Detection of the 2011 Tohoku tsunami south of Oahu, Hawaii, by high-frequency Doppler radio (HFDR)

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Pierre Flament
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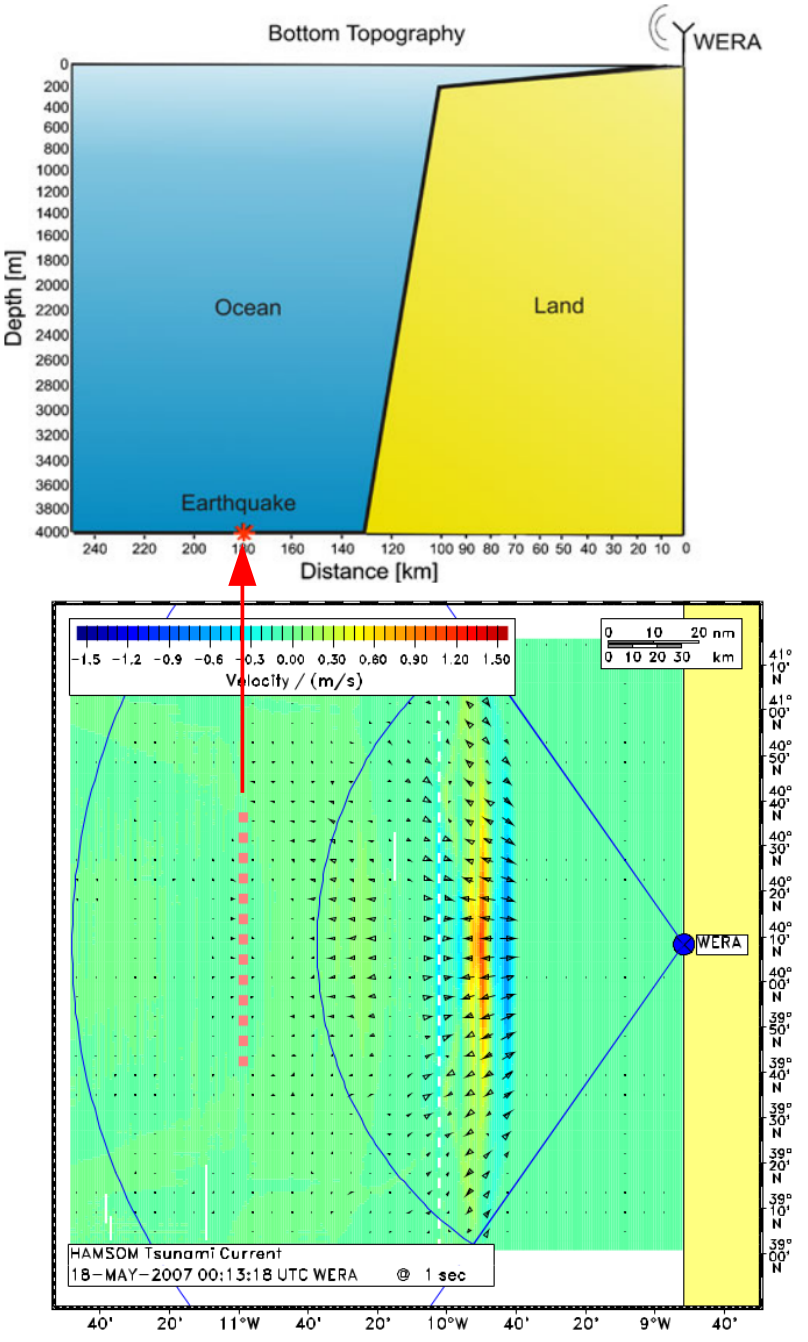
Doug Luther

Tsunamis and Surface Currents

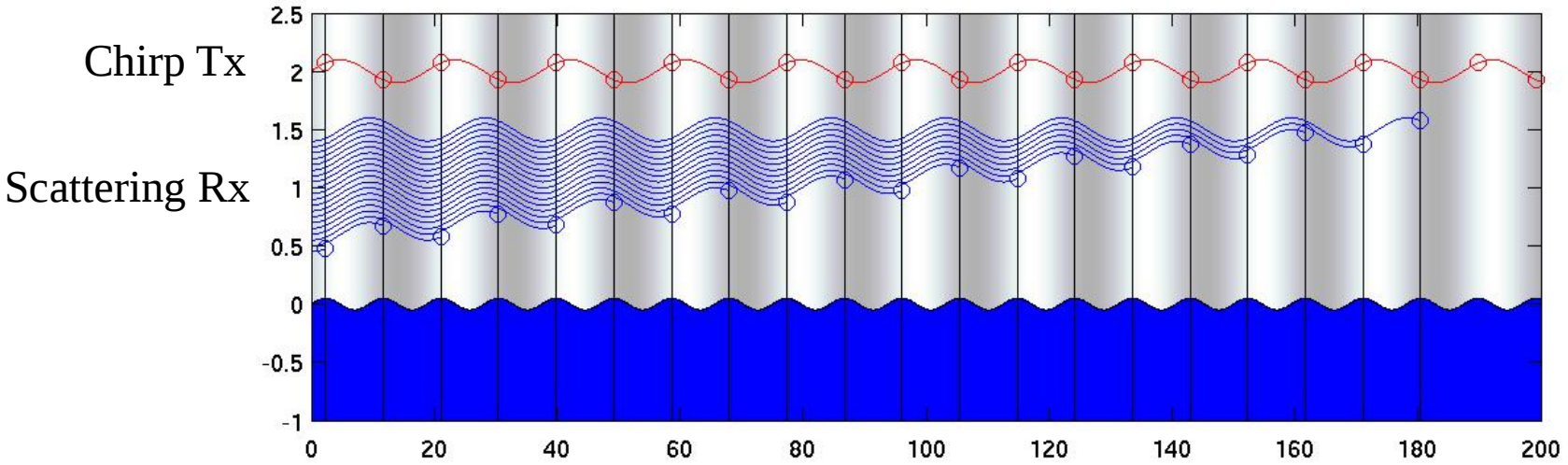
- Shallow water waves, $v = \sqrt{gh}$
- Shoaling increases water particle velocity, which acts as a surface current
- HFDR maps surface currents
- Technical limitations important when pushing the limits of HFDR



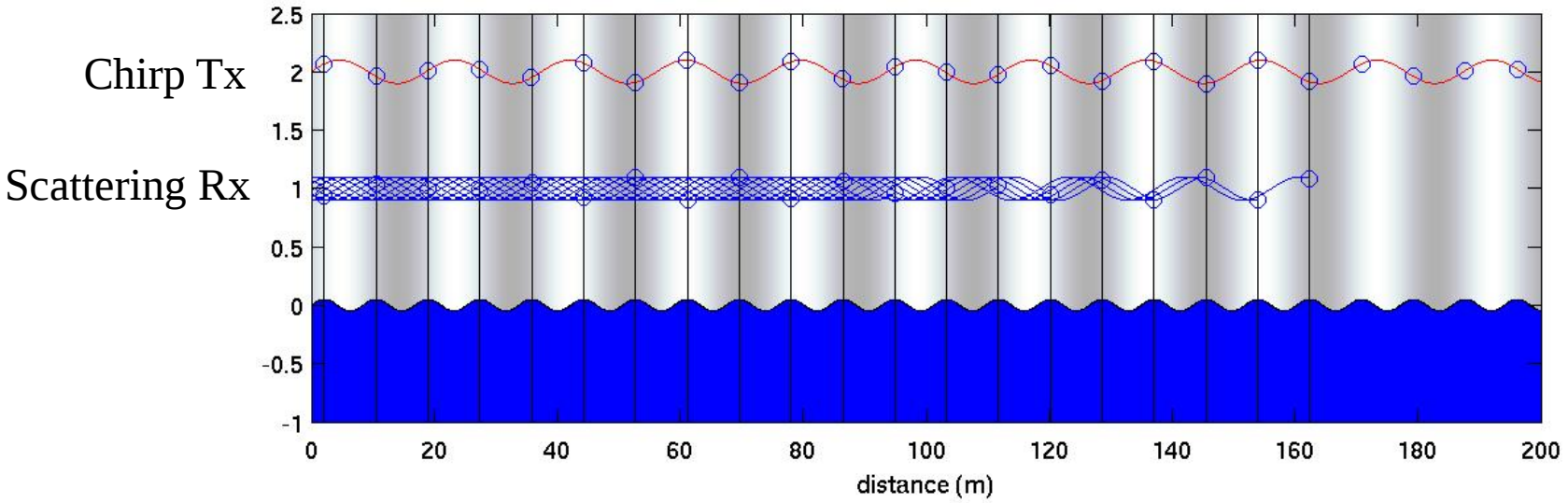
Gurgel et al., 2011

Bragg scattering of radio waves off ocean swell riding on tsunami waves

Additive backscatter at $\lambda_{ocean} = 0.5\ \lambda_{radio}$



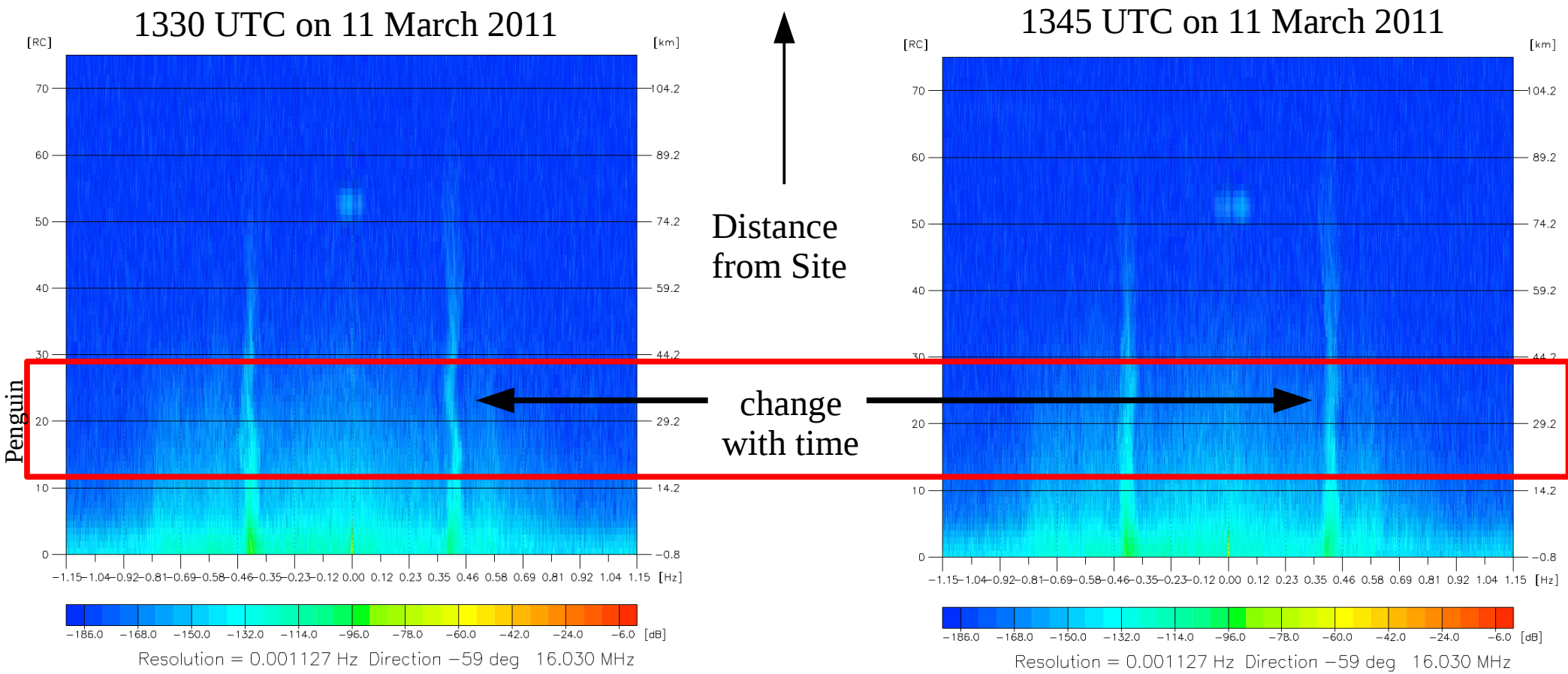
Random backscatter at other wavelengths



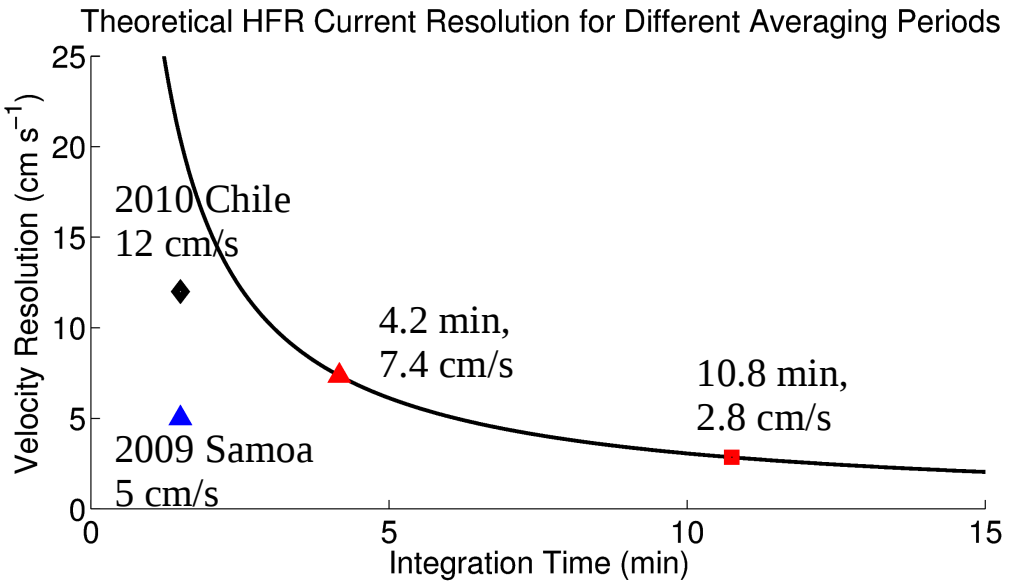
Not true Doppler radar

- Demodulation with complex transmit signal gives amplitude and phase
- Fourier Transform (FT) of a single chirp resolves range
- Second FT gives range-resolved Doppler spectrum of slow phase rotation rate

