2011 Tohoku Tsunami South of Oahu

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1. Introduction

High-Frequency Doppler Radio Scatterometer (HFDR) detects surface movement through Bragg scattering of radio waves off ocean surface gravity waves. Subtracting the theoretical wave velocity from the surface movement yields surface currents.

Tsunamis are shallow water waves with extremely long wavelengths. Their energy compresses and the wave height increases as the waves shoal. The individual water particles in each wave move faster as the water gets shallower. HFDR detects the movement of the particles at the surface and, because of how long the wavelength is, this surface movement looks like a patch of current. The speed and direction of each patch of current depends on where in the wave orbit the particles are, and, because a wave contains all parts of the wave orbit from one peak to the next, the tsunami appears as bands of current perpendicular to large-scale bathymetry [*Barrick* 1979]

While a tsunami may appear this way, frequently the resonant response is stronger. Currents associated with a tsunami are expected to be the strongest in shallower water, so that is also likely the best place to look for a direct or resonant response.

2. Location

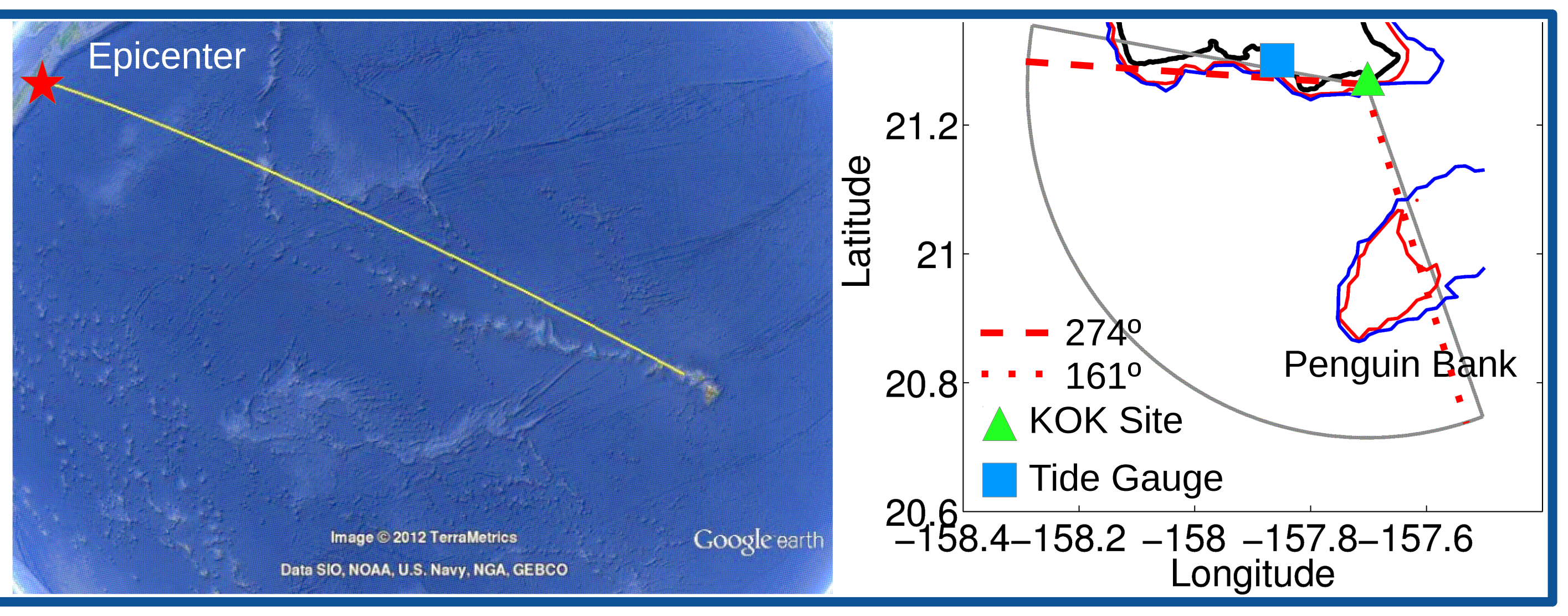

Figure 1. The tsunami travel path (left panel), arriving after 6000 km travel at 302°; the site location (right panel), with Koko Head (KOK) coverage area (grey line), site location (green triangle), tide gauge location (bllue square), and 50- and 100-m isobaths (red and blue lines, respectively).

