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Study of seismoacoustic signatures of the September 28th 2018 Sulawesi earthquake

Christoph Pilger[1], Peter Gaebler[1], Lars Ceranna[1], Alexis Le Pichon[2], Julien Vergoz[2], Anna Perttu[3], Dorianne Tailpied[3], Benoit Taisne[3]

[1]BGR / B4.3, Hannover, Germany
[2]CEA / DAM / DIF, Arpajon, France
[3]EOS, NTU, Singapore

Contact: christoph.pilger@bgr.de

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Abstract

A **magnitude 7.5 (Mw) earthquake** with subsequent landslides and tsunami occurred on September 28th 2018 at 10:02:43 UTC near the city of Palu on the Indonesian island of Sulawesi. It was a left lateral strike-slip event along the Palu-Koro fault with a depth of about 20 km. The rupture zone extended over a length of about 150 km in a nearly straight north-south direction with an average rupture speed of 4.1 km/s, thus indicating a **super shear earthquake**.

Clear and long-lasting infrasound signatures related to this event were observed by four infrasound arrays of the International Monitoring System (IMS) as well as one infrasound sensor by the Earth Observatory of Singapore (EOS). Although the stations **SING (Singapore), I39PW (Palau), I07AU (Australia), I40PG (Papua New Guinea) and I30JP (Japan)** are located in distances between 1800 km and 4500 km from the earthquake's epicenter (0.256°S, 119.846°E), distinct signals including seismic and acoustic arrivals were recorded at the infrasound arrays and associated to the event.

The super shear rupture as well as the **seismoacoustic coupling** to nearby (mountainous) terrain features have an impact on the infrasound emitted and subsequently observed.

