High Frequency Radio Oceanography:

Principles, technology and applications

The *radlab* group:

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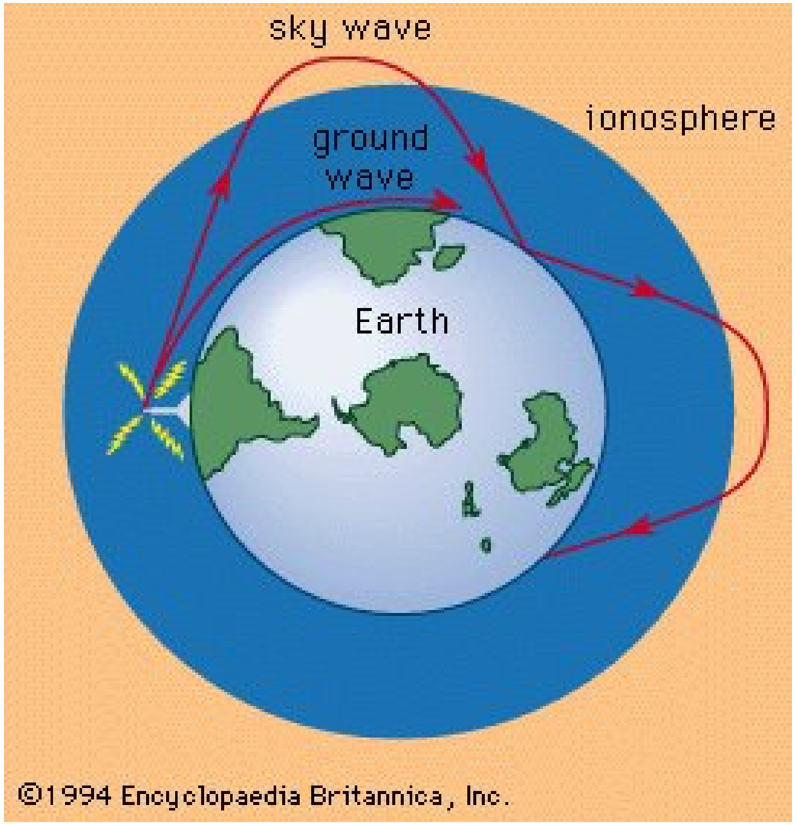
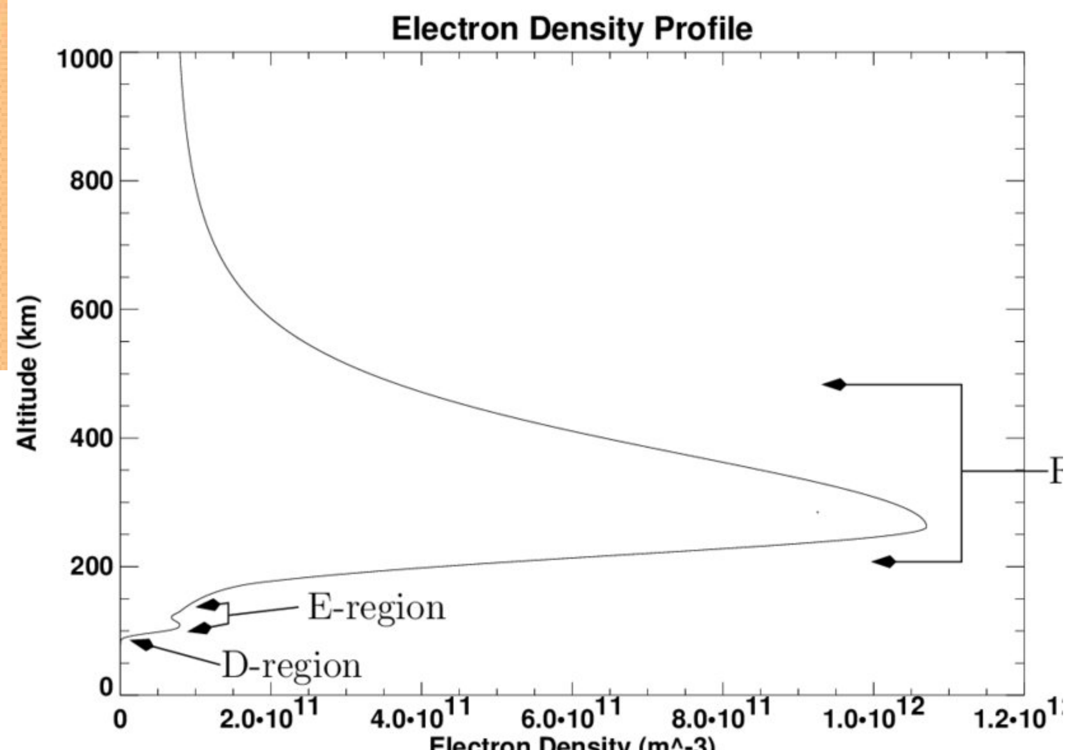
Peter Milne, John McLean (D-Tacq Solutions Ltd.)

