# The 2010 Haiti earthquake revisited: an acoustic intensity map from remote atmospheric infrasound observations

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POSTER

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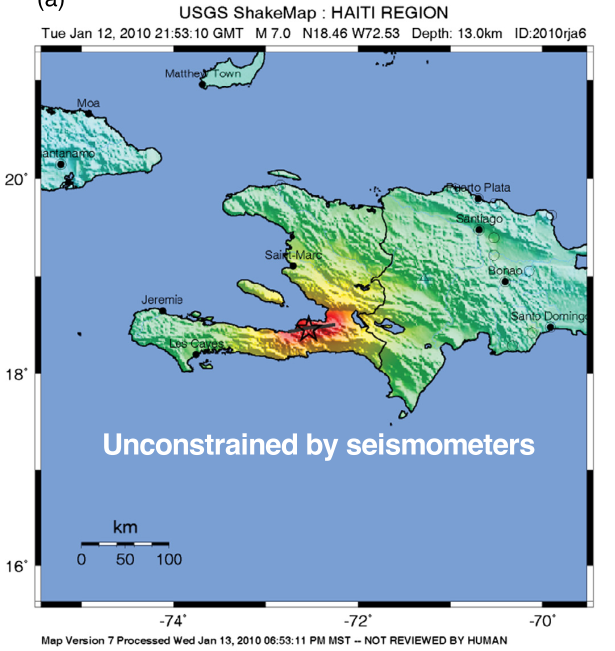
## ABSTRACT

In the days following the January 12, 2010 $M_W$ 7 Haiti earthquake the shaking intensity near the epicenter was overestimated and the spatial extent of the potentially damaging shaking was underestimated (a). This was due to the lack of seismometers in the near-source region at the time of the earthquake.

Post-earthquake scientific efforts included surveying damage on the ground, formulating GMPEs using seismic stations rapidly deployed to record aftershocks, and more complex forward propagation models. Based on these efforts the USGS updated the initial ShakeMap to better explain the observations.

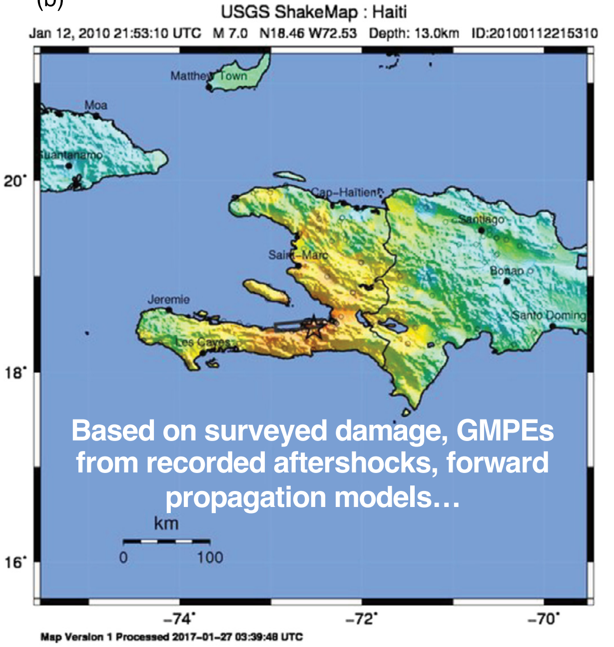
The updated ShakeMap (b), compiled by the USGS in January 2017, is much more detailed than the initial ShakeMap that did not incorporate any ground motion measurements nor reported damage.

(a)




| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(cm/s) | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

(b)




| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <0.05 | 0.3 | 2.8 | 6.2 | 12 | 22 | 40 | 75 | >139 |
| PEAK VEL.(cm/s) | <0.02 | 0.1 | 1.4 | 4.7 | 9.6 | 20 | 41 | 86 | >178 |
| INSTRUMENTAL INTENSITY | I | II–III | IV | V | VI | VII | VIII | IX | X+ |

Scale based upon Worden et al. (2012)