Departure of phase rotation rate from theoretical value is from current



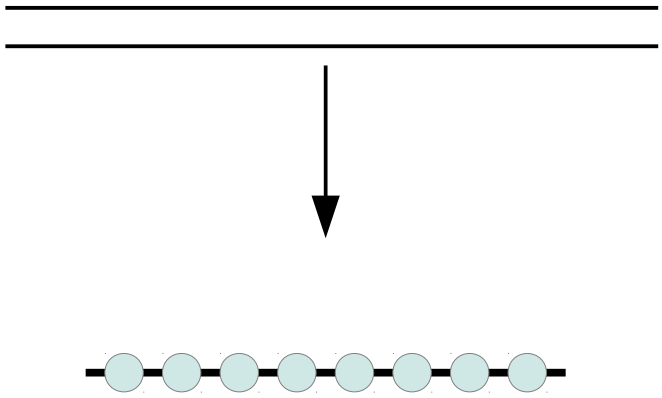
Velocity Resolution



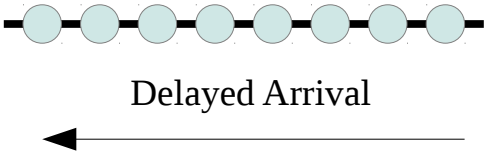
- Balance between high-frequency components and velocity resolution
- Least-squares fit of Gaussian to Bragg line in Doppler spectrum misleading
- Velocity error difficult to determine because of lack of proper comparisons

Beamforming

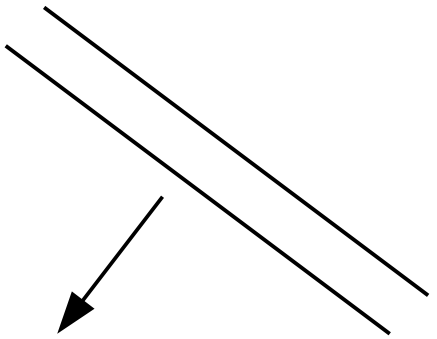
Adding antenna signals with appropriate delays to steer a beam

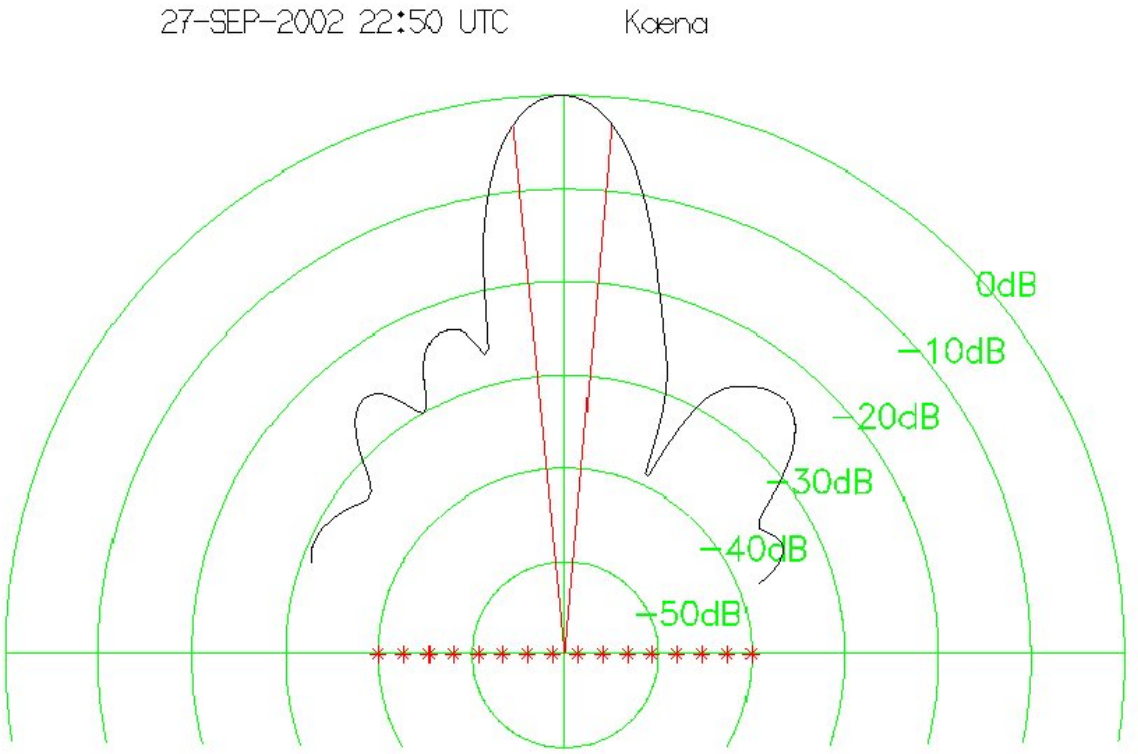


Simultaneous Arrival



Delayed Arrival



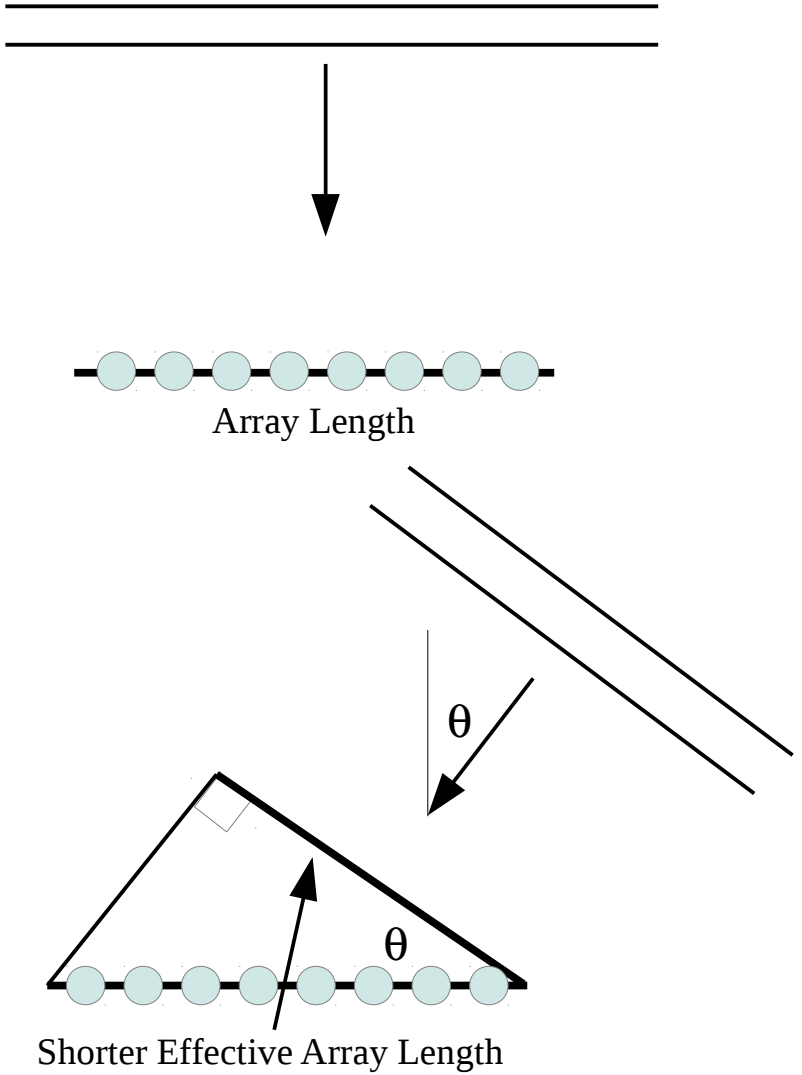


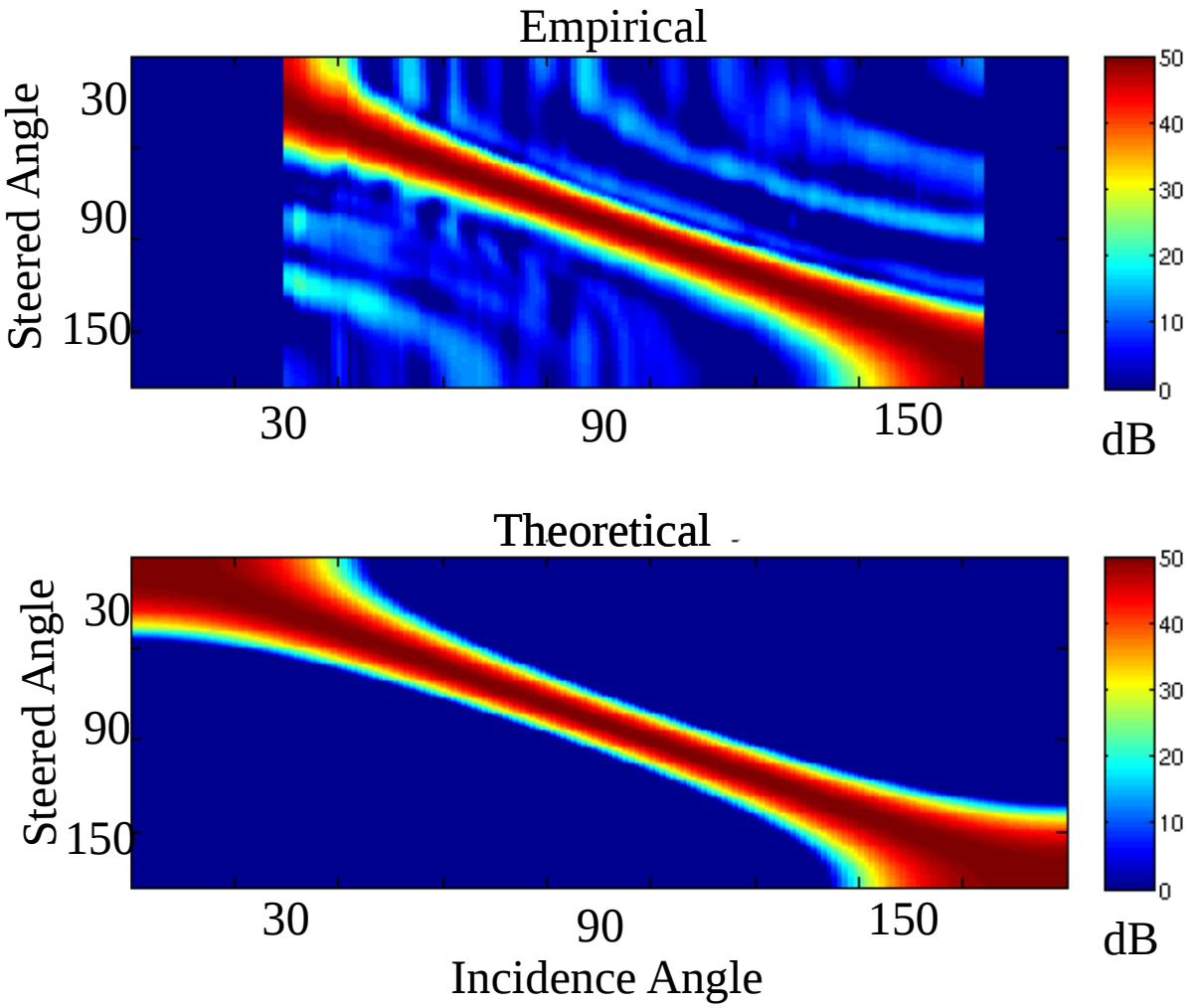
Ultra Spherical Window

Frequency = 16.050 MHz
Array spacing = 0.50 Lambda
Steering = 0.0 degrees
No. dipols = 16