The two areas of primary interest are the shallow shelf, Penguin Bank (middle right of right panel), which is covered by the HFDR 161° beam angle, and the near-shore area, with HFDR 274° beam angle.

3. Results

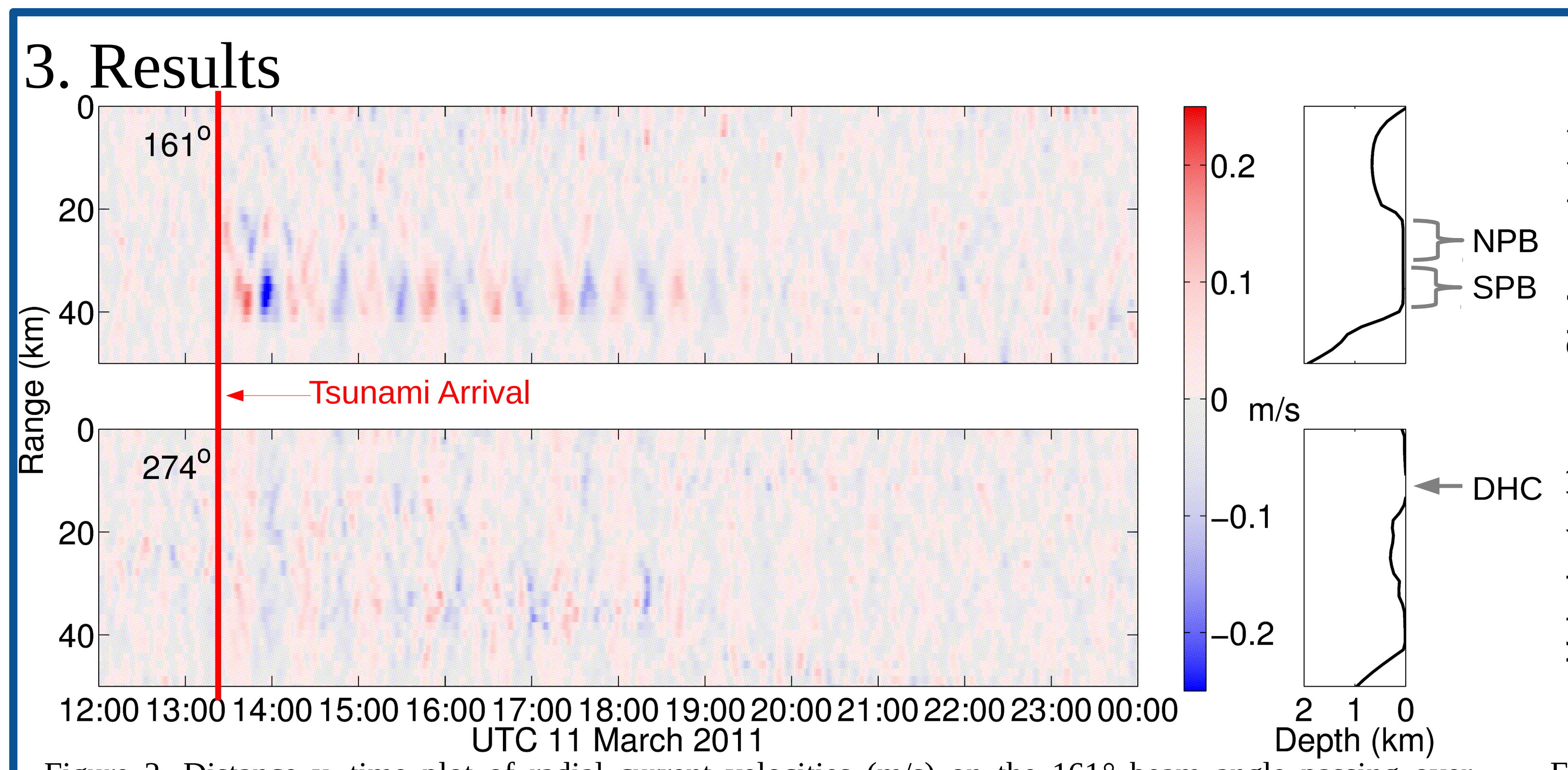

Figure 2. Distance v. time plot of radial current velocities (m/s) on the 161° beam angle passing over Penguin Bank, with bathymetry at right (top); similar plots, but for the 274° beam angle, which is near shore (bottom).