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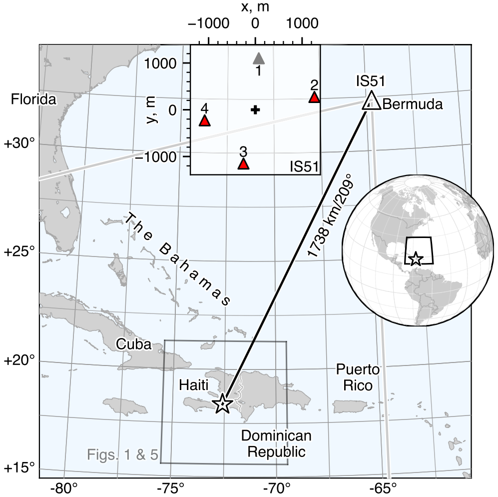


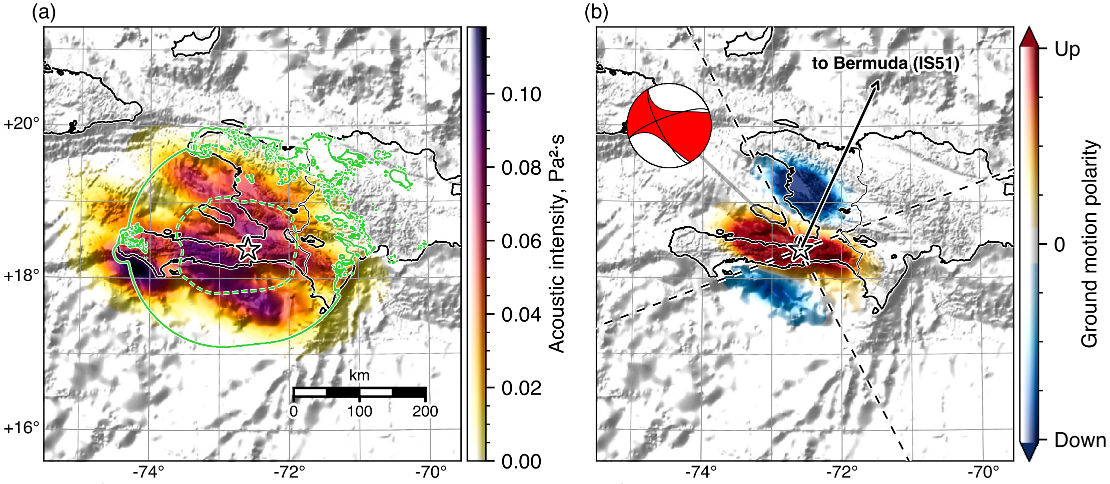


## ABSTRACT

Besides seismic waves, earthquakes generate infrasound, i.e., inaudible acoustic waves in the atmosphere. Here we show that infrasound signals, detected at distant ground-based stations, can be used to generate a map of the acoustic intensity, which is proportional to the shaking intensity. This is demonstrated with infrasound from the 2010 Haiti earthquake detected in Bermuda, over 1700 km away.

Wavefront parameters are retrieved in a beamforming process and are backprojected to map the measured acoustic intensity to the source region. The backprojection process accounts for horizontal advection effects due to winds and inherent uncertainties with regard to the time of detection and the back azimuth resolution. Furthermore, we resolve the ground motion polarity in the epicentral region and use synthetics generated by an extended infrasound source model to support this result.

We lay the groundwork that can potentially make infrasound-based ShakeMaps a useful tool alongside conventional ShakeMaps and a valuable tool for earthquake disaster mitigation in sparsely monitored regions.