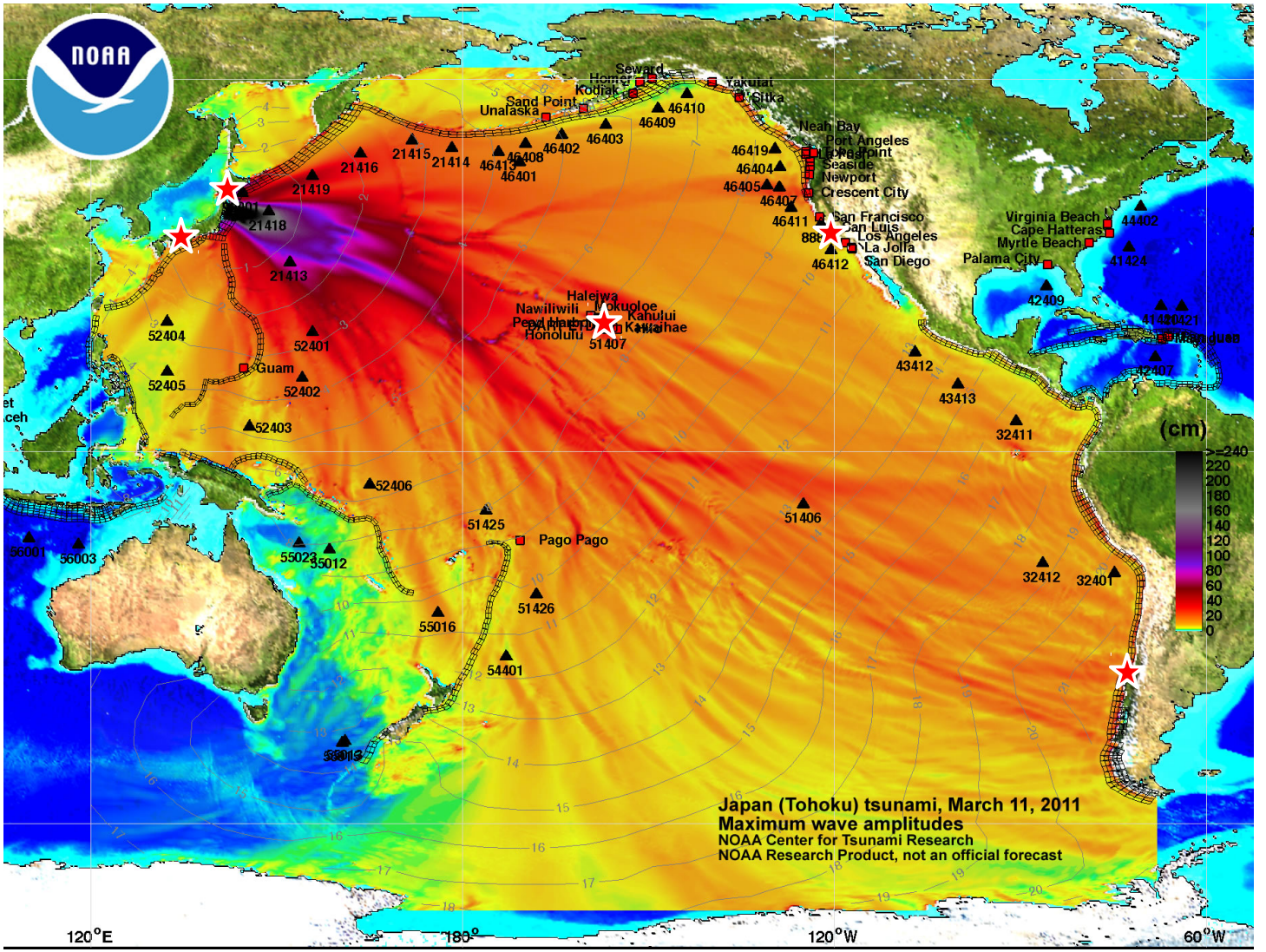
Samples = 512
Array length = 140.3 meters
Range Cell = 39
Target at 45.0 km

- Angular resolution inversely related to Rx array length
- High steering angle shrinks effective Rx array length





2011 Tohoku tsunami

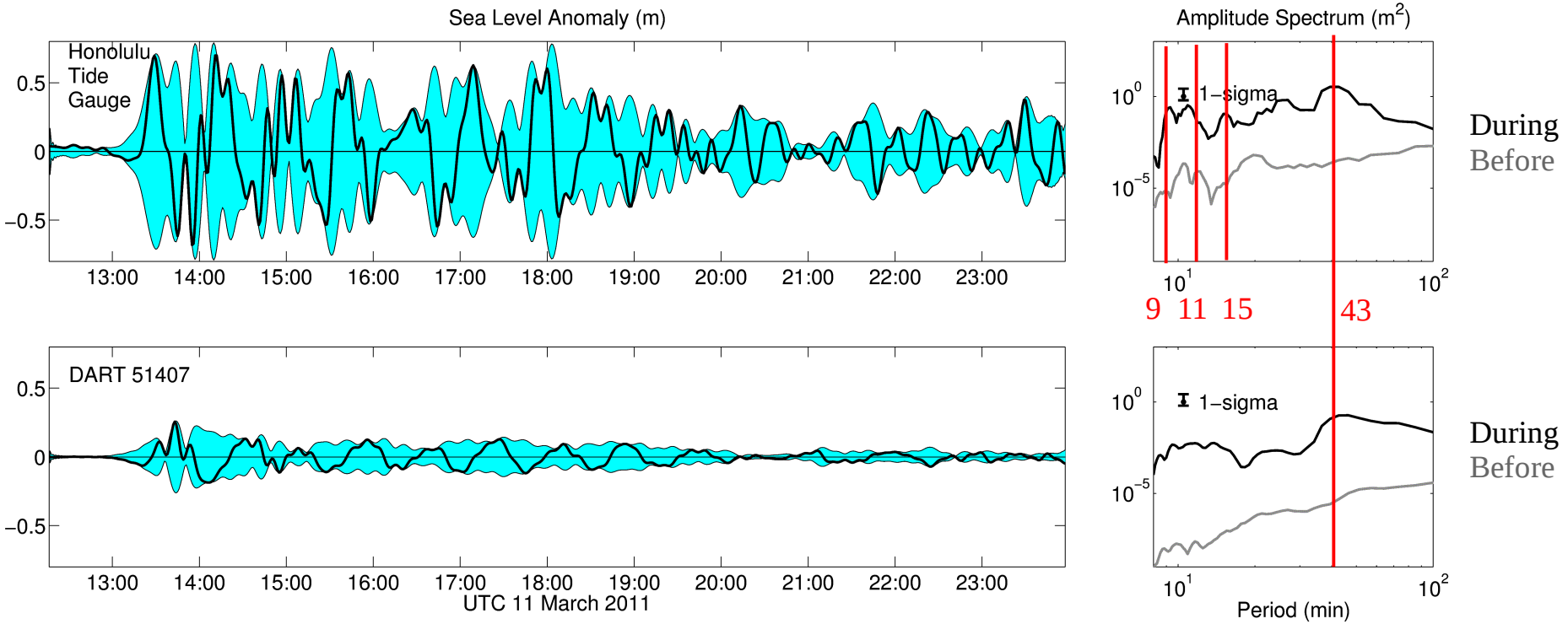


Mw 9.0 @ 0546 UTC on 11 March 2011

1.75 m at DART 21418

Sea Level Anomaly

- Shoaling, refraction and interference, resonance
- Harbor resonance: 9-, 11-, 15-, and 42-minute periods
- Island-chain/regional resonance: 42-minute period



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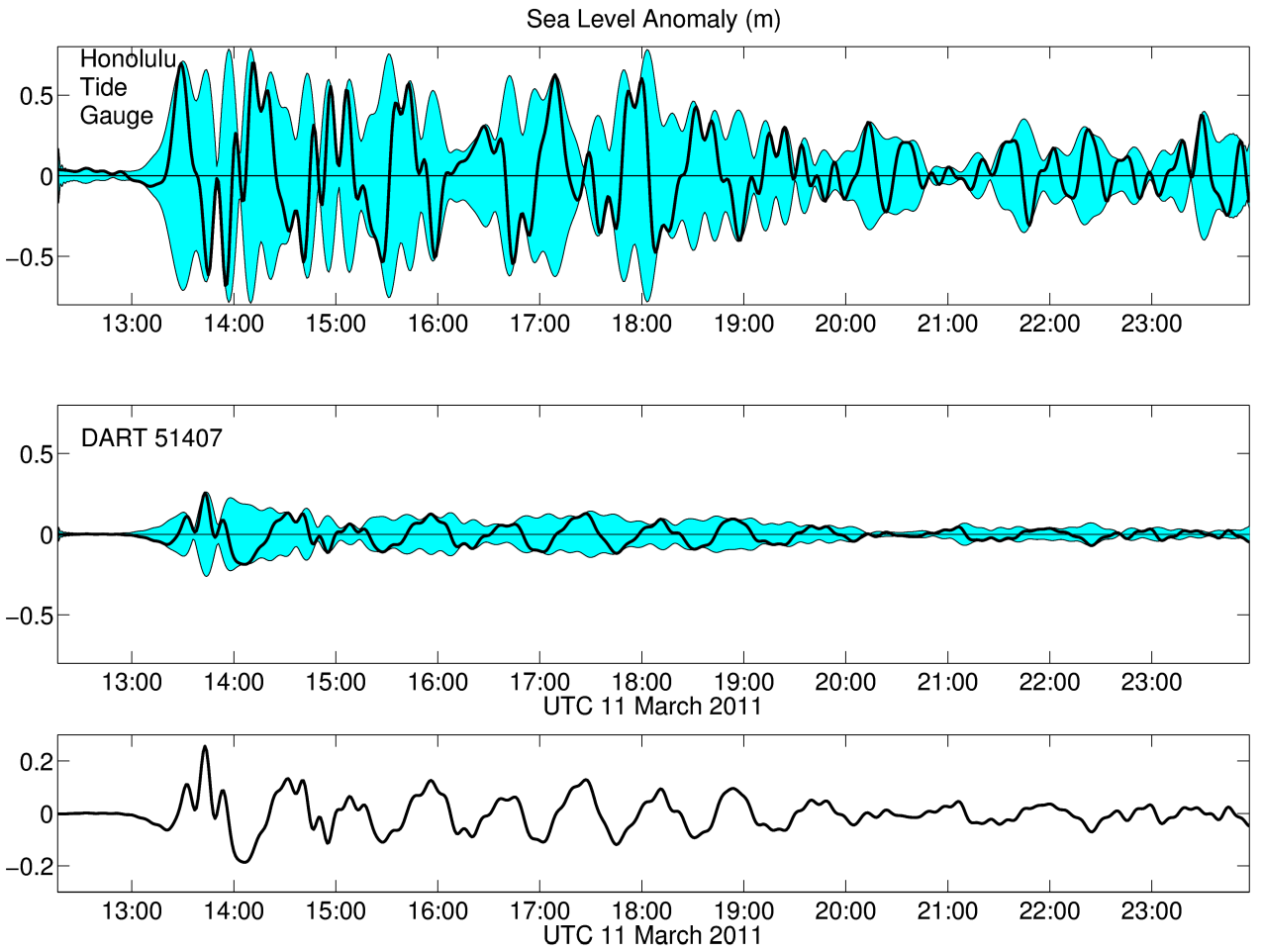
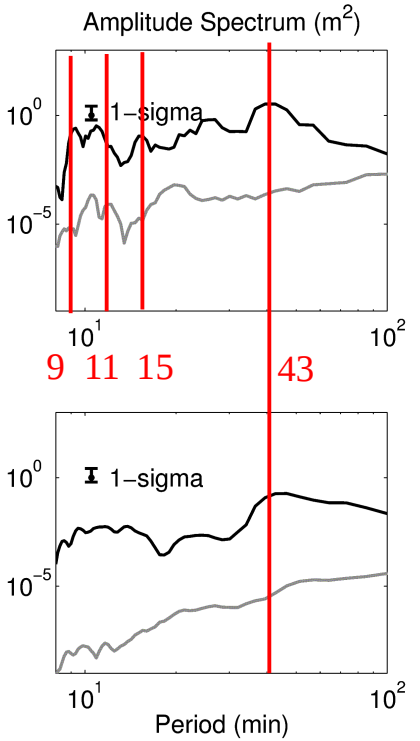
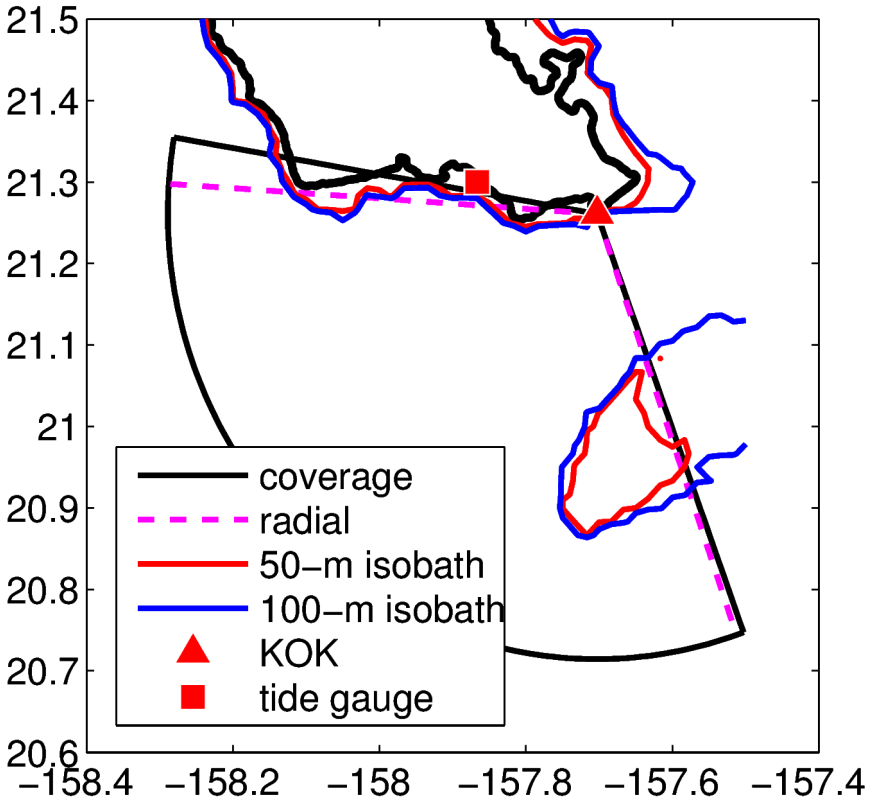