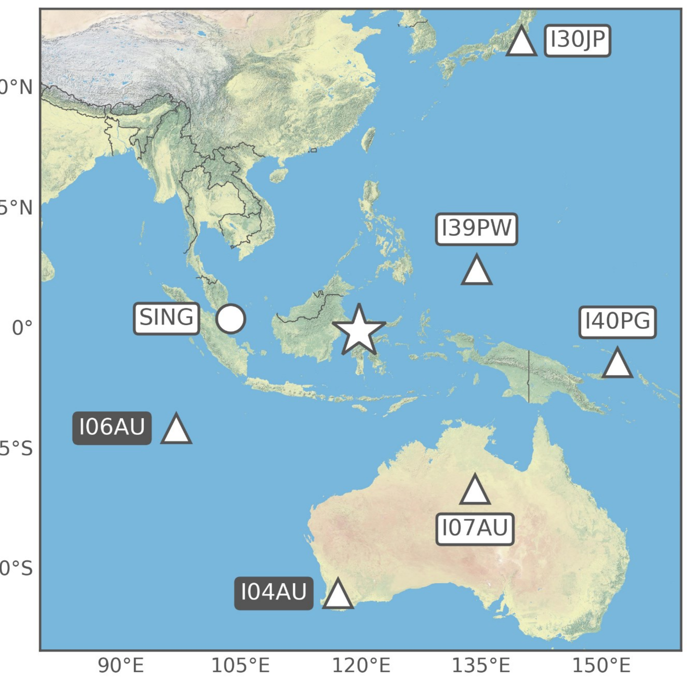

Figure 1: Earthquake epicenter and infrasound stations

Infrasound Observations

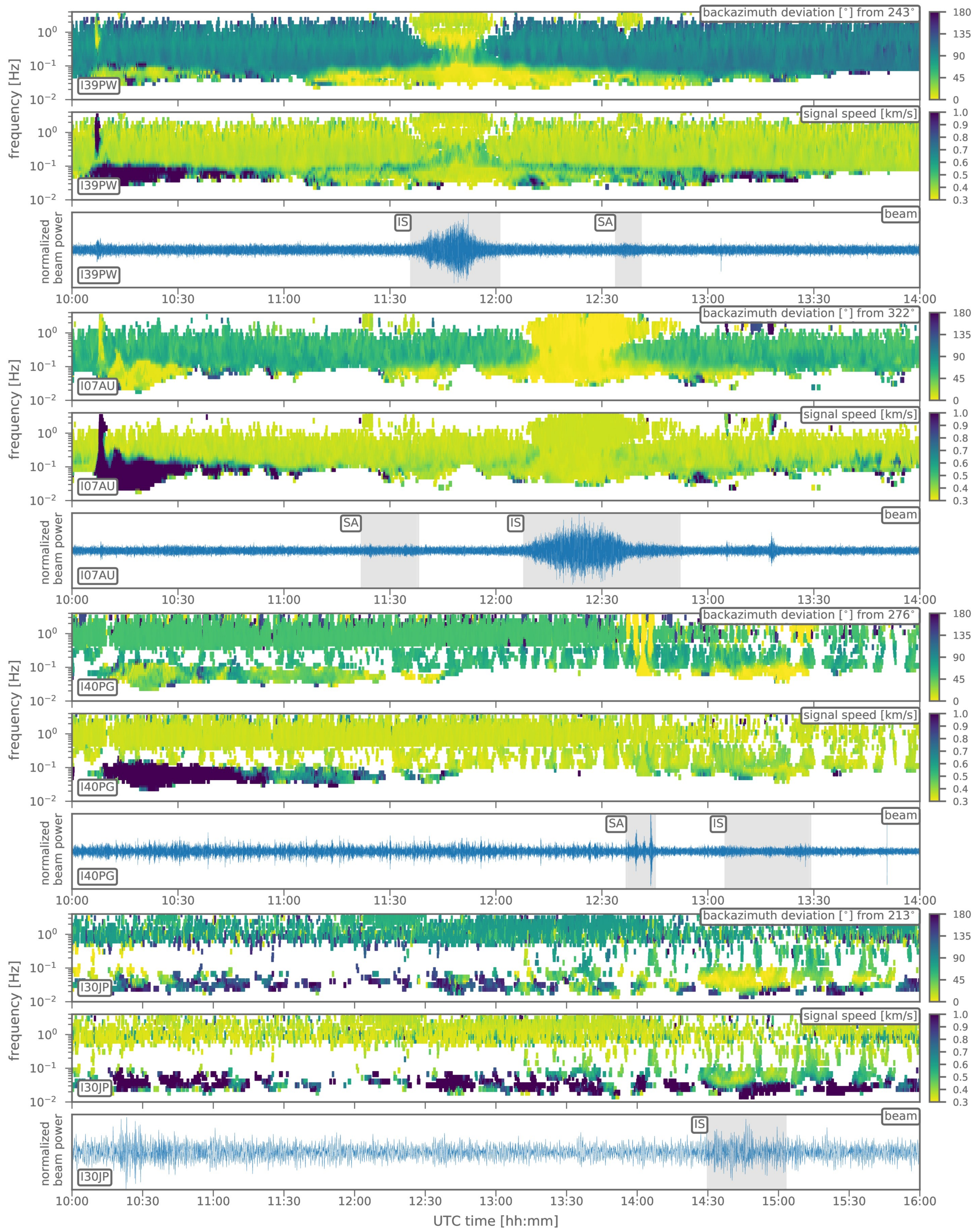

Figure 2: Waveform beams and PMCC-derived results for the four infrasound arrays I39PW, I07AU, I40PG and I30JP (stations are sorted by distance from above, three frames per station, station labels in the lower left corners). Shown in the corresponding stations' top frames are the observed back-azimuth deviations from the direction to the earthquake epicenter (see labels in the upper right corners), in the middle frame the observed apparent velocities and in the bottom frame the waveform beams. Signal onsets for infrasound (IS) and seismoacoustic (SA) arrivals are marked by grey boxes. The whole 360° back-azimuth observations are converted to deviation plotting (yellow colors indicating epicentral directions). Apparent velocities of 1 km/s and above indicate seismic arrivals (dark blue colors) instead of acoustic ones (yellow colors). Beams are bandpass-filtered between 0.6 and 4 Hz (for I30JP: 0.02 and 0.1 Hz). Six hours of data are shown for I30JP instead of four for the other arrays.