https://www.oceanphysics.org/

Electromagnetic propagation over conductive ocean

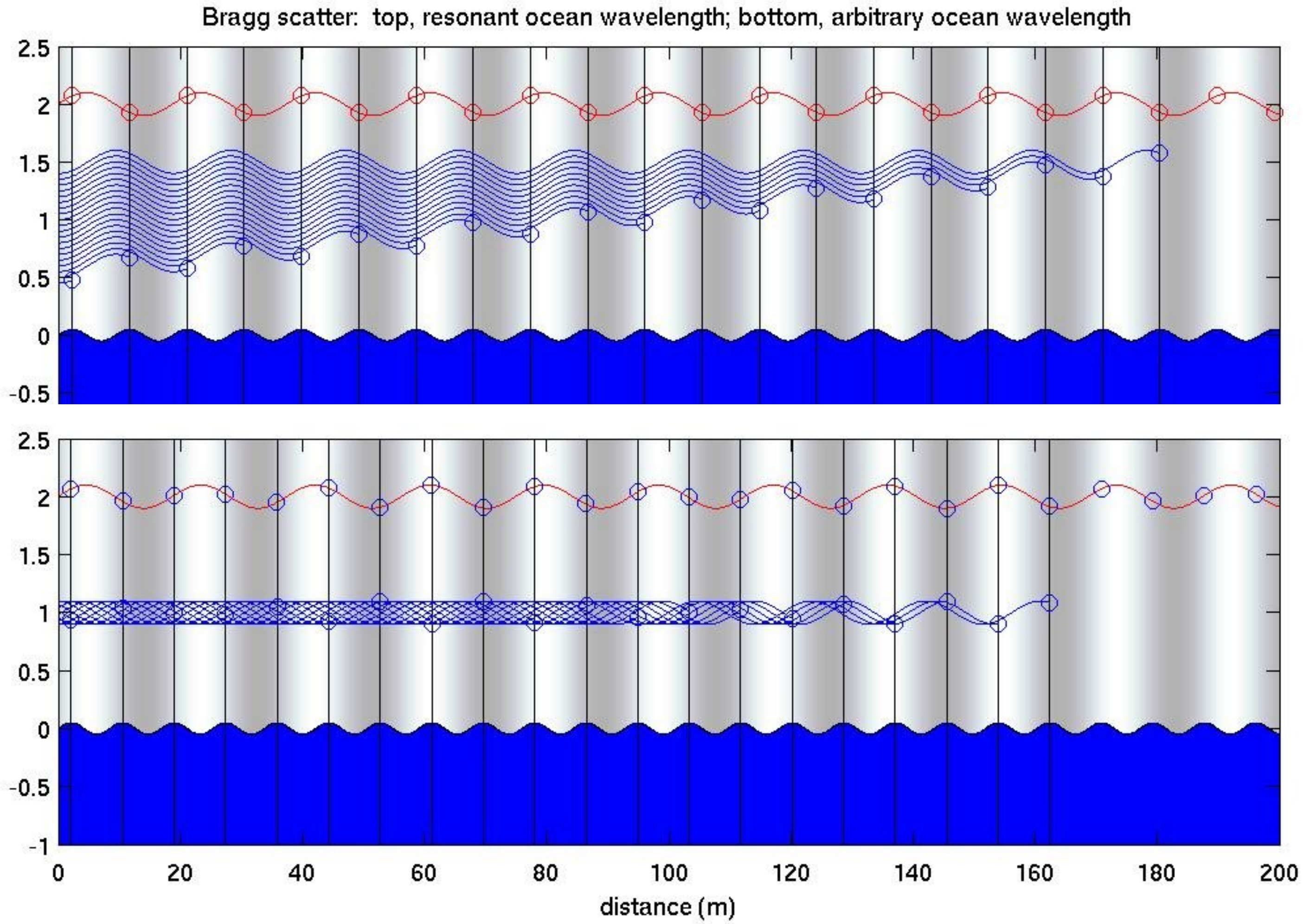


Conductivity:
- sea water 4 /Ω/m
- limestone 0.005 /Ω/m



Bragg-scattering from a water surface

Ocean Wavelength = ½ Radio Wavelength



UH Generic High Frequency Doppler Radar specifications

Modulation	FMCW linear chirp
Operating Frequency Range	from 3 MHz to 30 MHz
Transmitted RF-Power	typically 3-5 W, max. 50 W
Range	50 km/ 25 NM @ 27 MHz
	100 km/ 50 NM @ 16 MHz
	260 km/ 140 NM @ 8 MHz
Range Resolution	depends on authorized bandwidth c/2B 1.5km@ 100kHz, 150m @ 1MHz (voice 3kHz)
Azimuthal Resolution	better than 2 degrees

Current deployments of UH Generic HF radars:

- *Hawai'i, the Pacific Island Observing System (feeding into HFRnet):*

- 5 radars at 13.5, 16 and 26.5 MHz operating on Oahu, since 2009
- 2 radars at 16 and 24.5 MHz operating on Hawai'i, since 2012
- 2 solar-powered radars at 13.5 MHz in Guam and Rota, starting 2025

- *Mexico (UABC):*

- 3 radars at 24.5-26.5 MHz, covering Bahia de Todos Santos (Ensenada), installed 2015
- 2 long-range radars at 8 MHz range up to 250 km offshore Baja California, installed 2016
- 15 long-range radars at 7-8 MHz, covering the Gulf of Mexico, installed 2018

- *New England (WHOI):*

- 10 radars at 16 MHz mapping the New England shelf, starting 2018

- *Luzon strait (UPD-MSI, with TORI):*

- 3 long-range radars at 8 MHz, collaboration Philippines/Taiwan/Hawaii, 2019-2023

- *Quebec (ISMER):*

- 2 mobile solar-powered radars at 16 MHz deployed in the St Lawrence estuary, since 2018

- *France (IFREMER):*

- 1 long-range radar at 4.5 MHz over the southern Bay of Biscay, since 2021

- *Taiwan (NCU; NAMR; TORI; IHMT)*

- 21 radars at 25-30 MHz covering harbors around TW, since 2018

The Helical Antenna*

JOHN D. KRAUS†, SENIOR MEMBER, IRE

Summary—The helix is a fundamental form of antenna of which loops and straight wires are limiting cases. When the helix is small compared to the wavelength, radiation is maximum normal to the helix axis. Depending on the helix geometry, the radiation may, in theory, be elliptically, plane, or circularly polarized.

When the helix circumference is about 1 wavelength, radiation may be maximum in the direction of the helix axis and circularly polarized or nearly so. This mode of radiation, called the axial or beam mode, is generated in practice with great ease, and may be dominant over a wide frequency range with desirable pattern, impedance, and polarization characteristics. The radiation pattern is maintained in the axial mode over wide frequency ranges because of a natural adjustment of the phase velocity of wave propagation on the helix. The terminal impedance is relatively constant over the same frequency range because of the large initial attenuation of waves on the helix. The conditions for circular polarization are analyzed, and the importance of the array factor in determining the radiation pattern of a long helix is discussed.

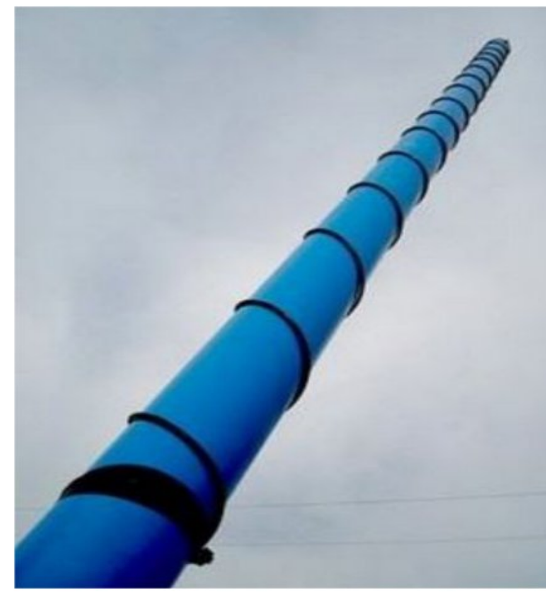
* Decimal classification: R125.1×R326.61. Original manuscript received by the Institute, June 7, 1948. Presented in part, 1948 IRE National Convention, New York, N. Y., March 23, 1948.

† Department of Electrical Engineering, Ohio State University, Columbus, Ohio.

Introduction

A HELIX is a fundamental geometric form. It has applications in many branches of physics and engineering. For example, in mechanical systems the helix or coil spring is a familiar structure; in electrical systems, a helical conductor or inductor is a common type of circuit element; and in many dynamic phenom-



The transmit antennas are normal-mode helical monopoles (Kraus, J.D., “The Helical Antenna”, *Proc. I.R.E.* 1949 pp. 263-272). They consist of an AWG-16 vertical wire of length λ/4 wound over a mast of height λ/8 and diameter λ/300, a 3-loop tuning air-coil, and a network of 4 underground radials of length λ/4 (λ is the electromagnetic wavelength). The air-coil diameter is adjusted to achieve resonance using a standard commercial VSWR meter.