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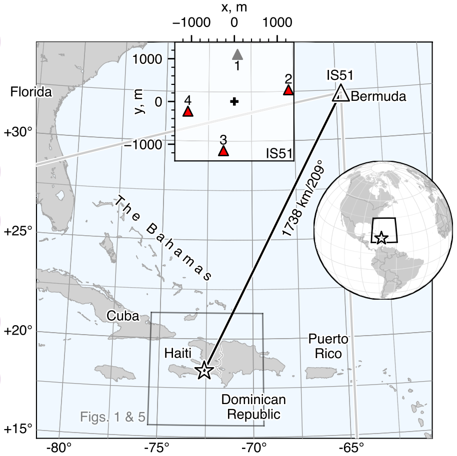
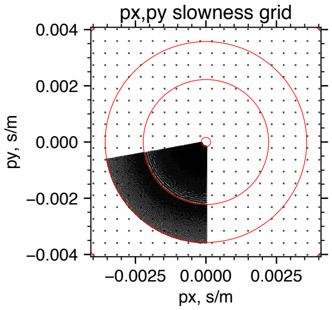
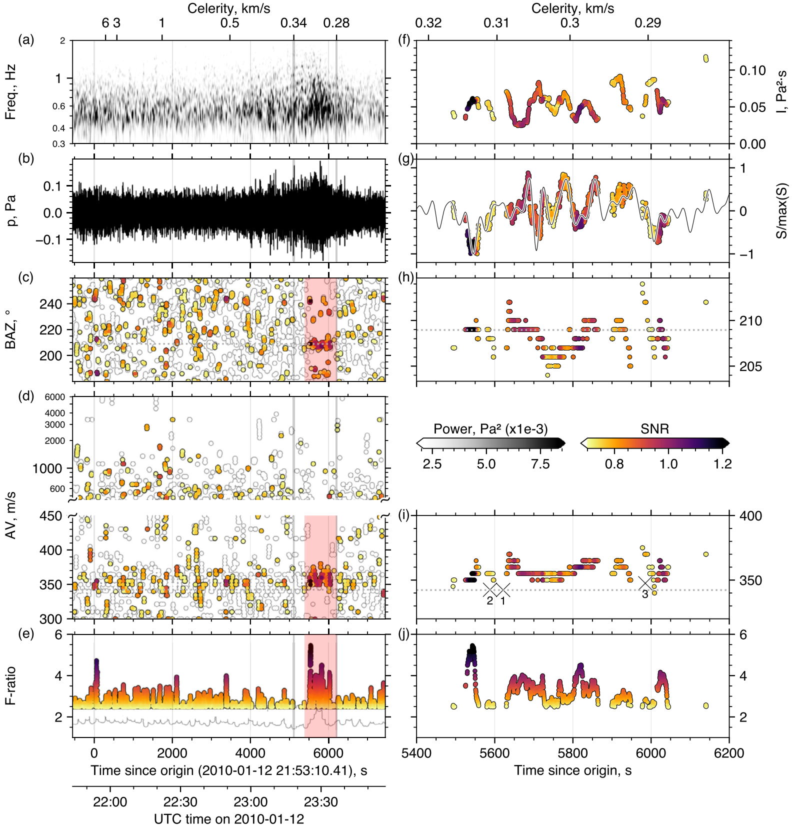
## ARRAY PROCESSING




Characteristic wavefront parameters are extracted in the beamforming process, namely, the direction of arrival back azimuth (BAZ), the speed of horizontal propagation over the array apparent velocity (AV), and the signal coherency in terms of SNR. Generally, epicentral infrasound signals are empirically characterized by a celerity (epicentral distance divided by the total travel-time) range of 0.34 to 0.31 km/s for stratospheric propagation and 0.31 to 0.28 km/s for thermospheric propagation. However, coherent signals (SNR > 0.7) are only detected between ~5500 and ~6100 seconds (celerity range of 0.32 to 0.28 km/s), mostly corresponding to the thermospheric celerity range. The right column focuses on detections that correspond to infrasound signals from the epicentral region. Only detections that fit our selection criteria (200° < BAZ < 220°, 320 < AV < 400 m/s, and SNR > 0.7) are shown.