The bands of anomalous currents between 20 and 31 km (North Penguin Bank, NPB) and between 31 and 43 km (South Penguin Bank, SPB) begin at ~1320 UTC. A tsunami traveling 6000 km in water 5-km deep would travel for 7.5 hours, with an arrival in Hawaii at 1316 UTC given the 0546 UTC earthquake.

There is no obvious pattern to the near-shore currents, as there is over Penguin Bank, besides the low-period background oscillation. The 232-m Diamond Head Crater (DHC) is located in the beam path at 10 km in range; the currents shown there are not real ocean currents but either the backscatter from land interpreted as currents or azimuthal side-lobe contamination from the 'forward' signal being so weak.

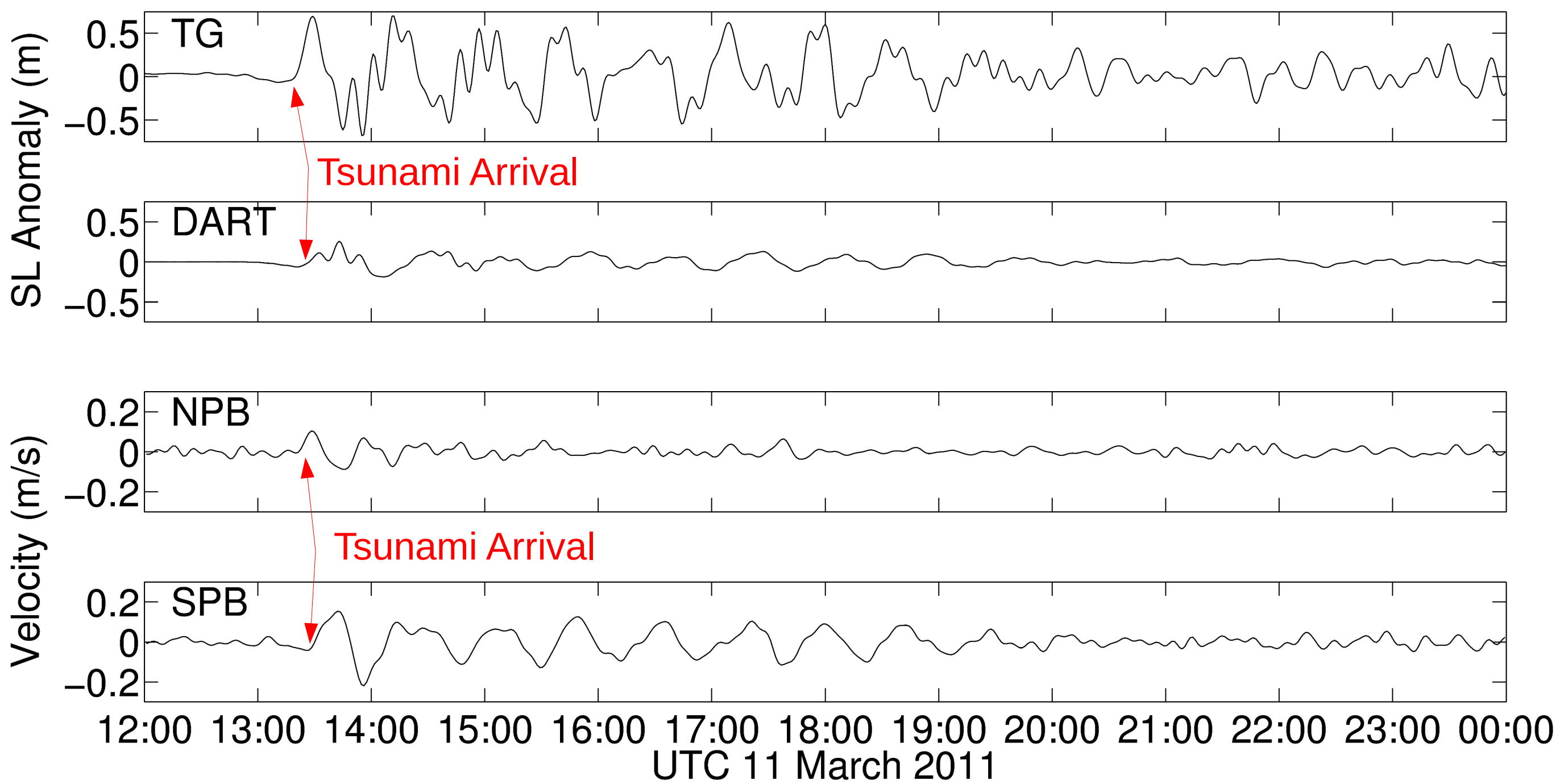

Figure 3. Time series plots of (from top) tide gauge anomalous sea level (TG), DART 51407 anomalous sea level (DART), NPB, and SPB. The magnitude of TG is much greater than DART, which is easily explained by the fact that TG is in 1.3 m of water, while DART is in 4.7 km of water, so the same wave has significantly more height in the former than the latter. The signal on SPB is much greater than that on NPB, but they have approximately the same depth. There must be some resonant response that has much greater impact on SPB to account for this difference.

The tsunami signal is first visible at TG at 1319 UTC, followed by 1322 at DART, 1323 at NPB, and 1329 at SPB. The northwestern arrival would seem indicate that the arrival order should be TG, NPB, SPB, then DART; however, the shortest path to DART does not travel through shallow water, unlike the arrivals at TG, NPB, and SPB.