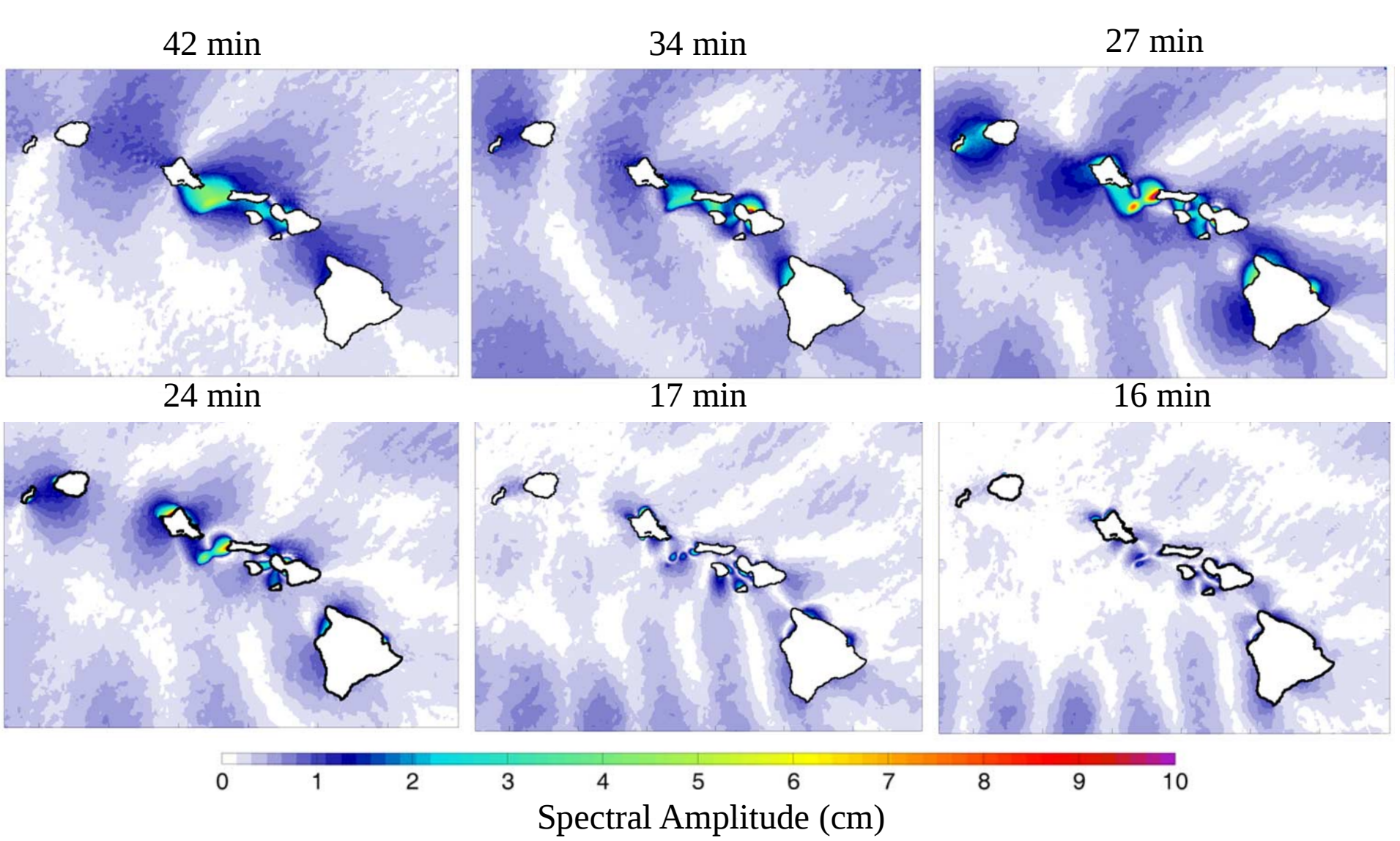


DART Clock

Oahu HFDR

- HFDR on south shore
- High pass: <2 hrs to remove tides
- Problems:
  - Complex arrival waves
  - No shelf to increase orbital velocity
- Penguin Bank & near shore shallows



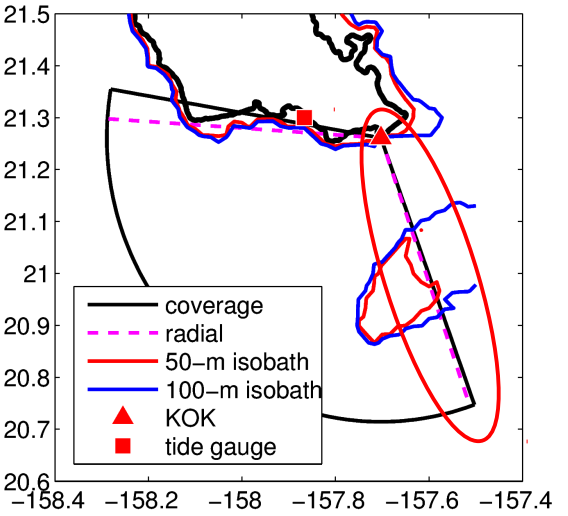


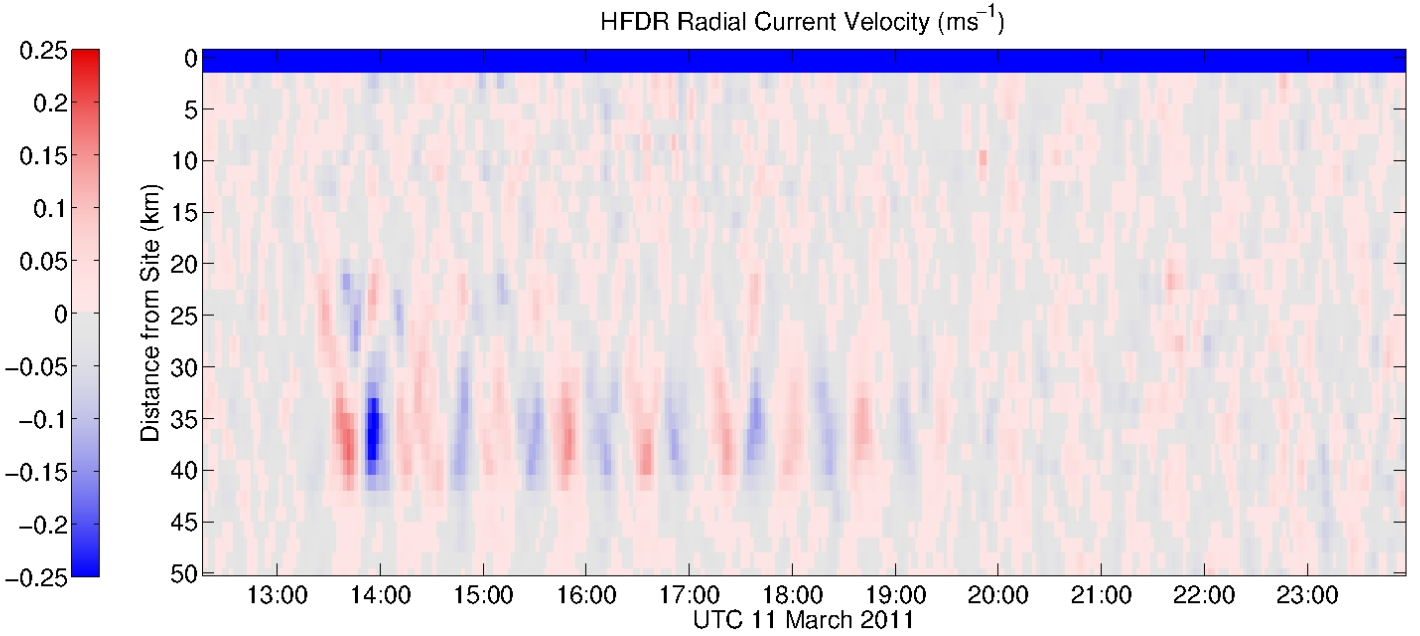
- 17-, 27-, and 42-minute oscillations strongest
- Strongest total spectral amplitude over Penguin Bank

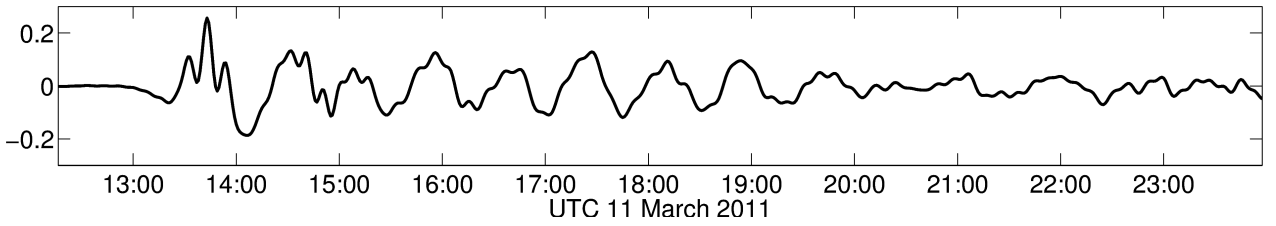
Munger and Cheung 2008

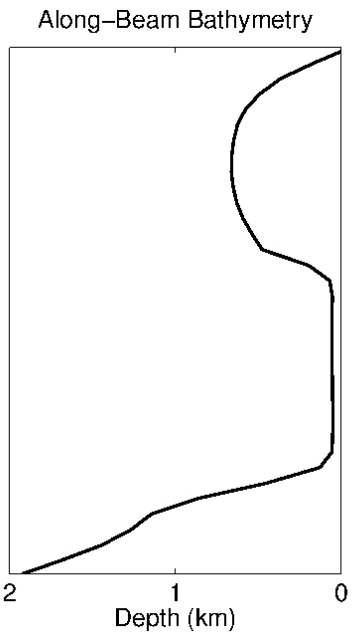
Penguin Bank

- Anomalous currents on crest of bank
- North-south asymmetry in current strength and duration







