  - different thrust levels
  - 1146 signatures
- Energy: $E = \sum_{t=0}^{t_{\mathrm{boost}}} F(t) \cdot v_e(t) \cdot \ln\left(\frac{m_0}{m(t)}\right) \cdot \Delta t$
- 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



Relation of infrasonic amplitude and energy released during the initial launch phase:

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

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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
- Focus on initial launch phase
- Automatic data processing
- New quality parameters
- 7367 signatures from up to 733 launches
- Propagation-corrected amplitude–energy relation

- Ground-truth reference data set for future acoustic & atmospheric studies
  - e.g., detailed investigation towards infrasound magnitude

Space Shuttle Endeavour launched from Kennedy Space Center on 16 May 2011

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