Attenuation Modeling

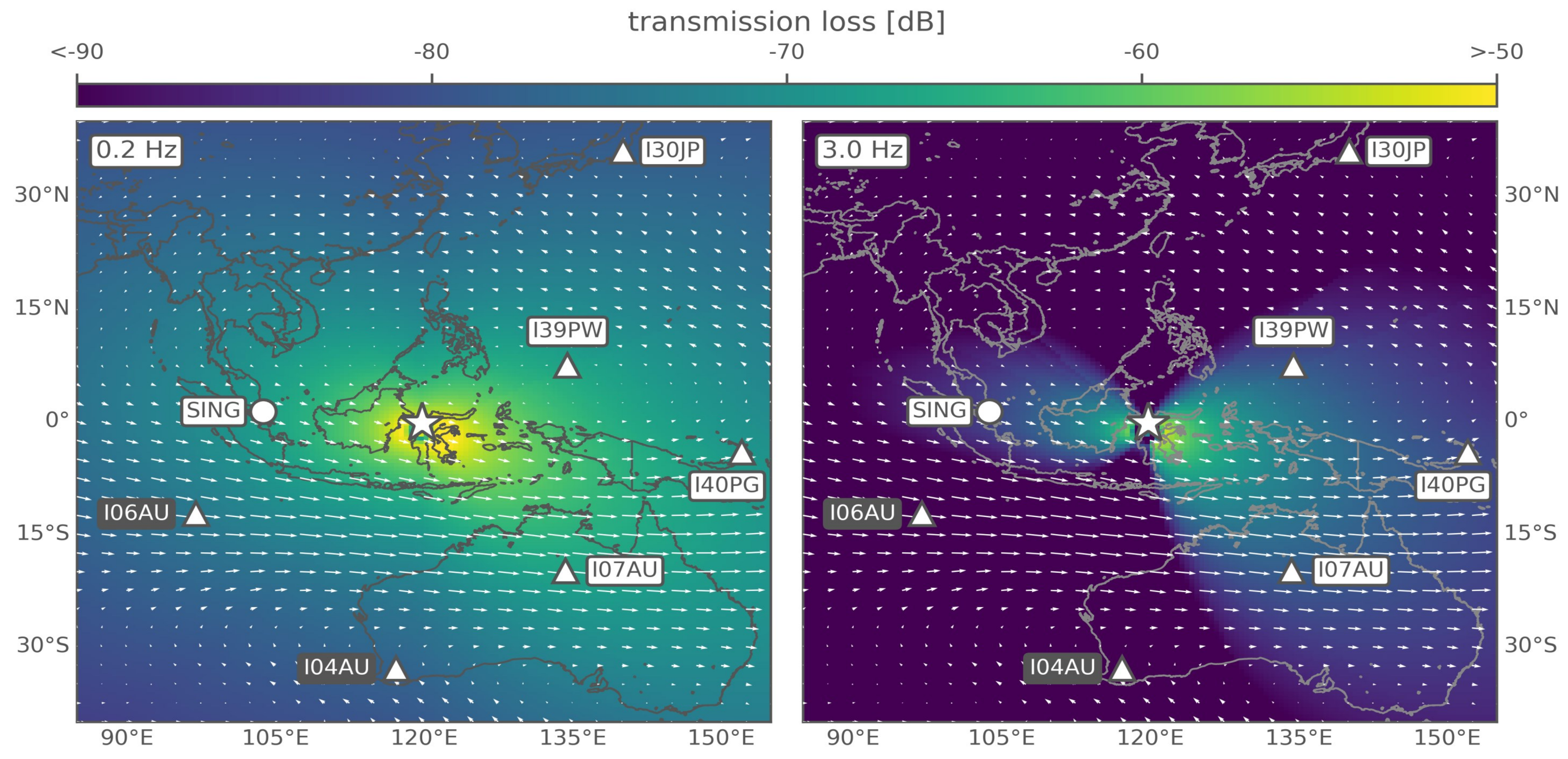

Figure 3: Attenuation map quantifying the acoustic pressure loss in dB (color-coded), calculated for 0.2 Hz and 3 Hz source frequencies on a 0.5° x 0.5° grid. Arrows show direction and intensity of the stratospheric wind field averaged between 30 and 60 km for the 28th of September 2018. The largest arrows represent a value of 25 m/s.