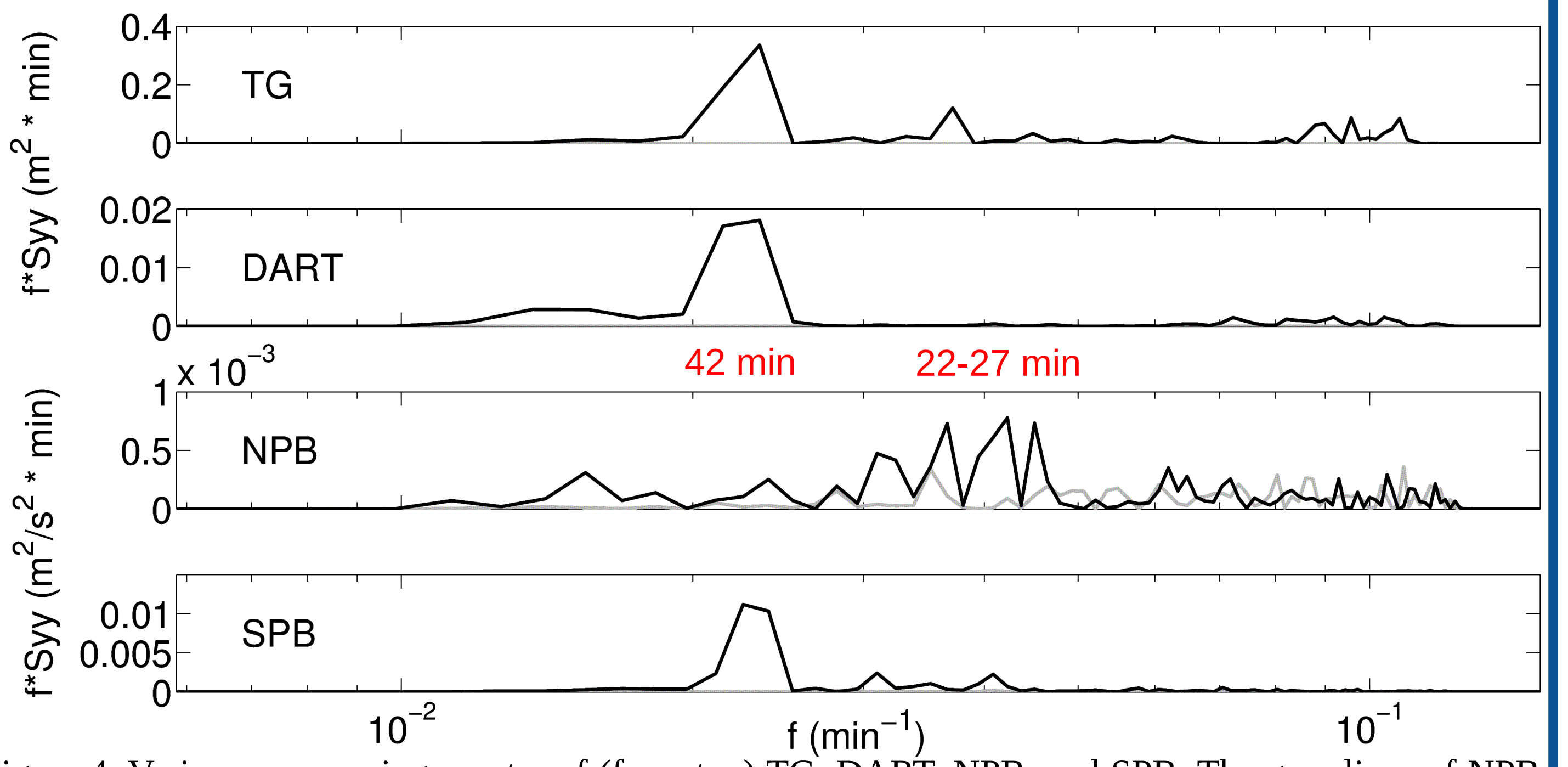

Figure 4. Variance-preserving spectra of (from top) TG, DART, NPB, and SPB. The grey lines of NPB and SPB are the spectra from before the arrival of the tsunami. The large peak shared by TG, DART, and SPB is at 42 minutes, which is the period of the island chain resonance found through tsunami modeling[*Munger and Cheung*, 2008]. The three largest peaks of NPB are at 22, 24, and 27 minutes. Modeling found modes of resonance at 24 and 27 minutes [Munger and Cheung 2008]. The 24-minute mode is a separate standing wave system over Penguin Bank, while the 27 minute mode is a standing wave that includes southeast of Oahu, including the harbor and explaining the 27-minute peak in that spectrum.

The 1 order of magnitude difference between TG and DART amplitudes is due to the ~50-cm difference in the amplitudes of their responses in the sea level. The responses at NPB and SPB have a similar magnitude with the exception of the 42-minute peak, which is 1 order of magnitude stronger than any other HFDR spectral peak.