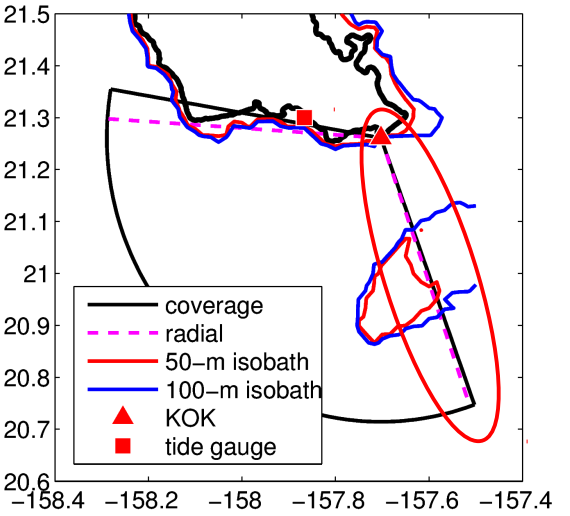


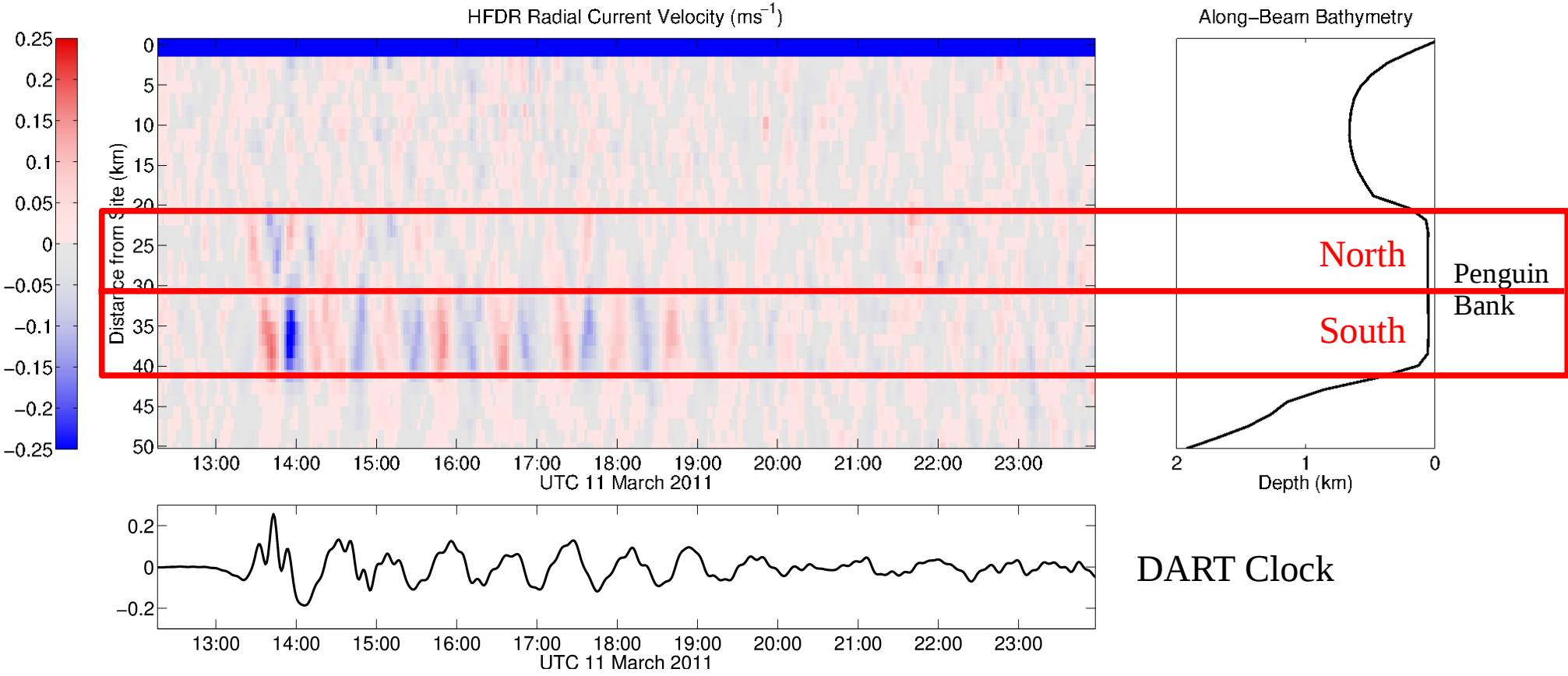
Penguin Bank

DART Clock

Penguin Bank

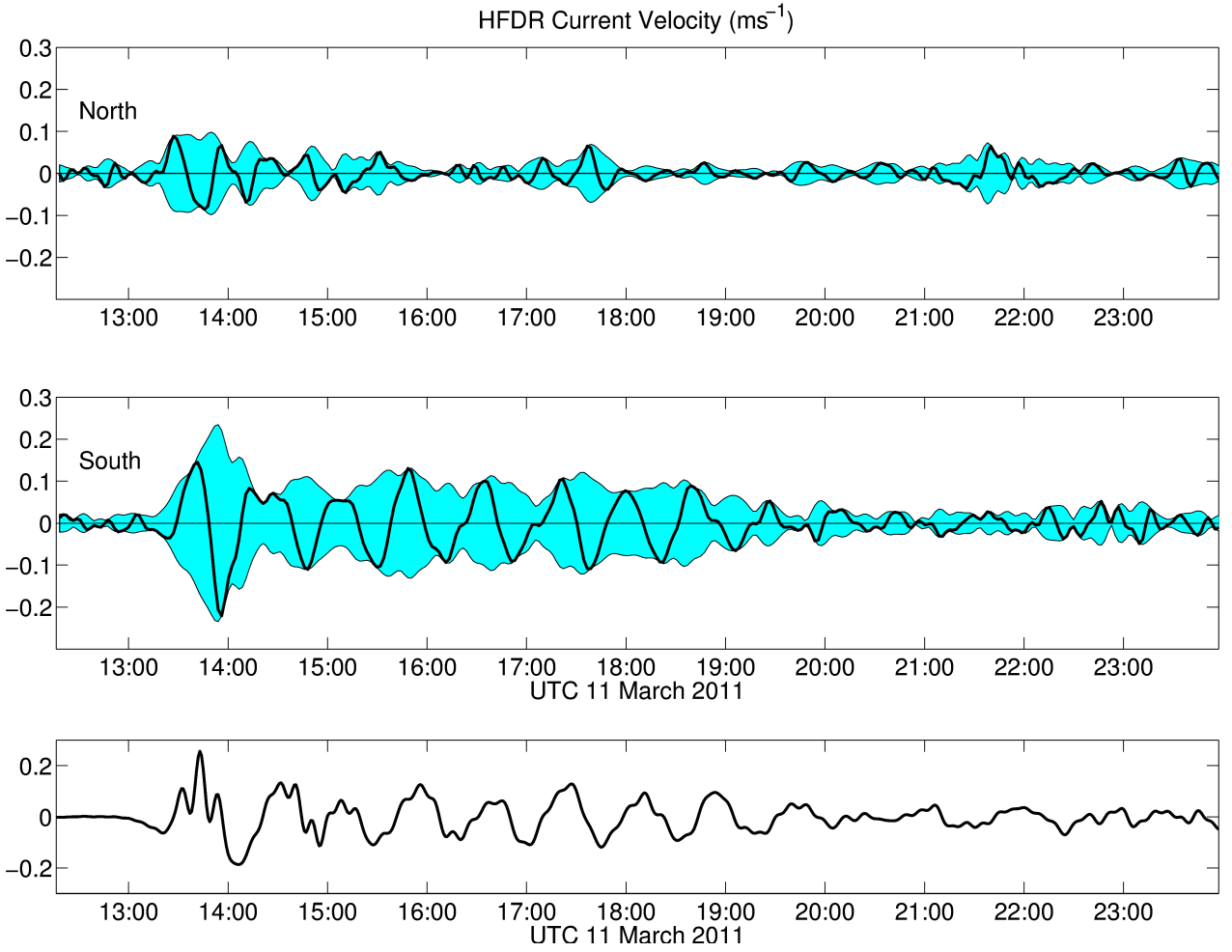
- Anomalous currents on crest of bank
- North-south asymmetry in current strength and duration

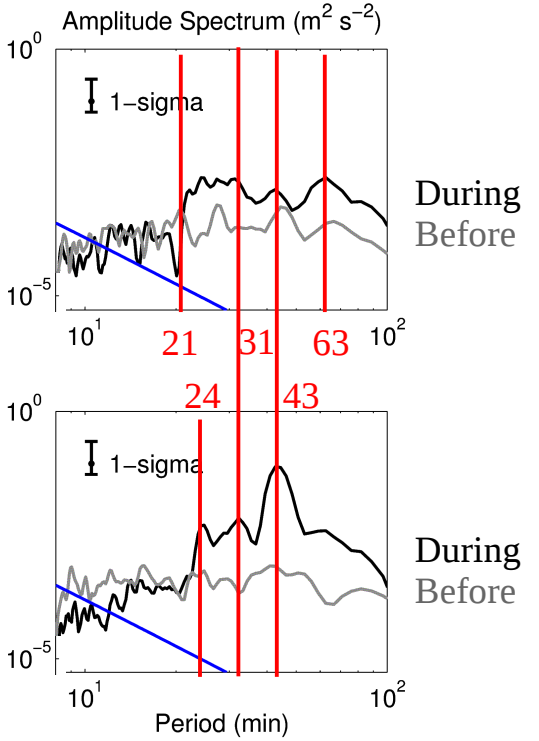




Currents averaged for north and south along radial line

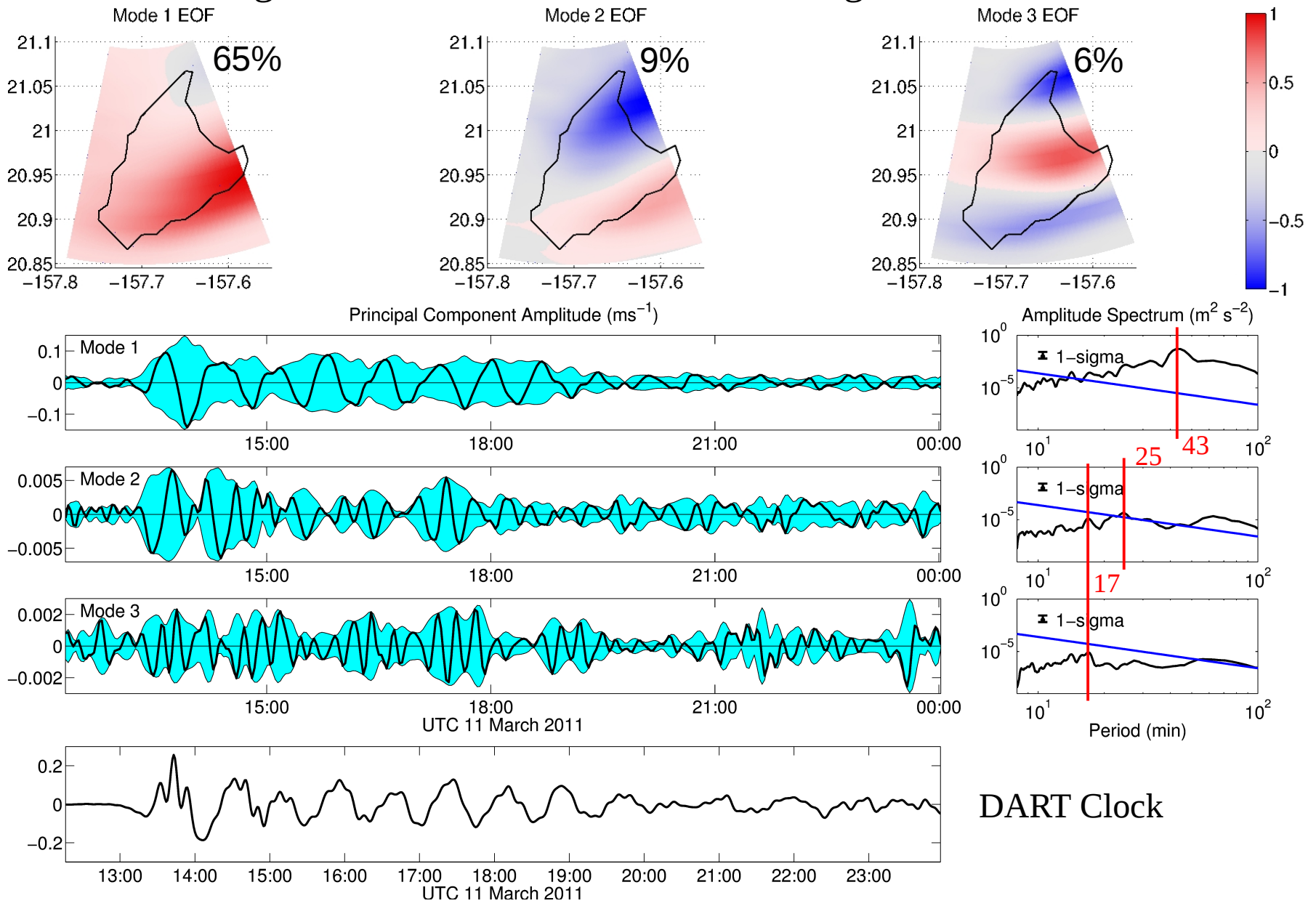
- Asymmetry still present
- Current max: North: 0.09 m/s, South: 0.22 m/s
- Peak periods: North: 21–31-, 43- 63-min, South:24–31, 43-min





DART Clock

- Mode 1: Standing half-wave, primarily South Penguin Bank
- Mode 2: Standing half-wave, primarily North Penguin Bank
- Mode 3 Standing full-wave, low S:N for tsunami signal

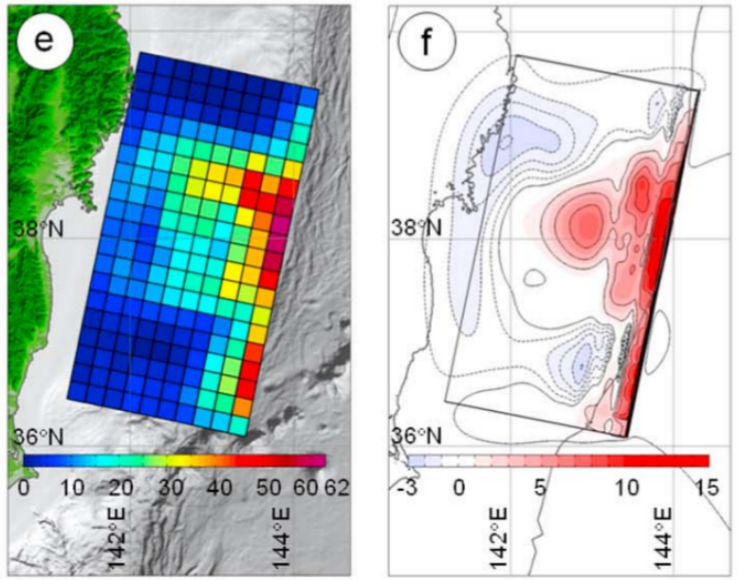


NEOWAVE

- Non-hydrostatic Evolution of Ocean WAVE
  [*Yamazaki et al., 2009, 2011*]
- Features
  - Dynamic sea floor deformation
  - Weak Dispersion
  - Hydraulic jumps and bores
- Validated/Assessed Locally
  [*Yamazaki et al., 2011; Cheung et al., 2013*]
  - DART 51407 & Kilo Nalu *p*
  - 4 tide gauges
  - 18 ADCPs