Baler (Ph.) Receiving Array   8 MHz range 260 km

Penghu island TW 32 antennas range 40 km @ 26.5 MHz

Frequency-modulated homodyne radar

- Δt is travel time to & return from range
- Δf is frequency in FFT that gives range
- Shorter times and lower frequencies are closer ranges
- Maximum range indicates a maximum time and maximum frequency
- 150 km R, 100 kHz B, 1/3 s Tchirp:
  - Δt = 2R / c = 1 ms
  - Chirp rate = B / Tchirp = 300 kHz/s
  - Δf = Dt * Rchirp ~ 300 Hz
  - Minimum Fs for Nyquist = 600 Hz

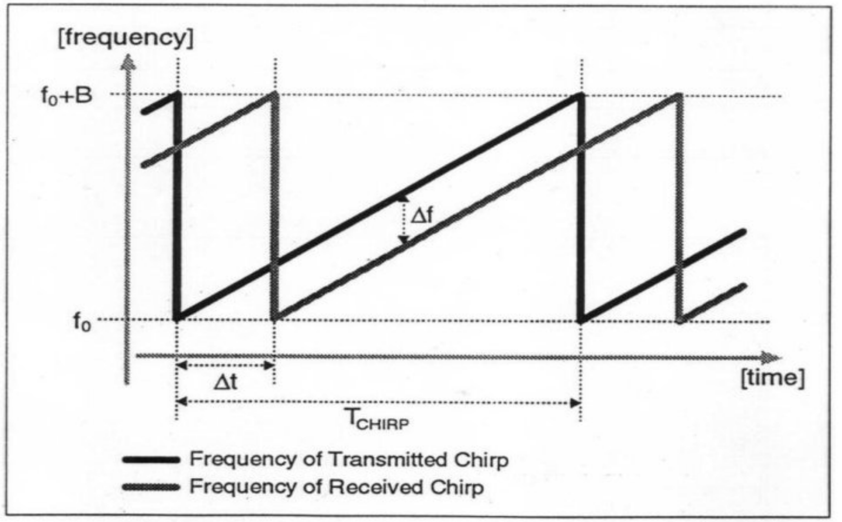


Figure 2: Range resolution using a frequency chirp.

Radial currents

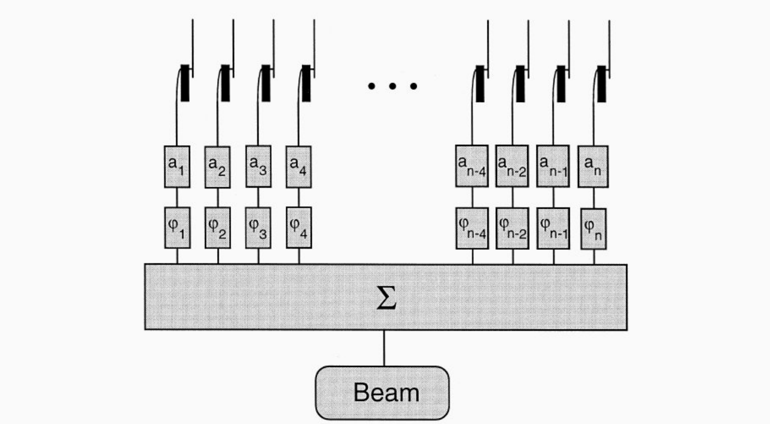
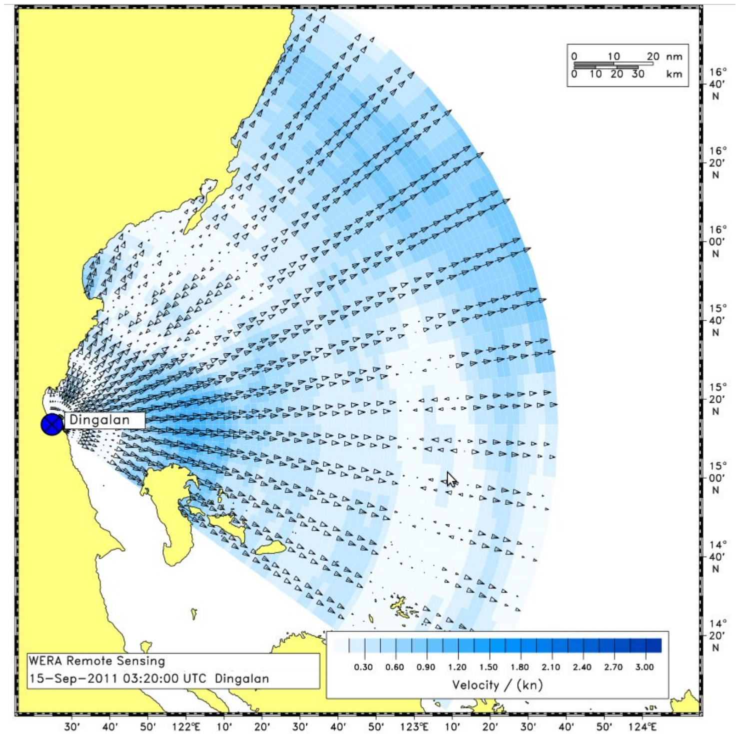
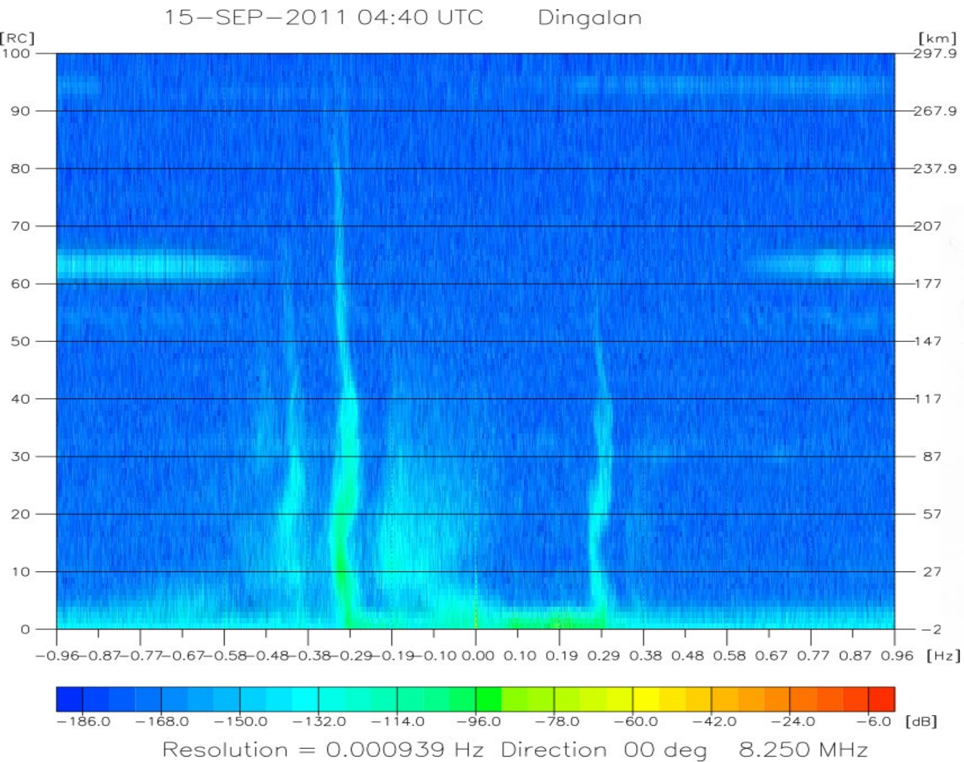
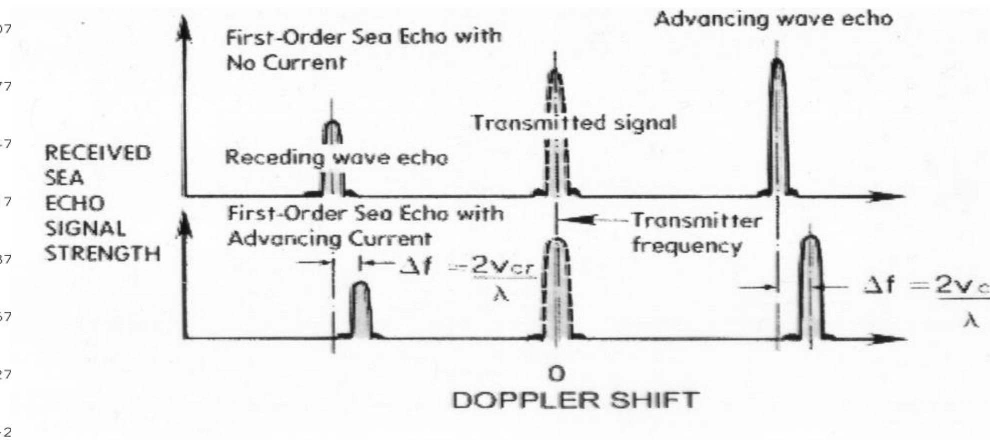