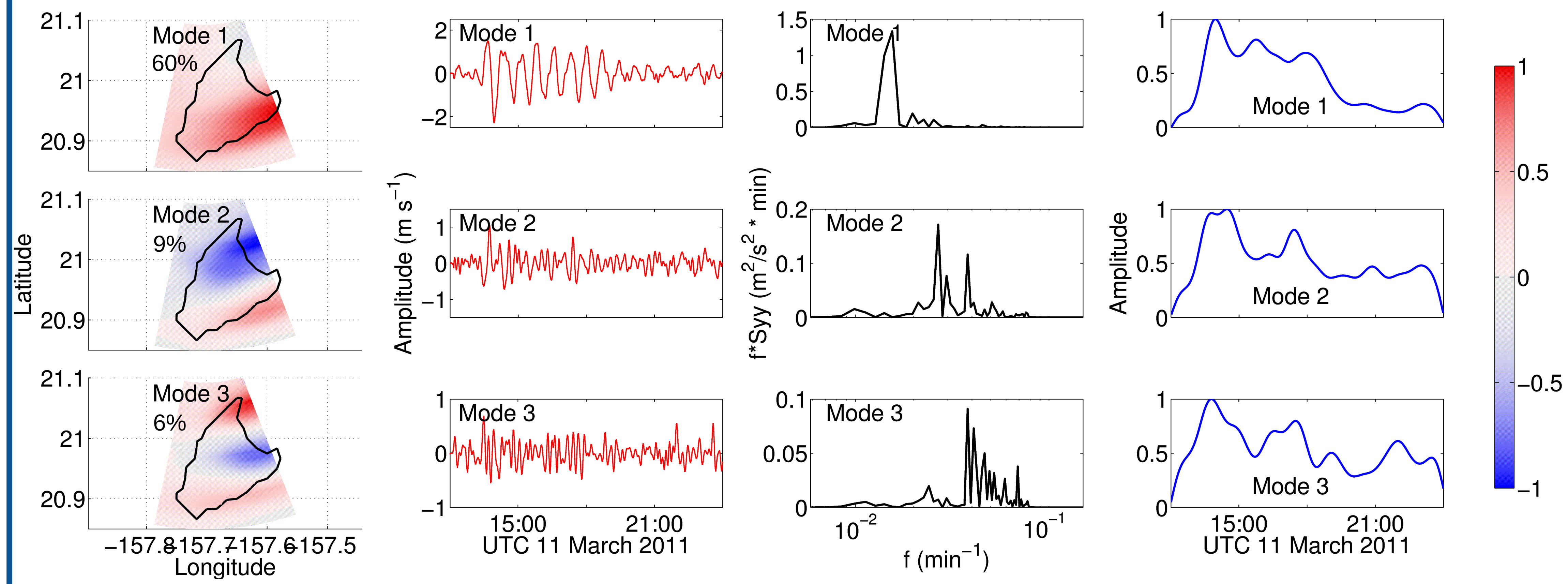

Figure 5. Penguin Bank empirical orthogonal function analysis results: plots of (from left, by column) spatial empirical orthogonal function maps (EOFs) over with 50-m isobath (black line), with the amplitude normalized to 1; associated time series or temporal expansion functions (TEFs); spectra of time series; and normalized amplitude of analytic signal derived from TEF (a proxy for energy).

EOF-1 shows large asymmetry in spatial expression of NPB v. SPB, which accounts for the difference in tsunami signal amplitude at NPB v. SPB. Asymmetries in EOF-2 and EOF-3 are not as great. All three TEFs show larger amplitudes starting at the tsunami arrival, though a simple decay in amplitude with time is only visible in TEF-1.

There is a shift in higher modes to higher-frequency content. The decay timescales, measured as time between maximum value and 1/e in energy, are quite similar for the three modes: 6 hours for modes 1 and 2, and 6.5 hours for mode 3. The actual decay is faster, though, because of the re-excitement of the modes.