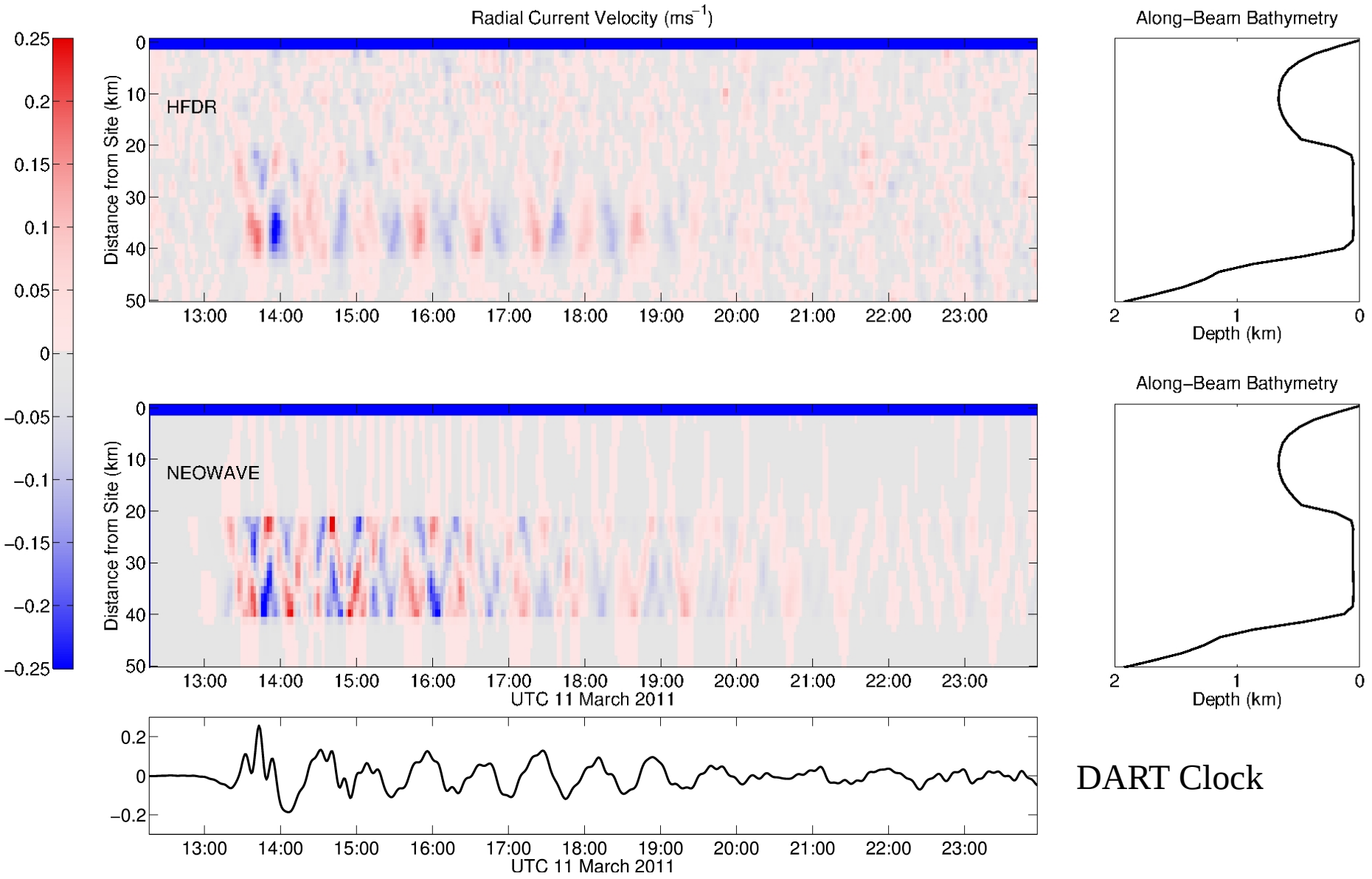
Slip Distribution

Vertical Seafloor Displacement

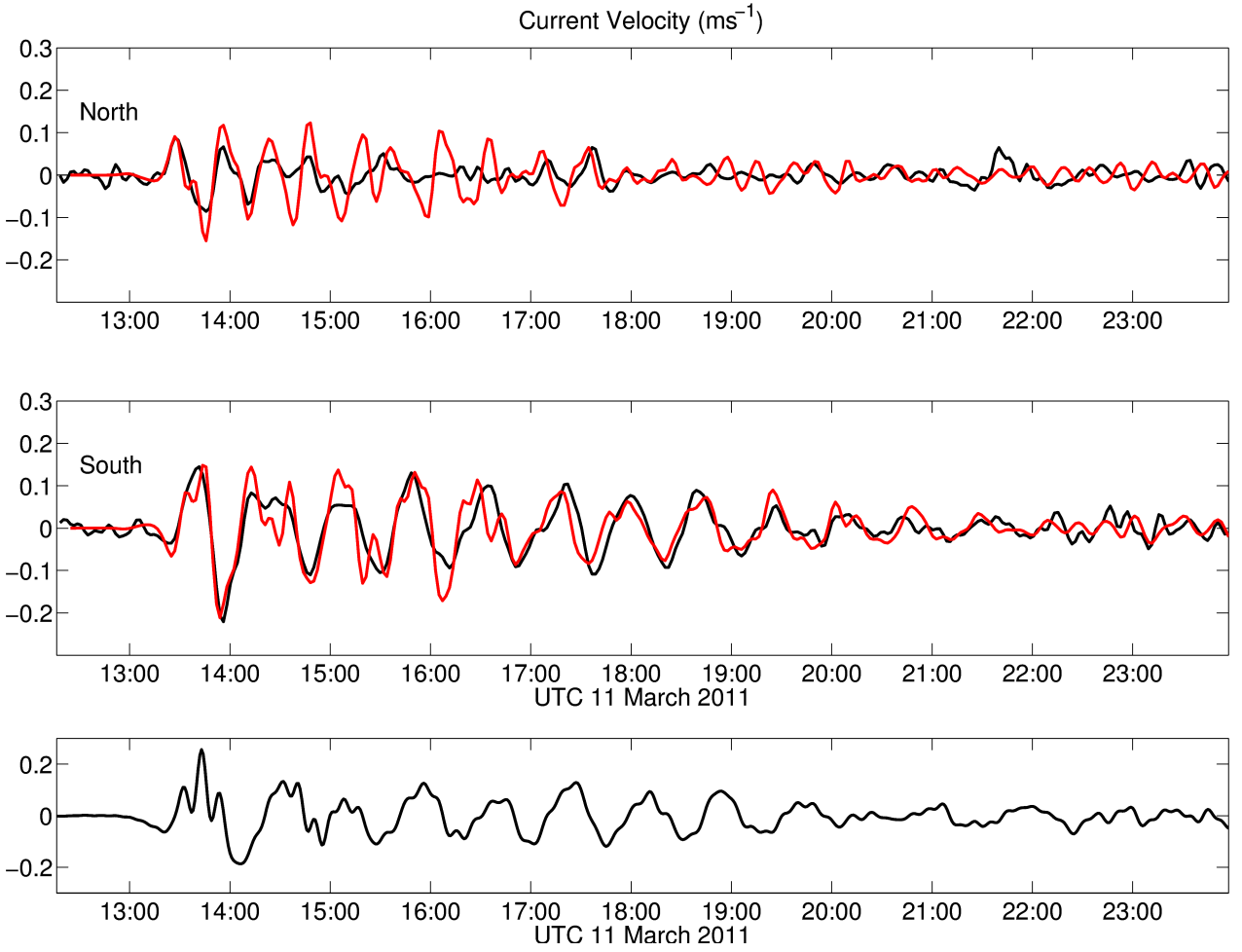


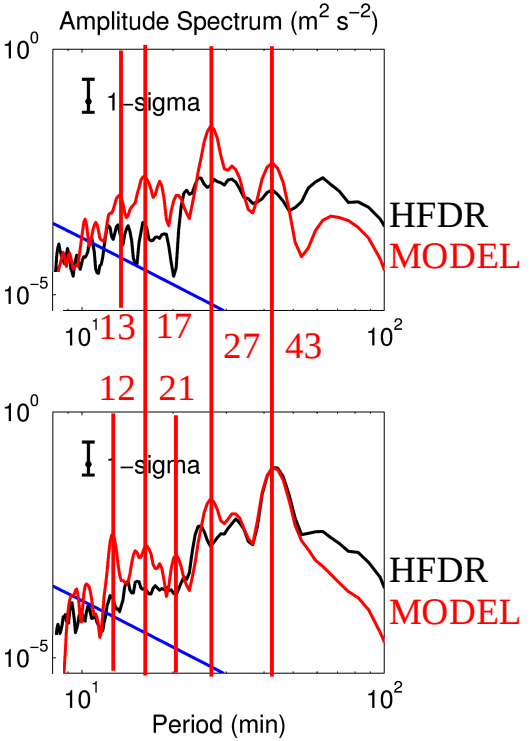
Yamazaki et al., 2012

NEOWAVE lacks strong north-south asymmetry



- North: agreement in amplitude and phase in first 2 oscillations
- South: agreement in amplitude and phase, plus 43-minute peak