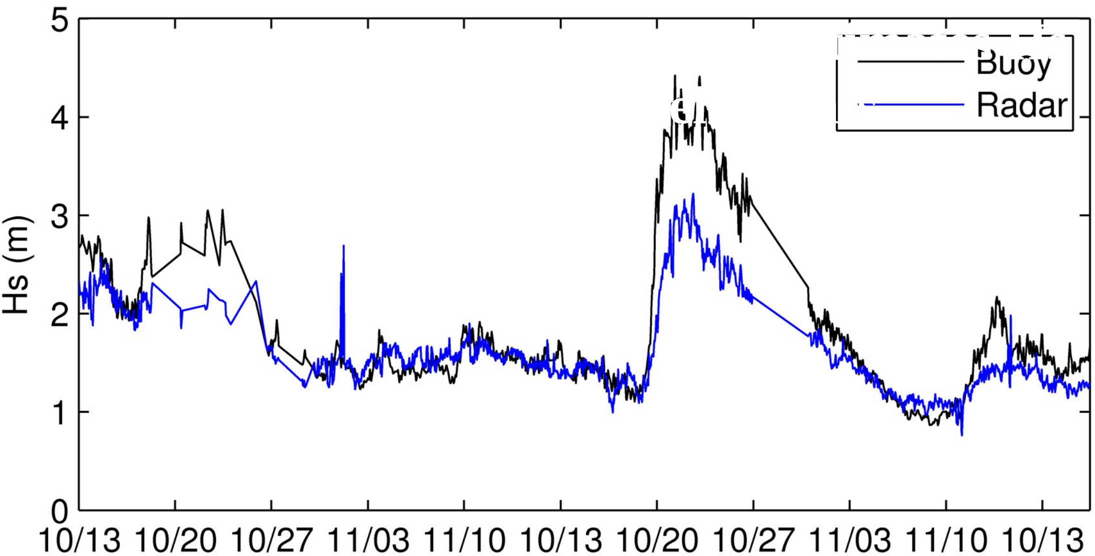
Fig. 10. Principle of beamforming. After weighing by a_i and phase shifting by φ_i the signals of n receive antennas are added.