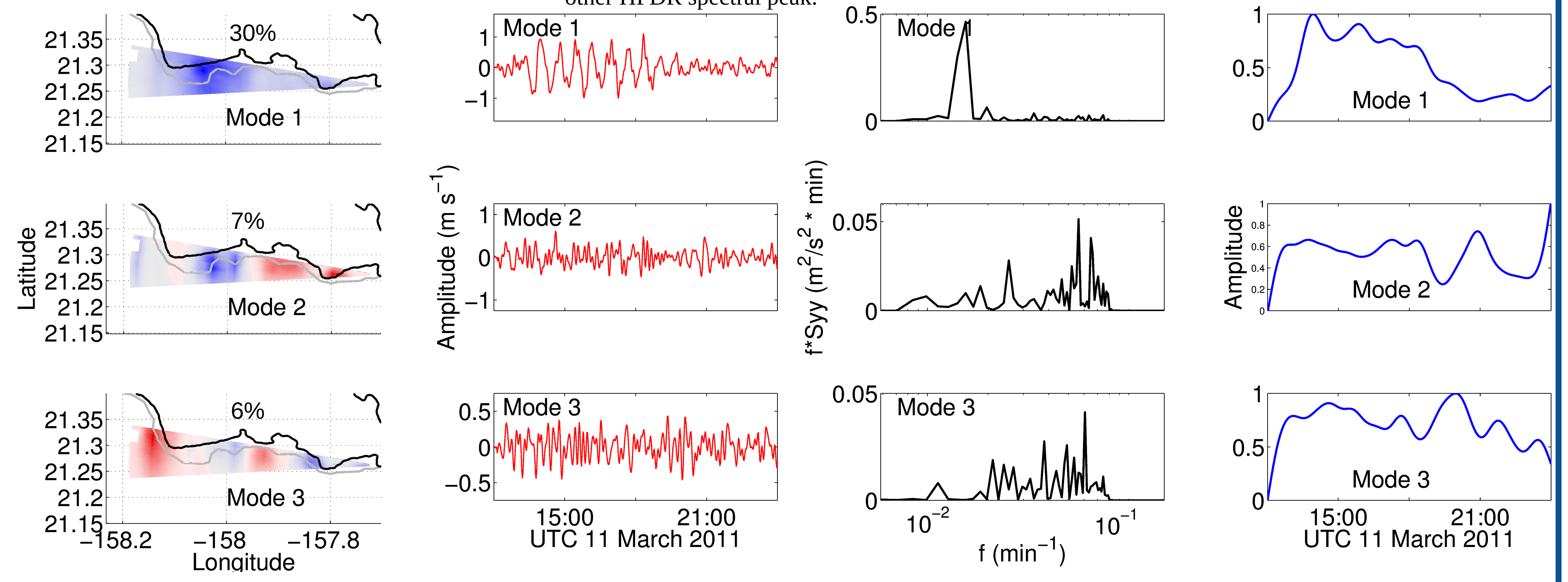

Figure 6. Identical to Figure 5, but for the near-shore area with coastline and 50-m isobath (black and grey lines, respectively). Note that any direct tsunami currents are expected to be cross-isobath, but the HFDR, which only detects currents radial to itself, is oriented to detect mainly along-isobath currents in this area so the expectation is to see very little besides possible along-shore resonant currents in the near-shore area.

Expression of the mode 1 EOF is primarily 30-40 km from the HFDR. The TEF shows a large jump in magnitude with the arrival of the tsunami, followed by ~6 hours of near-constant amplitudes before a very quick decay to ~1/3 of the original amplitude. The analytic signal shows a decay timescale of 6 hours.

The EOFs of modes 2 and 3 appears linked closely to the bathymetry. The TEFs do not appear to be tsunami-related because there is no large jump in amplitude at ~1320 UTC. The analytic signal for mode 2 is not indicative of single or periodic excitement and decay, while that of mode 3 appears to be related to later arrivals, possibly through the very small degree of dispersion tsunamis may experience However, the fact that this response is no greater than the .