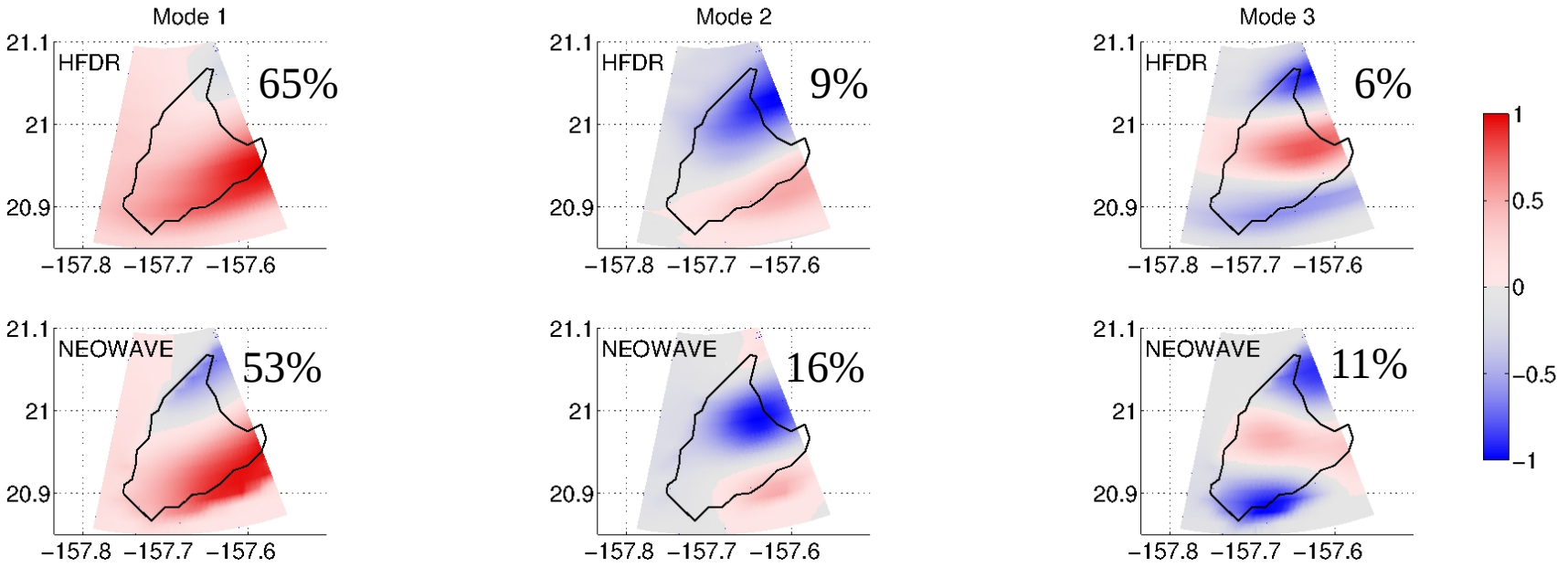




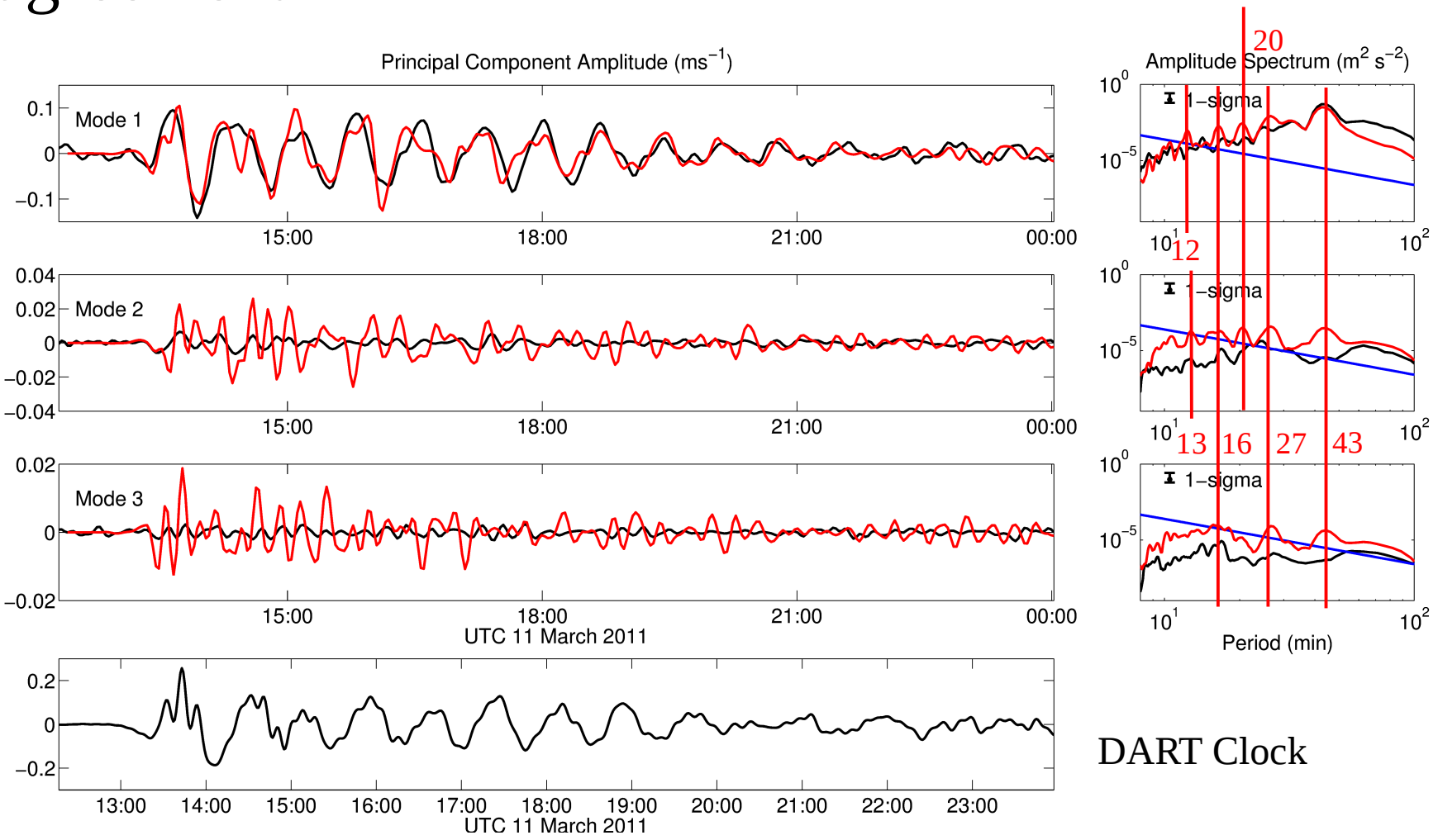
DART Clock

EOF Analysis

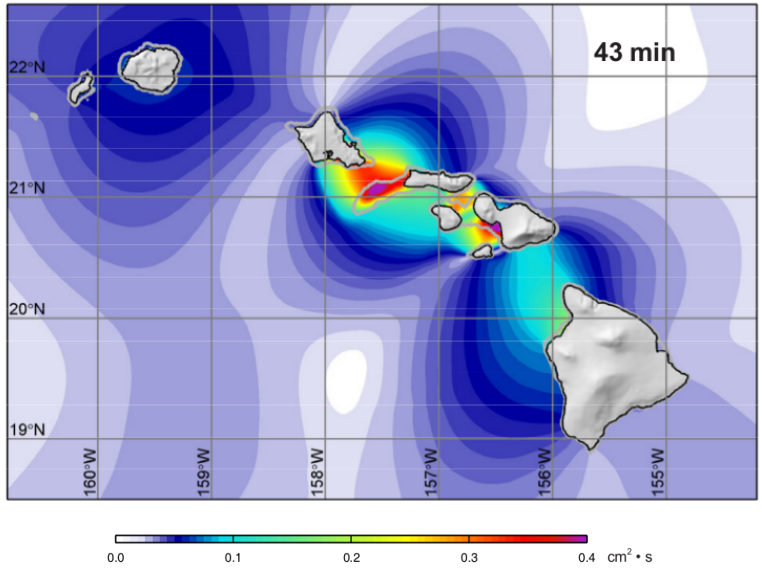
Similarities EOF maxima encourage further comparison



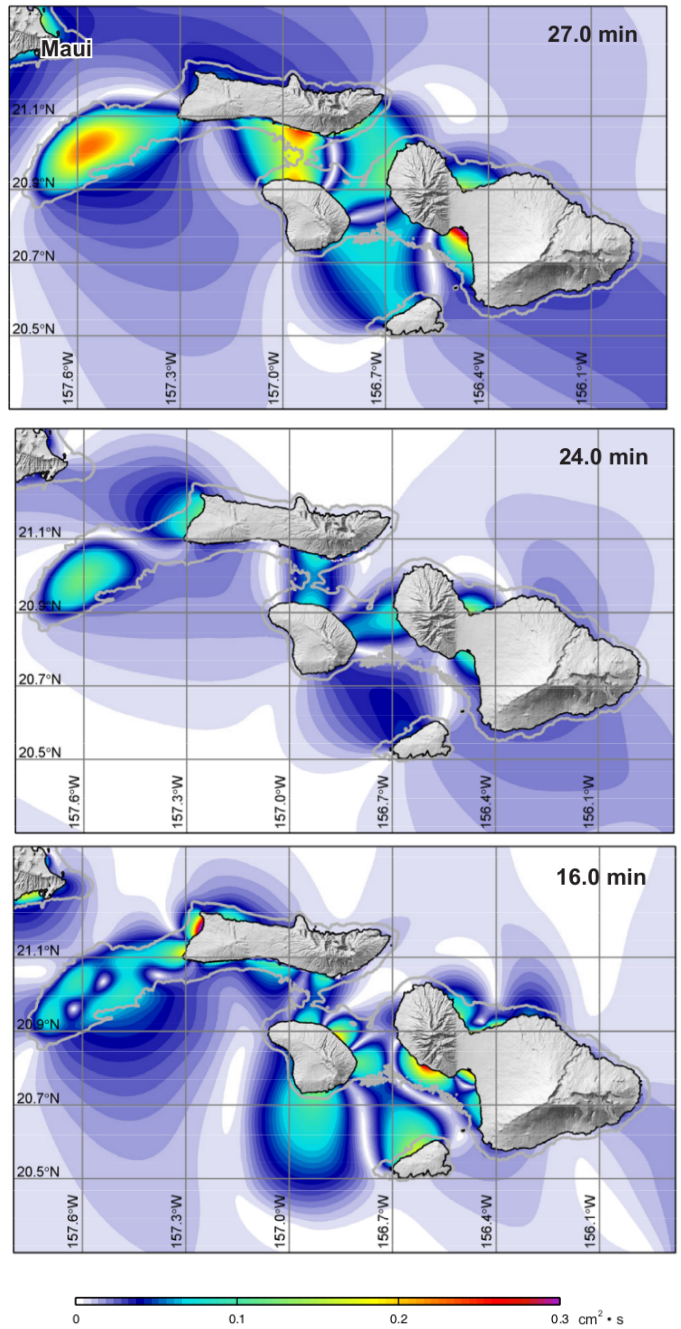
- Principal component 1: amplitude agreement, 43-min period agreement
- Principal components 2 & 3: no amplitude or period agreement



DART Clock



Spectral Amplitude (cm^2 s)



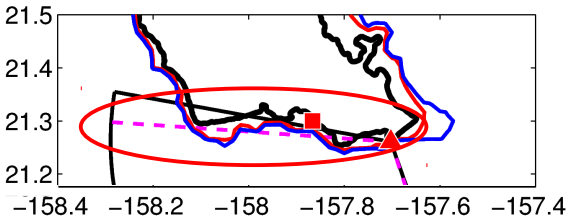
Spectral Amplitude (cm^2 s)

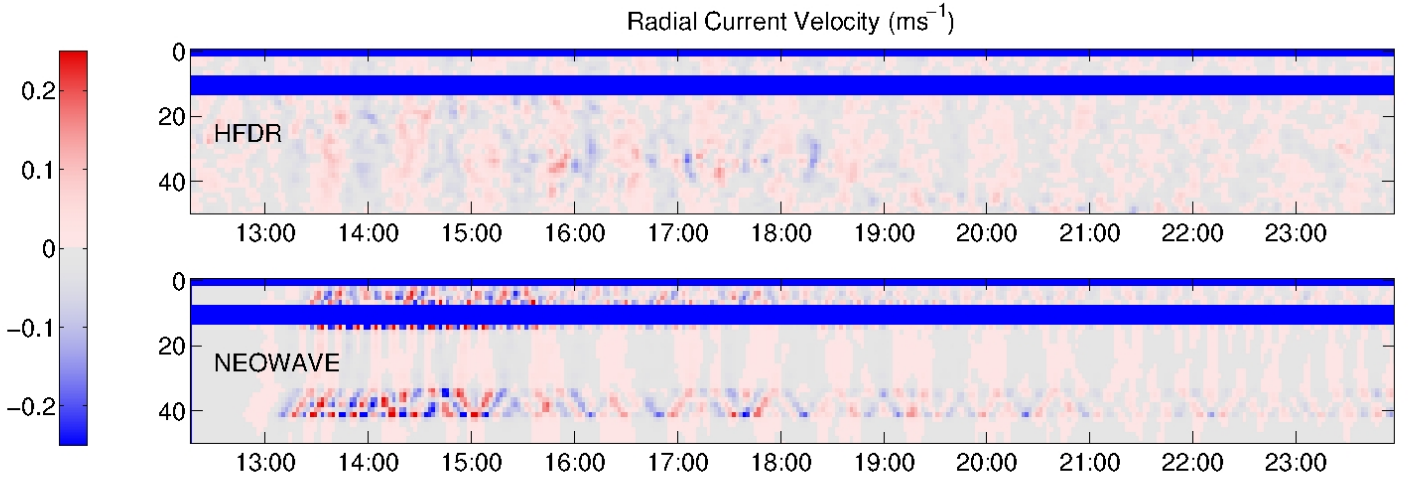
Standing waves formed by currents may be combinations of NEOWAVE sea level spectral modes

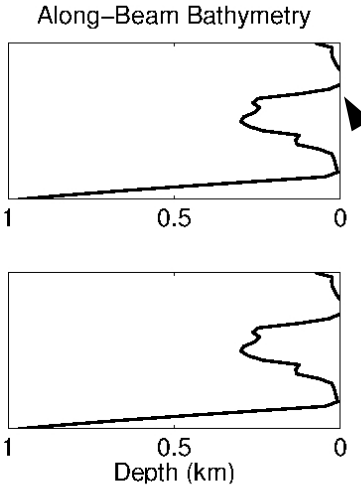
Cheung et al., 2013

Near Shore

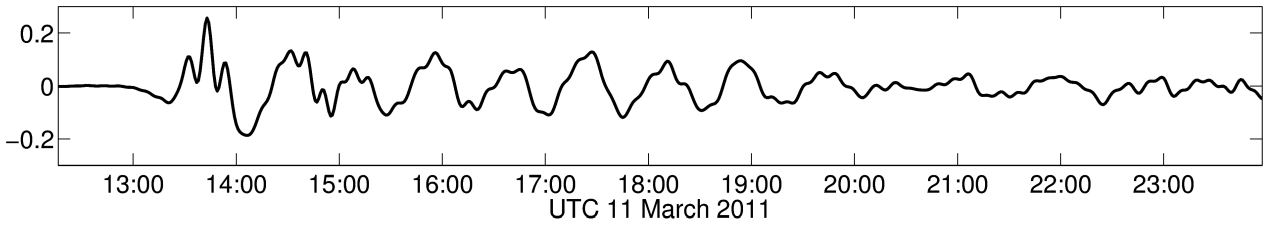
HFDR and NEOWAVE very different







Diamond Head



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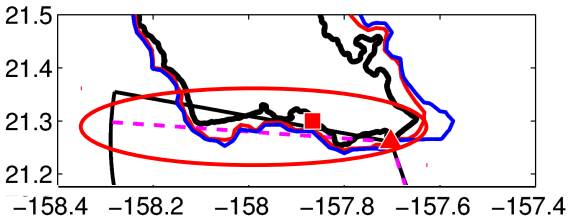