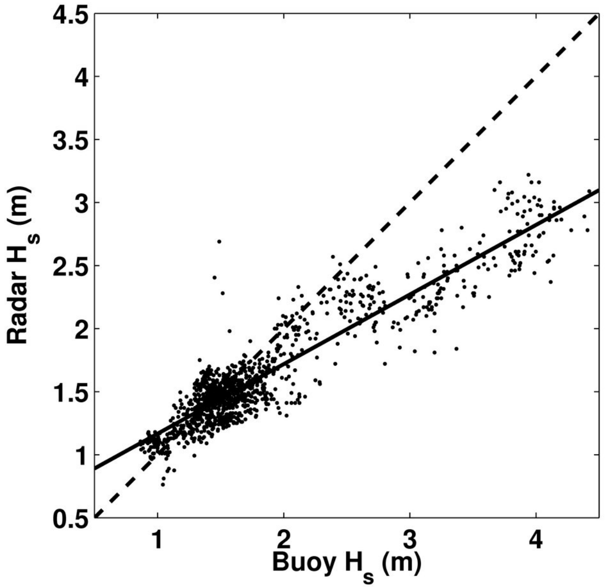


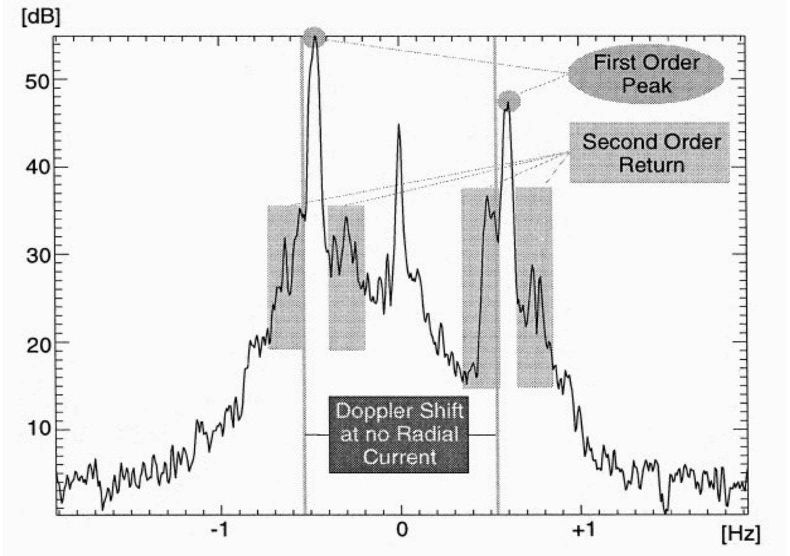


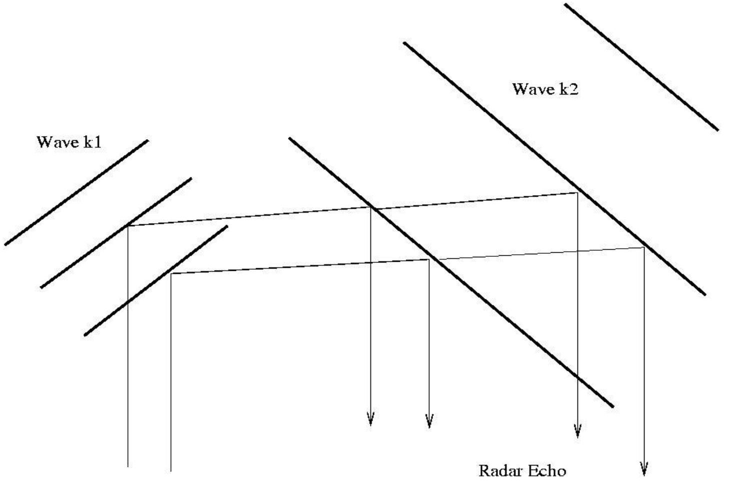


Significant waveheight (Hs):
buoy vs. HF radar

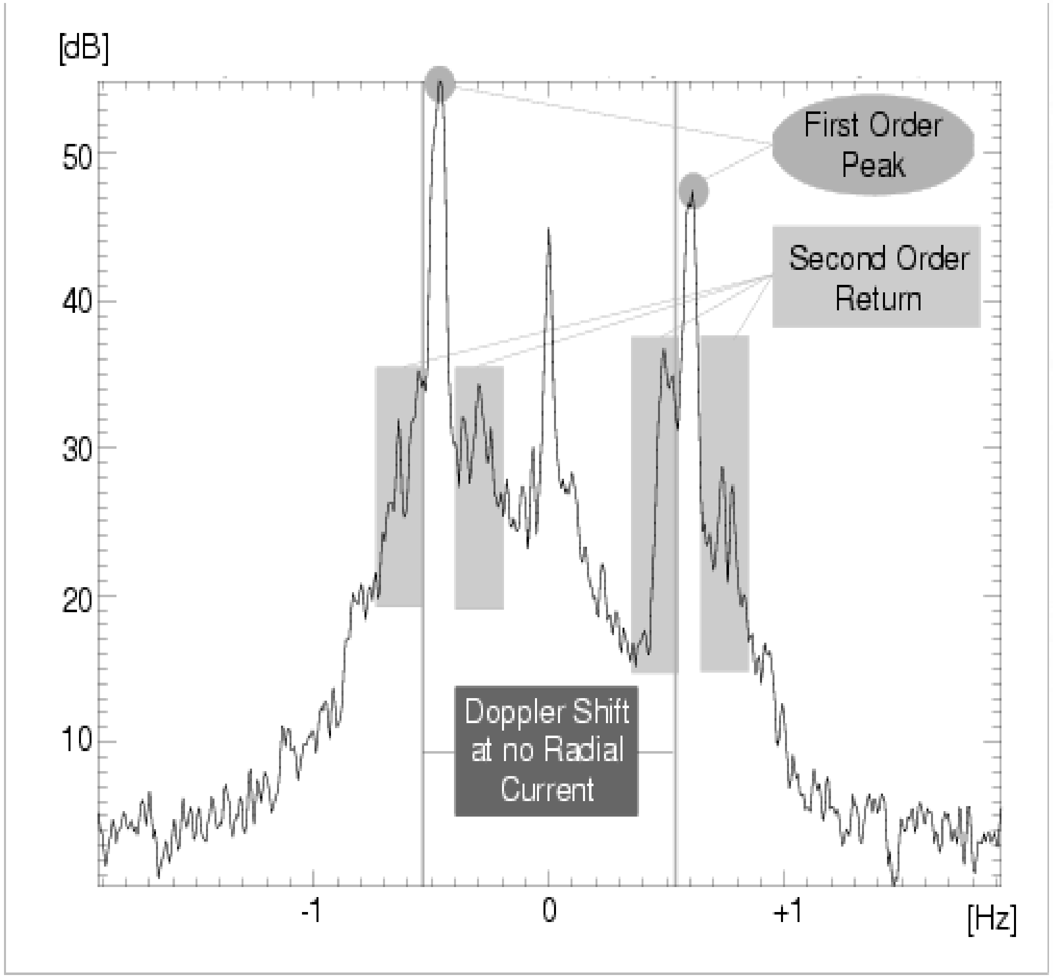








wind direction from HF radar



[*Gurgel et al.,1999*]

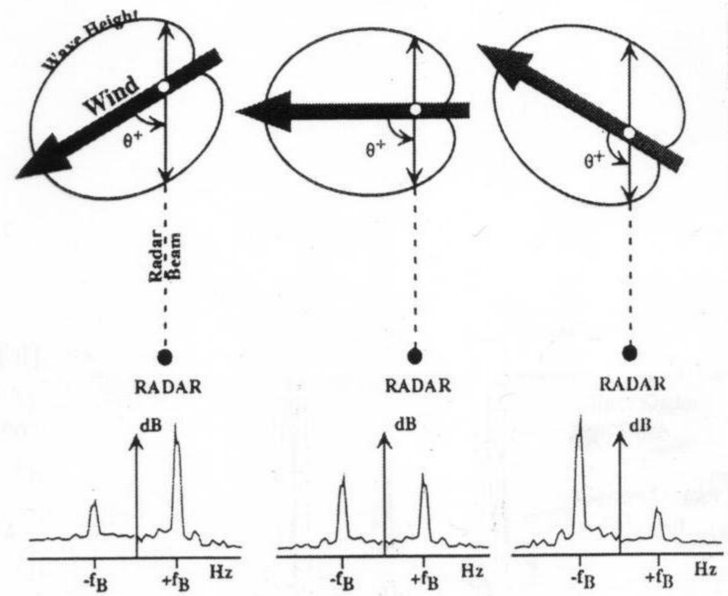


*Fig. 1: Sample distributions of surface wave energy as a function of angle relative to the wind direction for cases with wind blowing toward (**left**), at right angles to (**middle**), and away from (**right**) the radar look direction. Sample backscatter spectra below show relative heights of the approaching (+) and receding (–) Bragg peaks for each case and θ^+ denotes the angle between the wind and the approaching wave directions.*

[*Fernandez et al. 1997*]