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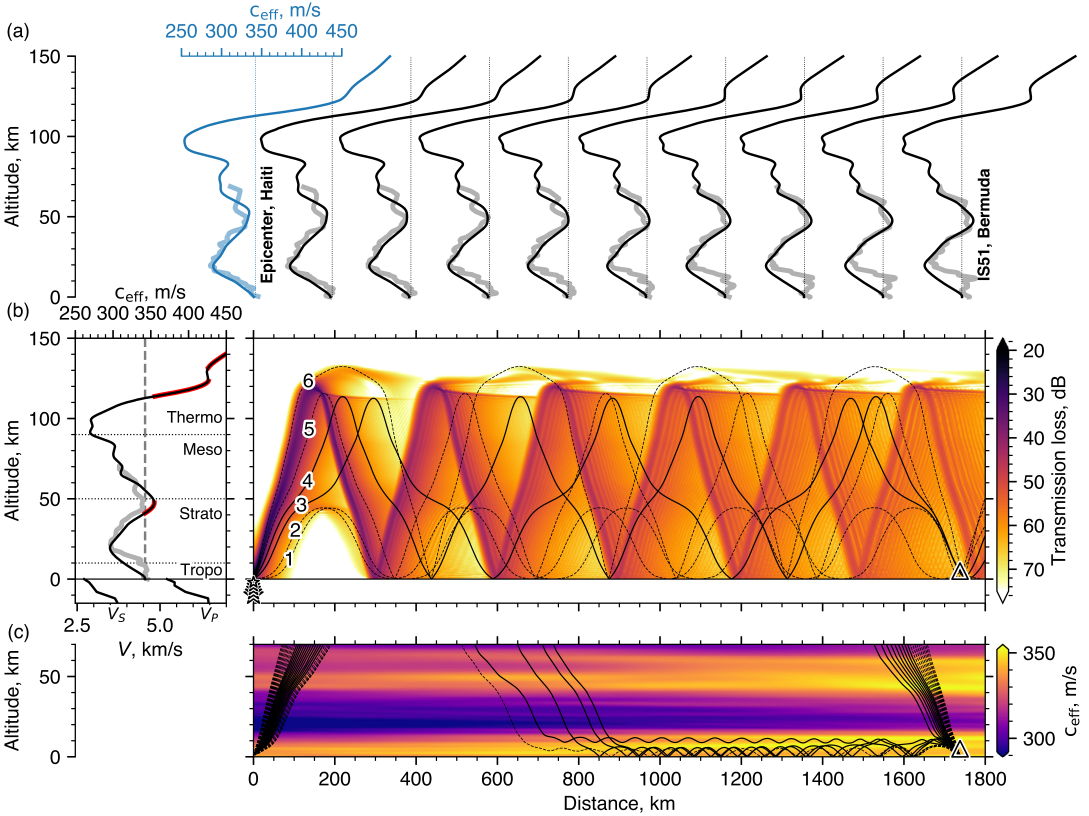
## PROPAGATION MODELING

Coupling and propagation modeling. (a) 10 evenly spaced effective sound speed profiles along the great circle path connecting the epicenter in Haiti to IS51 on Bermuda. Top axis shown for scale and indicates $c_{eff}$ of the leftmost profile. The climatology profiles are indicated by thin black lines, the ERA5 ECMWF profiles are indicated in thick gray lines. (b, left) Averaged effective speed of sound profile (values on the top axis) and seismic velocity profile (values on the bottom axis) used in the FFP and $c_{eff}$ ray tracer. For comparison, the ERA5 ECMWF profiles are also averaged and plotted as thick gray line. (b, right) Vertical section showing acoustic intensity transmission loss (TL) along the propagation path from a subsurface source in Haiti to IS51 on Bermuda island. The sources are indicated by stars with size corresponding to relative source magnitude. IS51 is indicated by a triangle. Eigen rays connecting the source region and IS51 calculated using the same $c_{eff}$ profile are overlaid. (c) Vertical cross section of effective sound speed calculated from ERA5 ECMWF specifications showing rays back-propagated along the theoretical back azimuth ±15°. Solid lines indicate rays corresponding to the observed range of inclination angles (7° - 25°) and dashed lines indicate rays outside that range.



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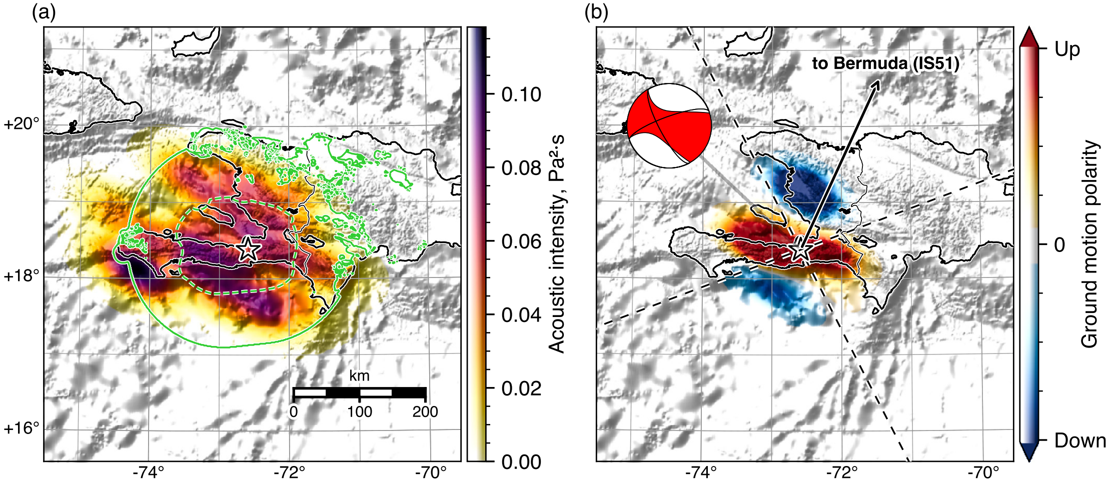
## BACKPROJECTIONS