Propagation Modeling

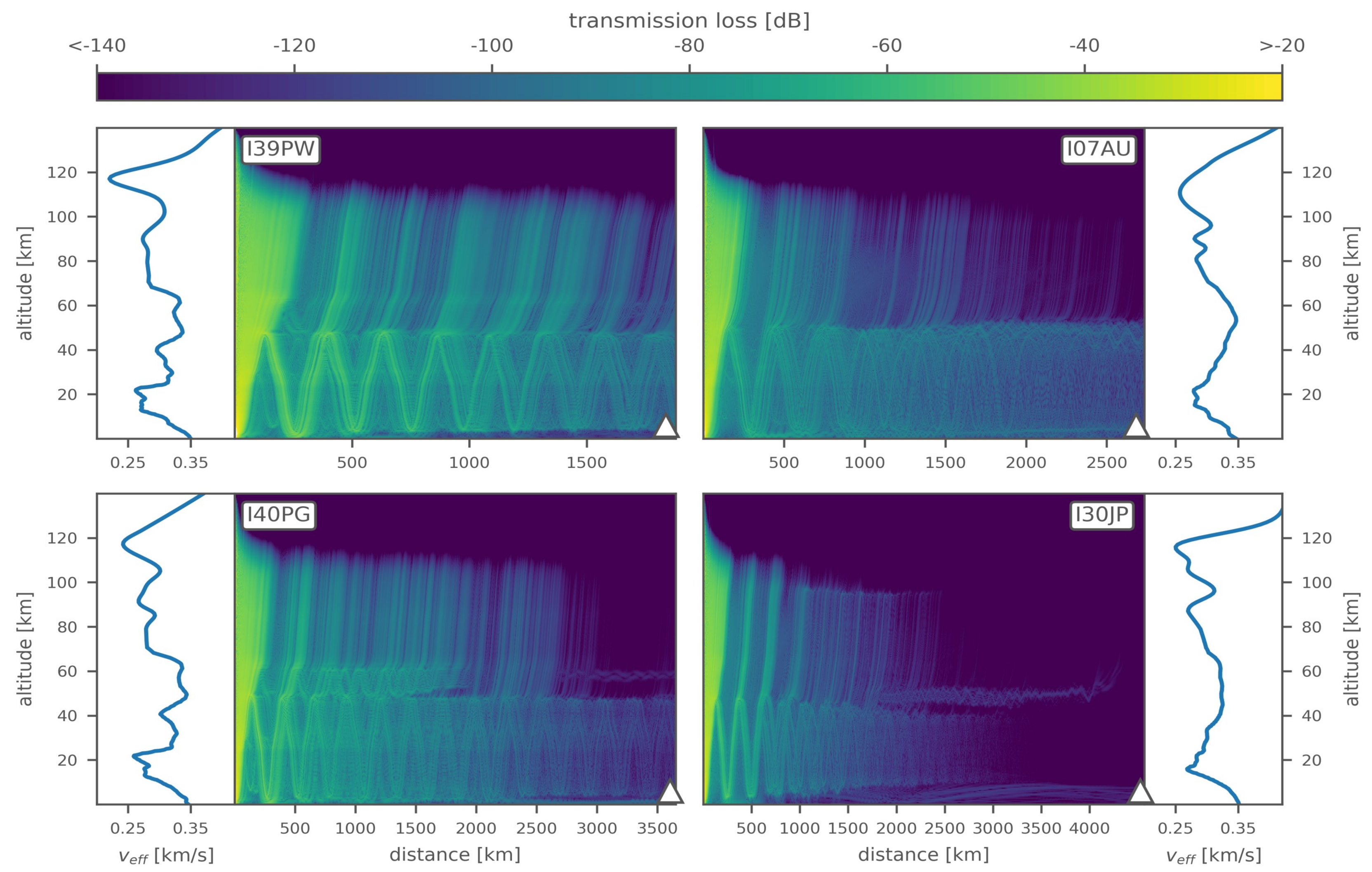

Figure 4: Propagation modeling between the Sulawesi earthquake epicenter (plot origin at 0 km distance) and the infrasound arrays I39PW, I07AU, I40PG and I30JP (respective triangles) using a range-dependent parabolic equation method, quantifying the transmission loss by atmospheric attenuation in dB relative to 1 km for a frequency of 1 Hz. Corresponding effective sound speed profiles (veff) are averaged over the complete propagation path.

Atmospheric Backtracking