4. Contamination

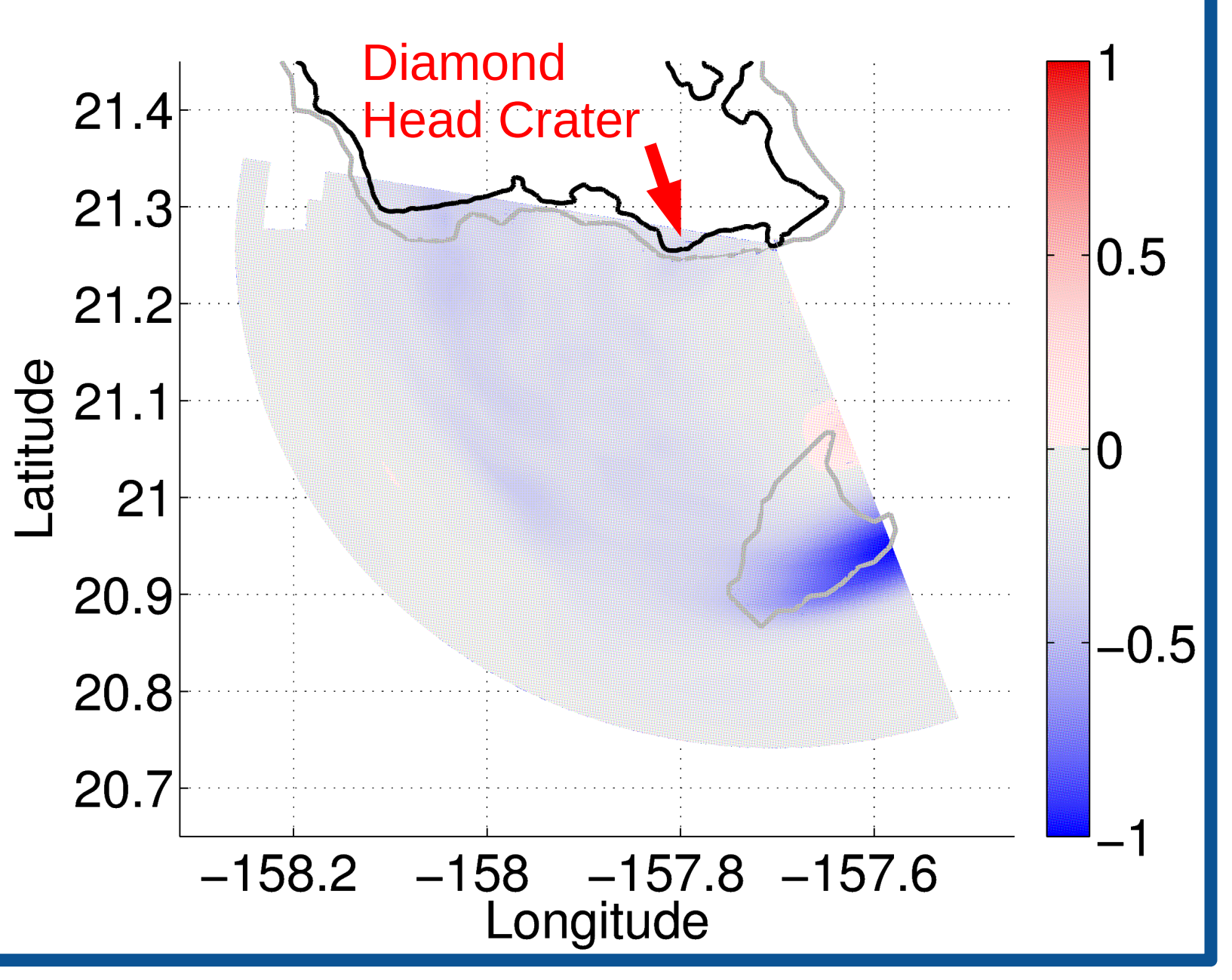

Figure 7. Map of coefficients of regression of Penguin Bank EOF-1 time series onto data in whole HFR domain. This indicates that shore EOF-1 and Penguin Bank EOF-1 are part possibly part of the same mode.

Beamforming antenna arrays detect signals primarily in the 'forward' direction with the main lobe, but there is still some signal detection from other directions, in side lobes, which are typically many dB lower in signal strength.

The signal near-shore may be explained by azimuthal side-lobe contamination, when the signal from a side lobe is stronger than the signal from the main lobe and is assumed to be a signal from the main lobe. If that is the case, then the side lobe was likely detecting currents over Penguin Bank while the main lobe was blocked by DHC.

5. Conclusions

HFDR detected the tsunami:

- HFDR, theoretical, TG, and DART very close together
- HFDR spectral peaks match previous tsunami modeling
- HFDR mode energy decay after initial excitement and re-excitement

NPB and SPB were different:

- Different modes of oscillation experienced, asymmetric expression over Penguin Bank
- Mode-1 over SPB strong enough to overcome the fact that the second mode over NPB
- Long-period oscillations accounted for more of the variance and energy than short-period oscillations
- Energy decay scale on Penguin Bank - roughly 6 hours

Near-shore tsunami and other currents:

- Mode-1 amplitude increased greatly with the arrival of the tsunami, long-period oscillations consistent with island chain resonance
- Mode-2 and mode-3 lack increase in amplitude following tsunami arrival

Azimuthal side-lobe contamination possible:

- Similarities between mode-1 in near-shore and Penguin Bank
- Regression of Penguin Bank EOF-1 to data shows same mode covers both Penguin Bank and near-shore
- 232-m DHC between KOK and much of Oahu's south shore

References

Barrick, D. E. [1979]. *Remote Sens. Environ.* 8: 353-358.

Munger, S., and K.F. Cheung. [2008] *Geophys. Res. Lett.* 35: L07605.

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