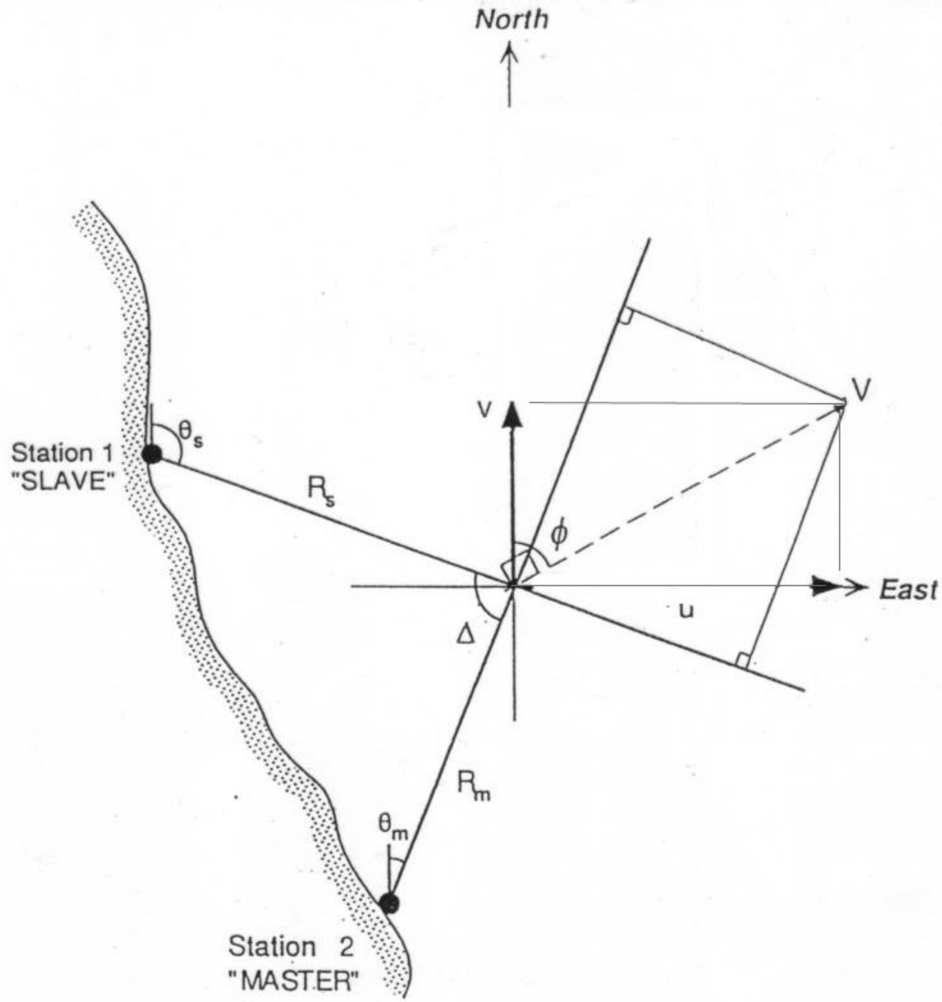
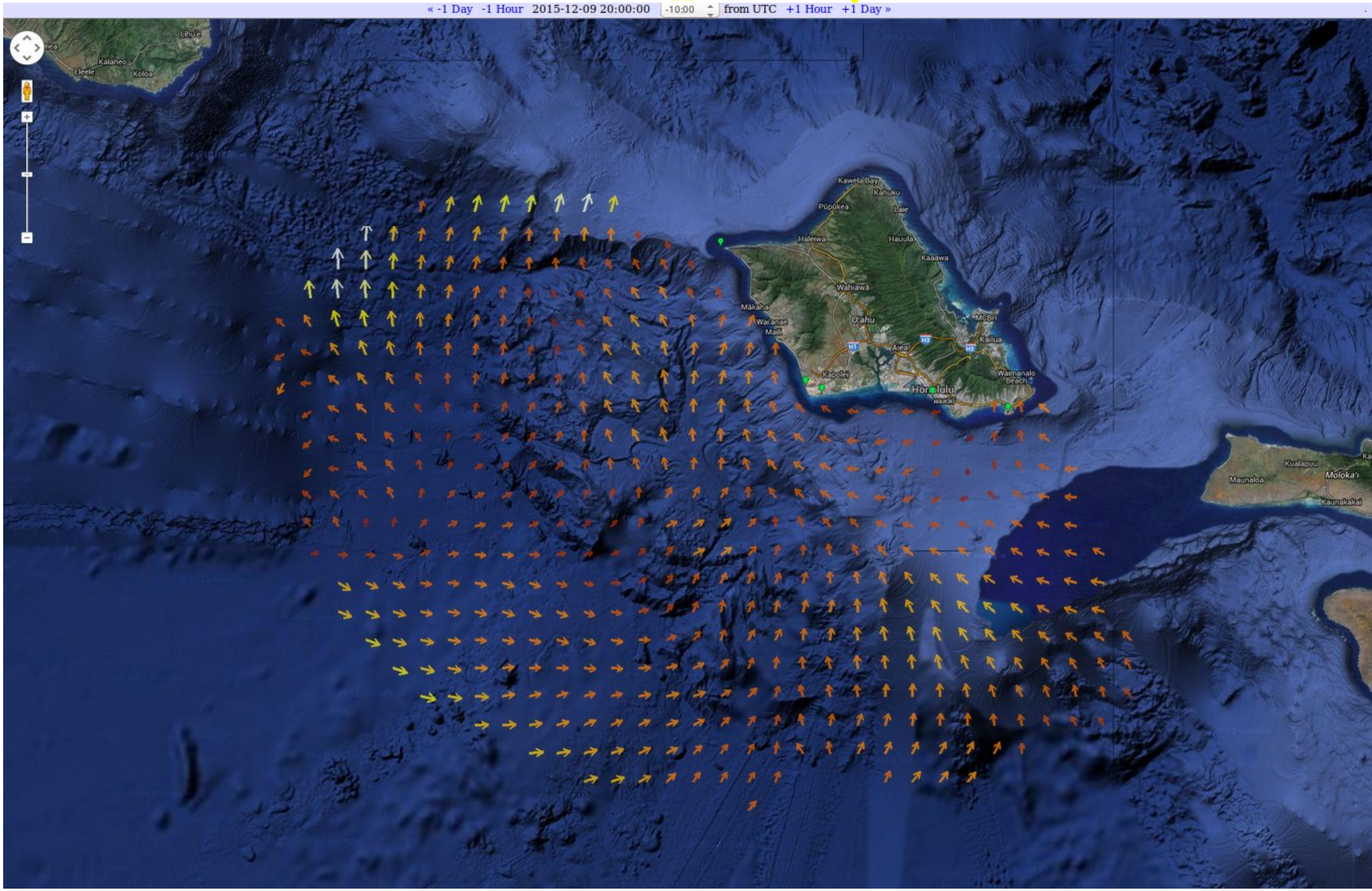
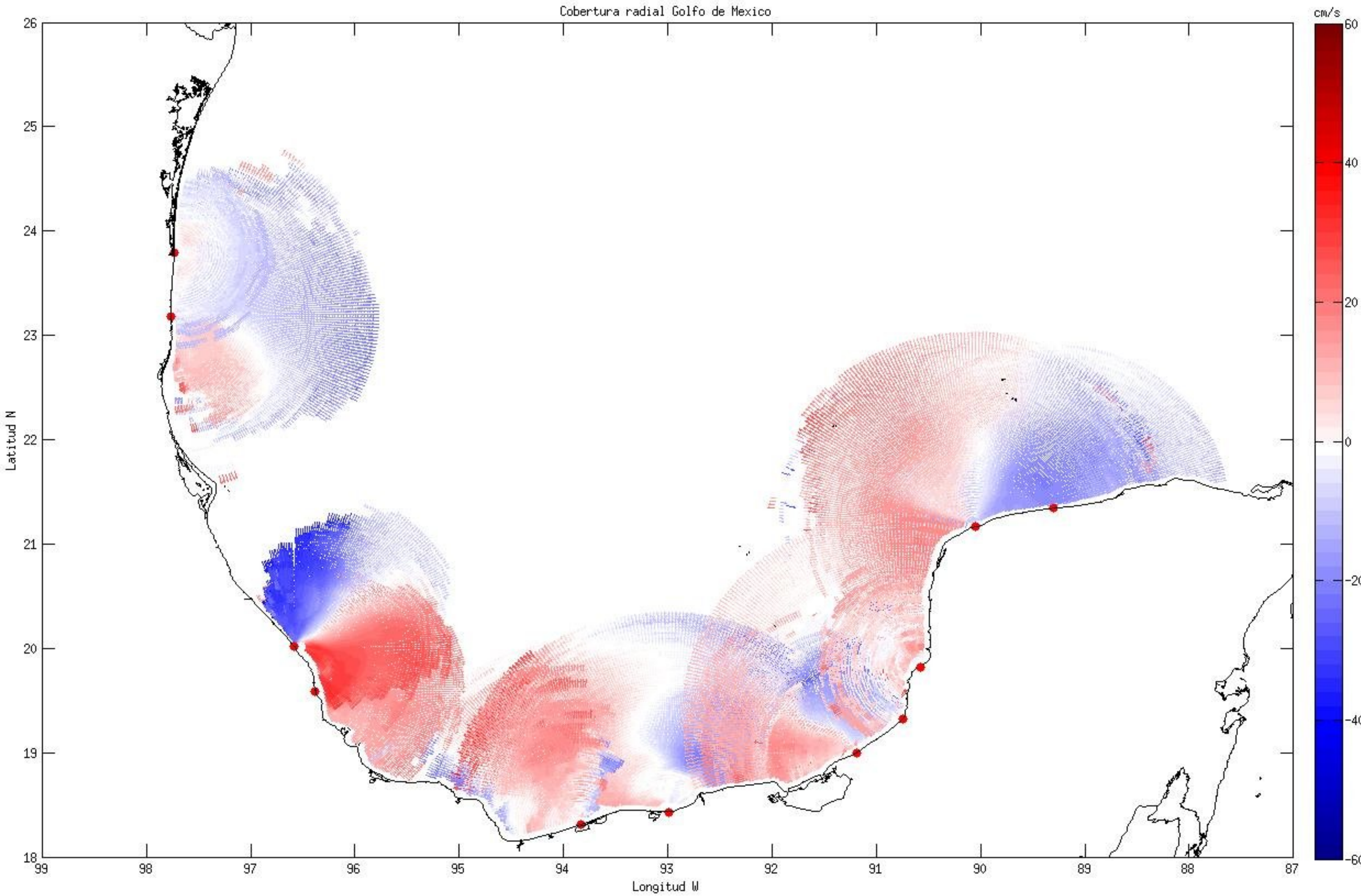