The severity of ground shaking generally decreases with distance from the epicenter, however, near-surface geology, topography, and the source radiation pattern, contribute to local variations in ground shaking intensity. This variability is captured by the coupled acoustic pressure field over the disturbed region. The radiated signals from the different sub-patches in the near-source region remain ordered in time throughout the propagation from the epicentral region to Bermuda, and the variability of acoustic pressure perturbations from one location to another can be retrieved.

The acoustic intensity *I* (integral of the square of the pressure) associated with each detection window is mapped to the detection patch that best corresponds to the associated travel-time and back-azimuth.

Similarly, the pressure-time integral *S* in each detection window, which yields a positive or negative overall sum, indicates whether the detection patch mostly moved upward or downward.




(a) Acoustic intensity map from backprojection of infrasound detections showing the acoustic intensity *I* measured at IS51 mapped onto the source region. The $I_I$=5 contour lines from the initial (broken line) and updated (solid line) USGS ShakeMaps are overlaid in green. (b) Source radiation pattern from backprojection of infrasound detections, red indicates upward motion, blue indicates downward motion. The beachball representation of the moment tensor and nodal planes are overlaid. The direction to IS51 on Bermuda island is indicated by an arrow (~45° to the nodal planes).

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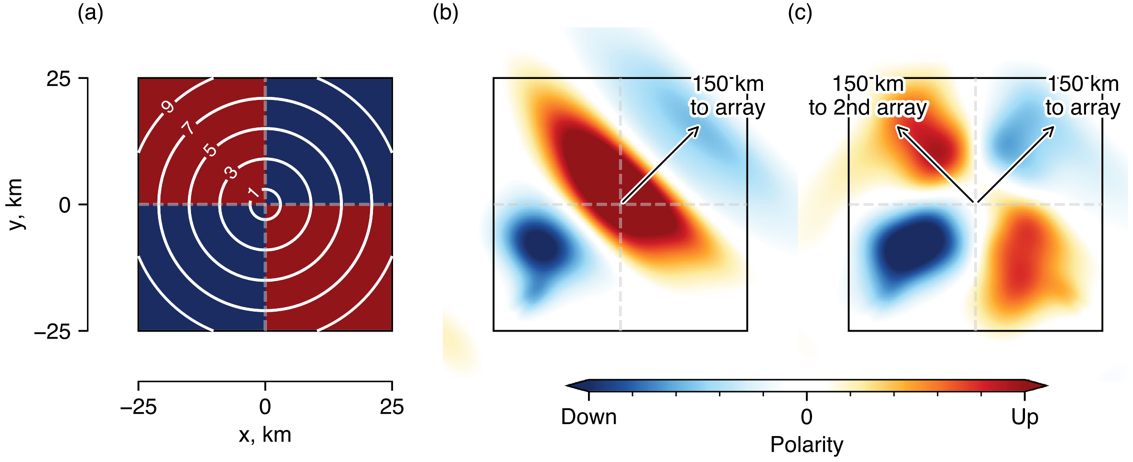
## RAYLEIGH INTEGRAL

To better understand this result, a conceptual model is set up to simulate the acoustic pressure field from an extended infrasound source, as illustrated in (a). Pistons in the top-left and bottom-right quadrants (first and third) are prescribed a positive (upward) STF, and pistons in the top-right and bottom-left quadrants (second and fourth) are prescribed a negative (downward) STF. The activation of each piston is offset in time to mimic a radially propagating seismic wave with a moveout velocity of 3 km/s from the simulated epicenter at the center of the extended source.