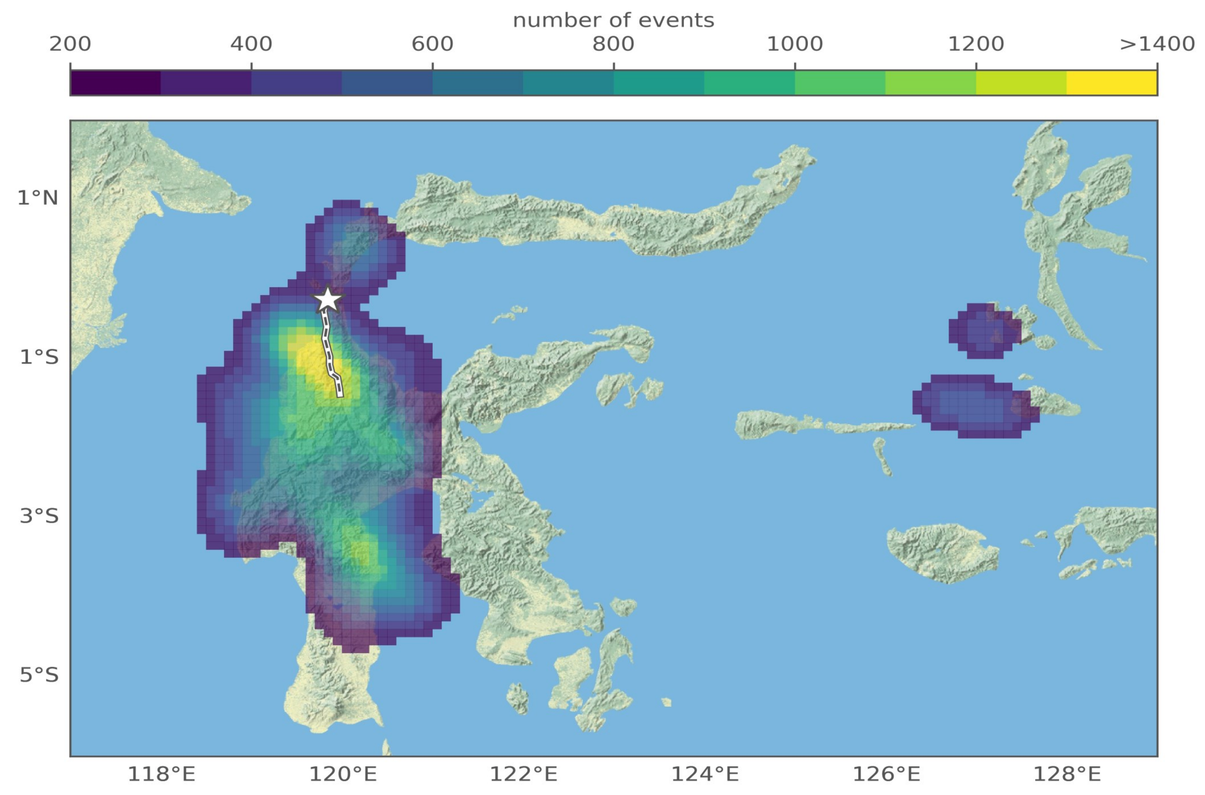

Figure 5: Back projection of the combined PMCC detections from I39PW, I07AU, I40PG and I30JP. Considered is each PMCC pixel's back-azimuth as well as a combination of 4 km/s seismic and 0.3 km/s acoustic celerities, resulting in seismoacoustic conversion locations. Color-coded event density for these locations is shown on a 0.1° x 0.1° grid, highlighting regions with more than 200 back-projected pixels per grid node. The epicenter is marked by an asterisk, the rupture zone traced by a dashed line.