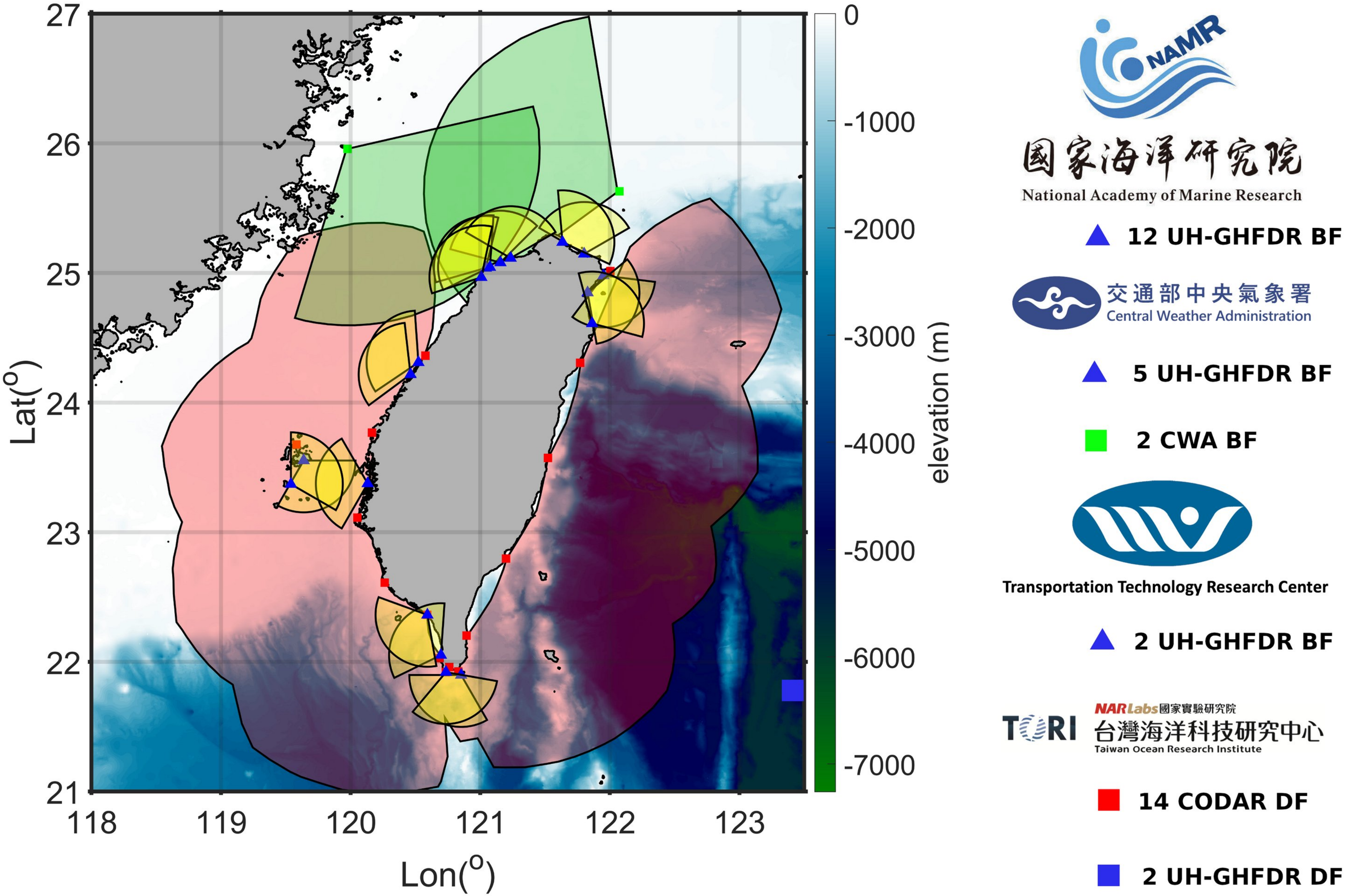
Figure 2. Schematic for determining the resulting vector current from velocity components of two intersecting radials.

University of Hawaii Pacific Ocean Observing System hourly currents



HF radar network for the Gulf of Mexico
20 radars, 6-8 MHz
with Universidad Autonoma de Baja California