Synthetic waveforms are calculated for a four-element array in the far-field, 150 km away from the epicenter at 45° to the nodal planes to mimic the orientation of IS51 with respect to the nodal planes of the Haiti earthquake. Wavefront parameters are extracted in a beamforming process, and then used in the backprojection process. The pressure-time integral S in each detection window is used to infer the ground motion polarity of each detection patch.




Extended source modeling and backprojection. (a) Extended source setup with four quadrants: red indicates upward motion, blue indicates downward motion. White contour lines indicate isochrons of piston activation time in seconds. (b) Source radiation pattern inferred from backprojection of synthetic infrasound signals using one array located 150 km away from the epicenter, 45° to the nodal planes in the direction indicated by the arrow. (c) Superposition of source radiation patterns inferred from backprojection of synthetic infrasound signals using two arrays located 150 km away from origin at 45° to the nodal planes in the direction indicated by the arrows.

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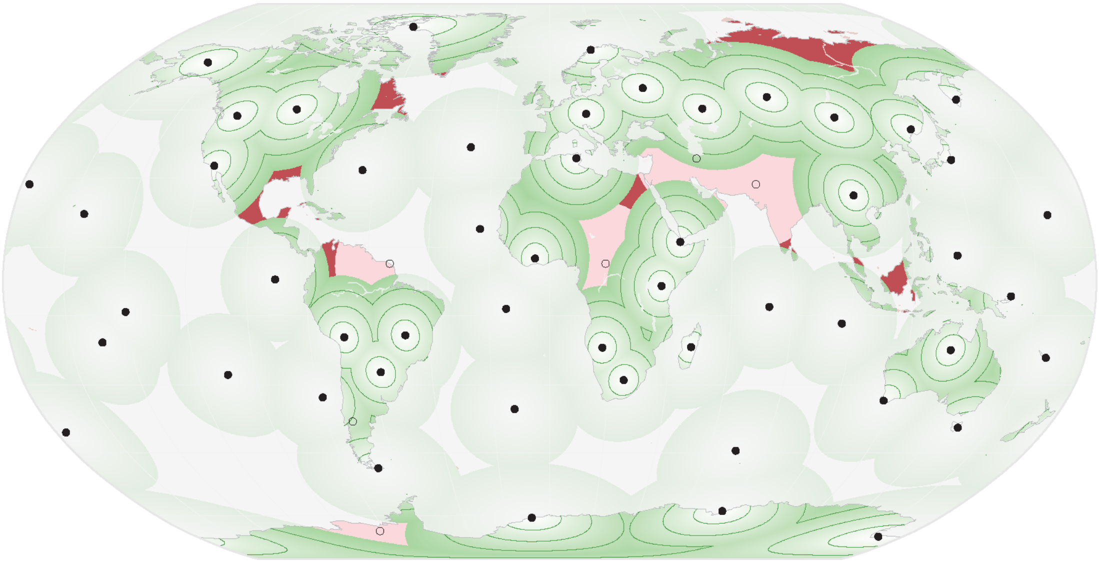
## DISCUSSION AND CONCLUSIONS

- Backprojections of infrasound signals have been shown to be in correlation with earthquake ground motions prior to this work but for shorter propagation ranges and only for stratospheric infrasound (Marchetti et al., 2016; Walker et al., 2013; Hernandez et al., 2018). For the first time, infrasound that has propagated over 1700 km is used to outline the region where shaking intensity is sufficiently large to lead to damage.
- We demonstrate the potential of remote infrasound detections for mapping the acoustic intensity over an earthquake source region.
- The expected infrasound travel-time over 2000 km assuming a thermospheric waveguide is approximately 2 hours under typical propagation conditions. This means that an acoustic intensity map can be produced faster than other methods such as damage analysis on the ground or from aerial and satellite imagery. This can be done for earthquakes almost anywhere on land or close to shore. The techniques presented here, together with the coverage extent, make it plausible to use infrasound as a global earthquake disaster mitigation technique for the first time.



Acoustic intensity map potential of the IMS. The green gradient shading indicates coverage of the currently installed infrasound stations (full circles). Green shading corresponds to distance out to 2000 km. Contour lines spaced 30 minutes apart indicate travel-time to the nearest station, calculated on the basis of thermospheric propagation. The light red shading indicates regions that will be covered by planned stations (empty circles). Dark red regions correspond to landmass that will remain uncovered by the IMS for this application.