Comparison to other Earthquakes

Event	Detecting IMS stations	Source type / signal evaluation
Denali, Alaska/USA, 03.11.2002, Mw 7.9, depth 4.9 km	I53US, I10CA	**Super shear earthquake,** short duration (10 minutes), strong infrasound at I53US (nearby), weak infrasound at I10CA (remote) generated by topography, also seismic arrivals
Sumatra Andaman, Indonesia, 26.12.2004, Mw 9.3, depth 30 km	I52GB, (others)	**Same region, normal shear earthquake,** long duration (30 minutes), strong infrasound, also seismic arrivals and secondary sources related to tsunami and tsunami-shoreline interaction
Quinghai, China, 13.04.2010, Mw 6.9, depth 17 km	I34MN	**Super shear earthquake,** short duration (<10 minutes), weak infrasound, no signal at stations in Japan or Russia, no seismic arrivals
Craig, Alaska/USA, 05.01.2013, Mw 7.5, depth 10 km	I53US, (I56US)	**Super shear earthquake,** short duration (<10 minutes), weak infrasound, I56US signals probably from other source, also seismic arrivals
Porgera, Papua New Guinea, 25.02.2018, Mw 7.5, depth 25.2 km	I06AU, I07AU, I39PW, I40PG	**Same region, normal shear earthquake,** long duration (20-60 minutes), strong infrasound related to nearby topography, also seismic arrivals
Kokopo, Papua New Guinea, 14.05.2019, Mw 7.5, depth 10 km	I22FR, I39PW, I40PG	**Same region, normal shear earthquake,** long duration (10-60 minutes), strong infrasound related to nearby topography, also seismic arrivals

Table 1: List of events similar to the 28th September 2018 Sulawesi earthquake, either in their super shear nature or in their regional origin. Comparably strong events were chosen with magnitudes of Mw>6.5 so that infrasound generation and detection can be expected. The "detecting IMS stations" (not necessary a complete list) as well the "source / signal evaluation" are estimations following data analyses performed by authors of this study.

Summary

Main findings are:

- Infrasound stations of the IMS network (**Figure 1**) detect clear signals from the Sulawesi super shear earthquake in up to 4500 km distance.
- Observations and analyses derived from NDC-in-a-box DTK-GPMCC (**Figure 2**) highlight low back-azimuth deviations pointing towards the earthquake epicenter as well as seismic, seismoacoustic and acoustic signal groups related to the event
- Attenuation calculations (**Figure 3**) and atmospheric conditions confirm favorable conditions for detections from stratospheric propagation at stations I39PW, I07AU, I40PG and SING, in good agreement with the observations
- Propagation modeling using a range-dependent parabolic equation method (**Figure 4**) confirms stratospheric propagation for these stations and only thermospheric propagation to I30JP (corresponding to lower celerities and frequency content)
- Signal backtracking (**Figure 5**) identifies a region around the earthquake rupture zone and in the vicinity of distinct topography to be the source regions of the generated signals
- Comparison to other earthquakes (**Table 1**) identifies strong similarities to other regional events (e.g. Papua New Guinea), but provide no indication about a connection of the super shear nature of the event and the intense infrasound generation

Conclusions and applications:

- Strong infrasound is generated in the earthquake rupture zone and by nearby topography, propagating over large distances
- It is possible to use IMS station recordings for back-tracking observed infrasound to epicentral and secondary source regions
- This event provides a good opportunity to study earthquake-generated infrasound and its source mechanisms in large detail
- It stimulates seismoacoustic follow-up studies and method improvements in the context of CTBT monitoring and verification

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