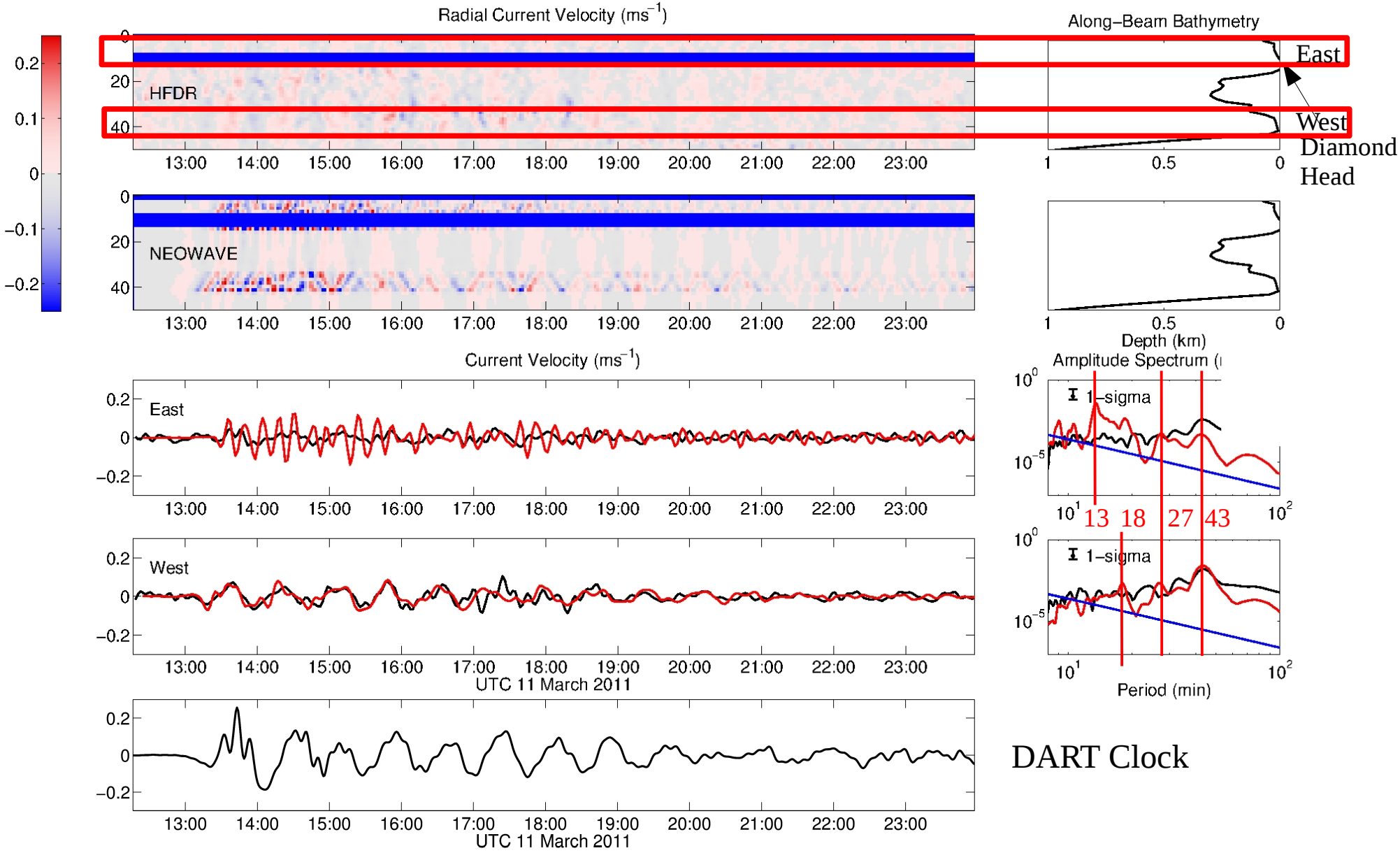

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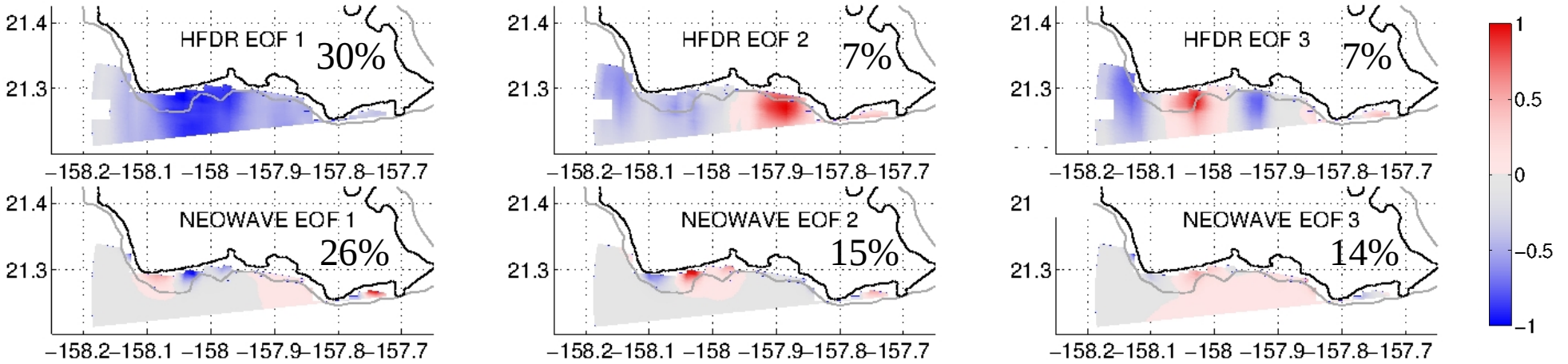
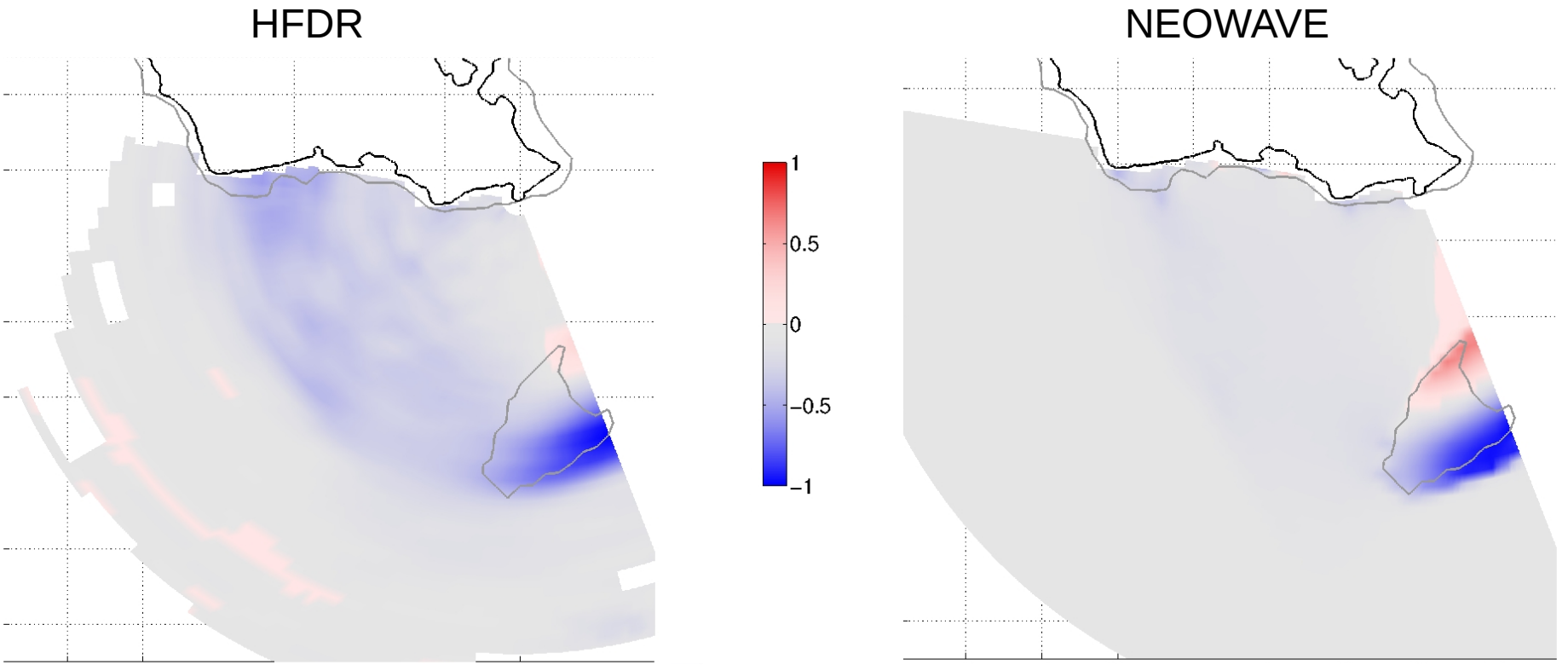


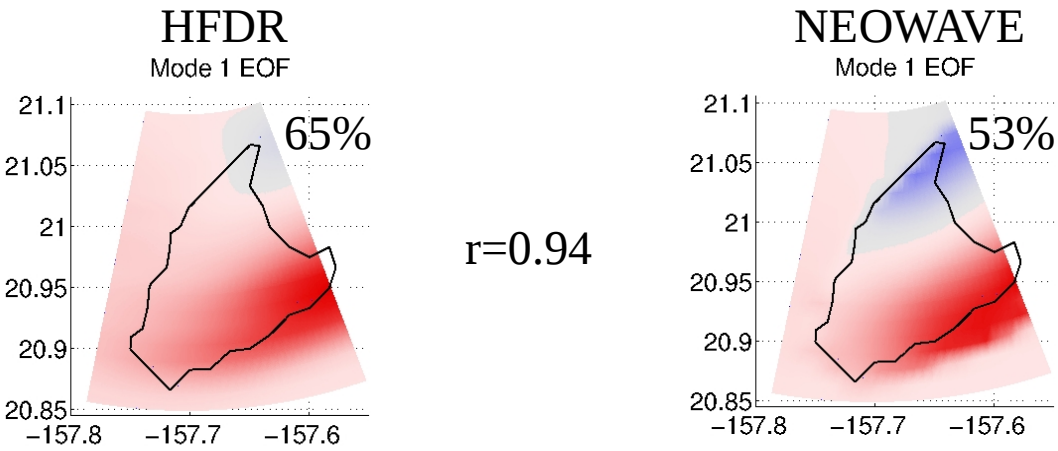
- HFDR current maxima large in size (range and angle)
- NEOWAVE current maxima small and hugging the coastline
- Angular streaking in HFDR due to reduced angular resolution at large steering angles

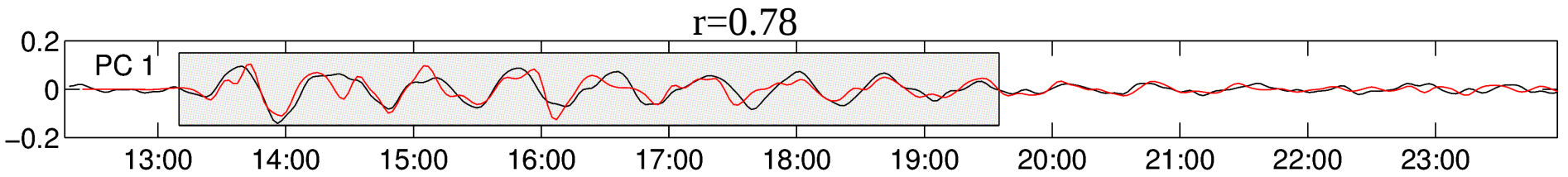


- HFDR arc from Penguin Bank to near-shore likely azimuthal side lobe contamination
- Lowered angular resolution on Penguin Bank follows the bank's currents

HFDR as a Model Validation Tool

- Model already validated with ADCP
- What HFDR can contribute: 2-D validation
- Good correlations despite less-than-ideal setup





Conclusions

- HFDR detects island chain/regional resonance over Penguin Bank and possibly in near-shore area
- Tsunami current resonance is asymmetric over Penguin Bank, and provides evidence of standing half and full waves in sea level height
- Currents are smeared due to angular resolution degradation when beamforming at high incidence angles
- HFDR can be a tool in 2-D model validation

- Verification of tsunami with HFDR possible in real time
- Deploy HFDR on Molokai or Lanai to fully map Penguin Bank
- Addition of HFDR to warning system useful or not, depending on local bathymetry

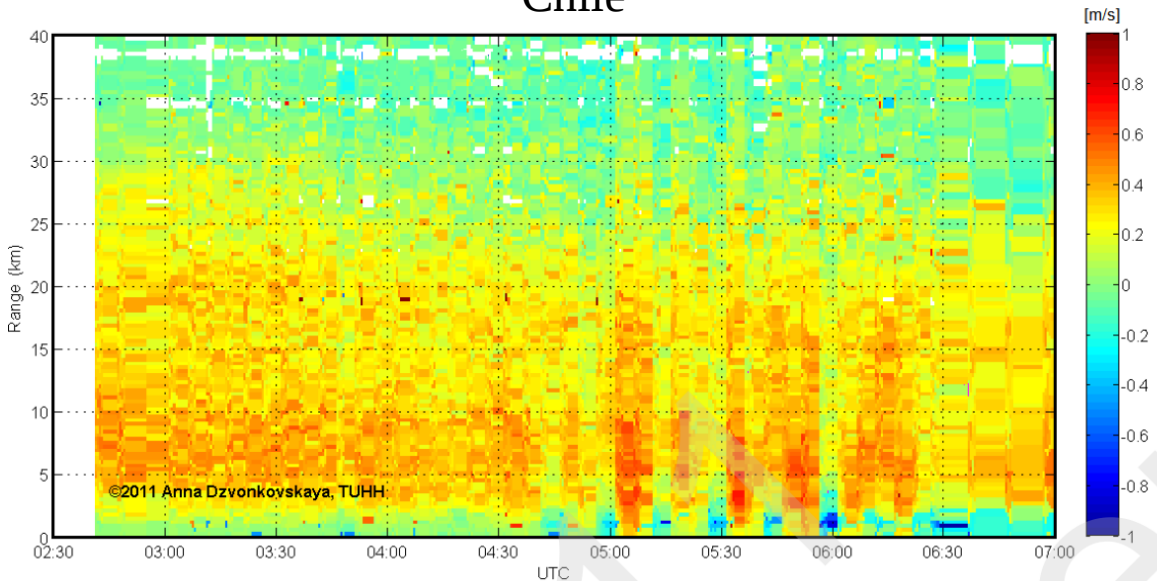
Gerard Fryer; "Ultimate Disaster: Mega Tsunami," National Geographic

Acknowledgements

- Student Support: Department of Homeland Security
- HFDR funding: PacIOOS

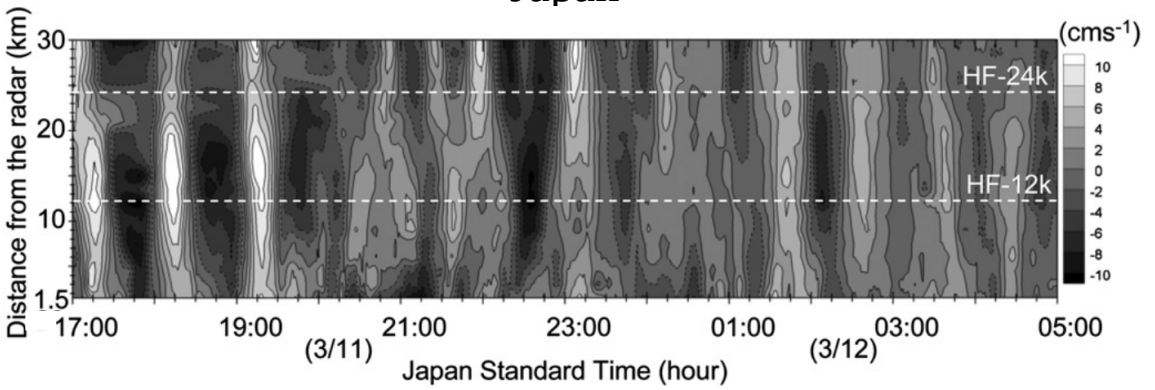
Previous Detection with HFDR

Chile



Dzvonkovskaya et al., 2011

Japan



Hinata et al., 2011