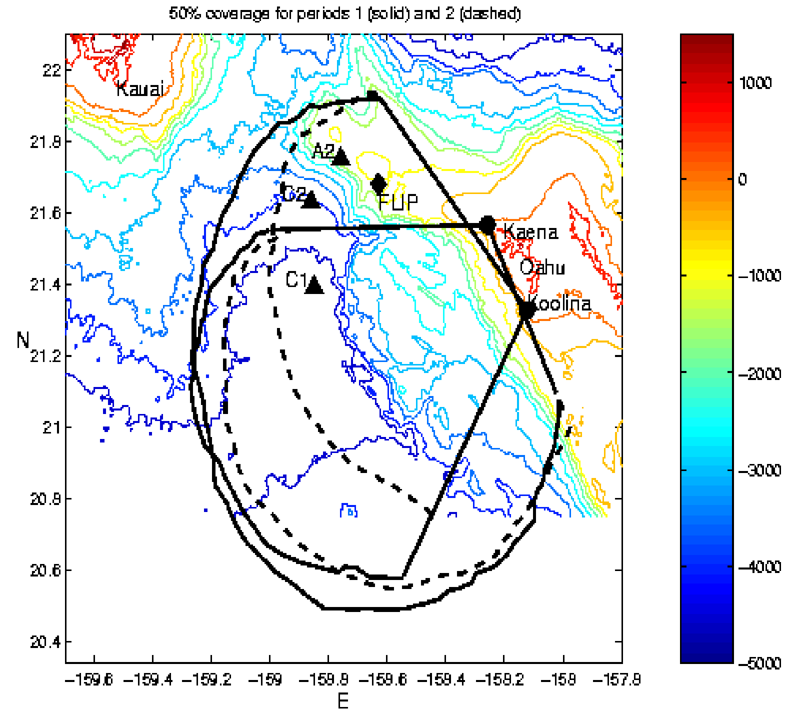


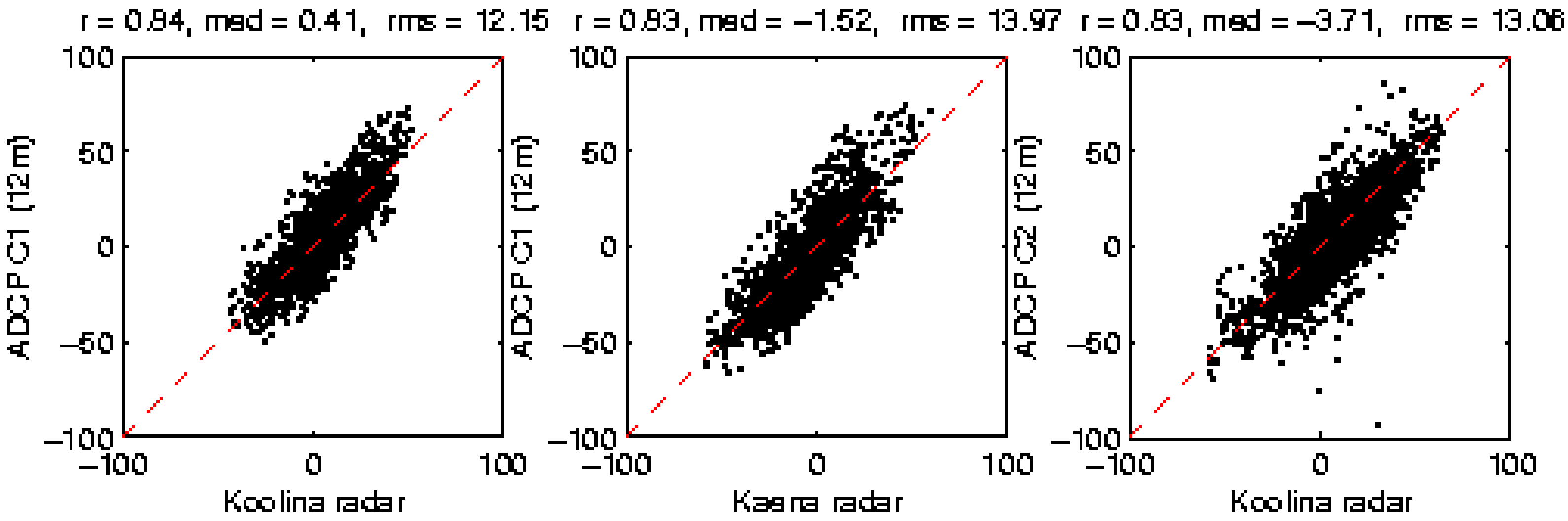


Taiwan HF Radar Coverage and Bathymetry Map.

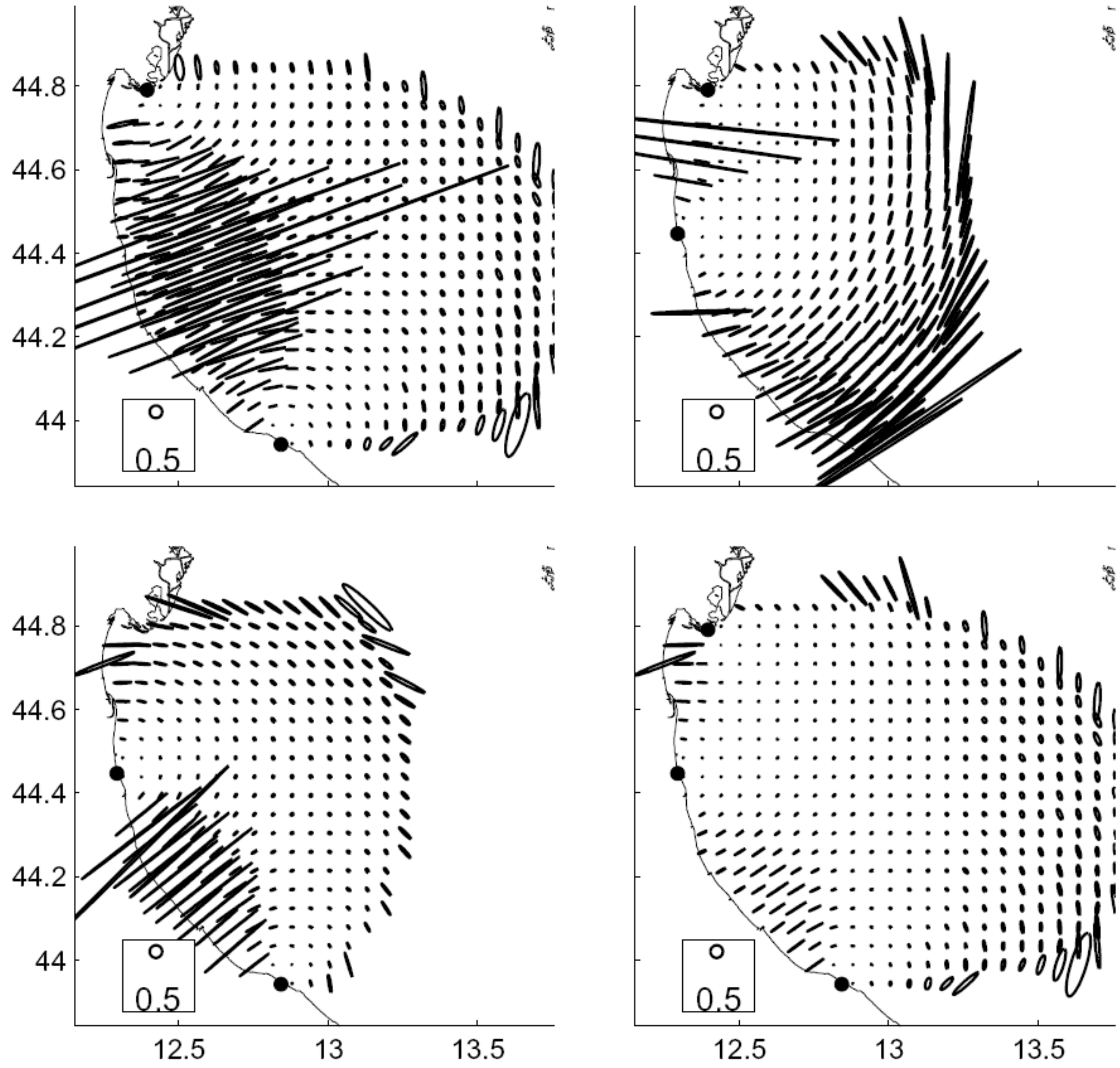
Validation:

High Frequency Radar Currents
(16 MHz, 1 m)
vs.
Acoustic Doppler Current meters
(300 kHz, 12 m)

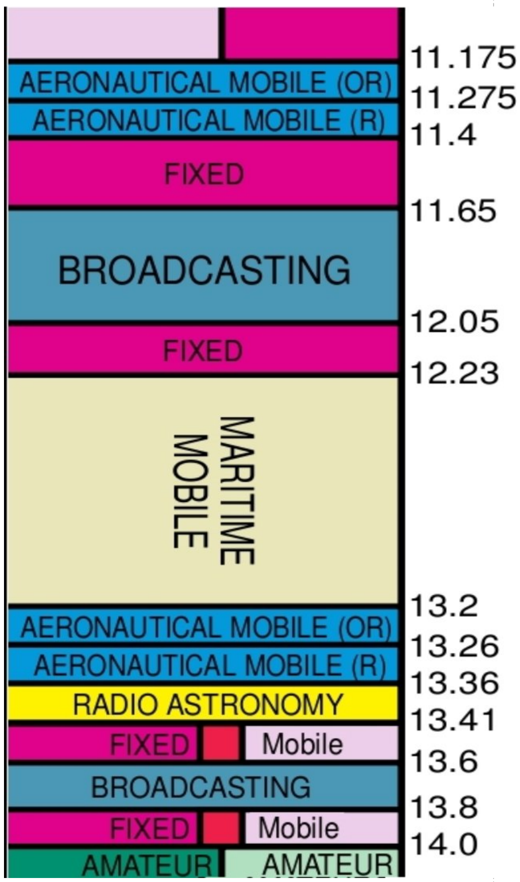


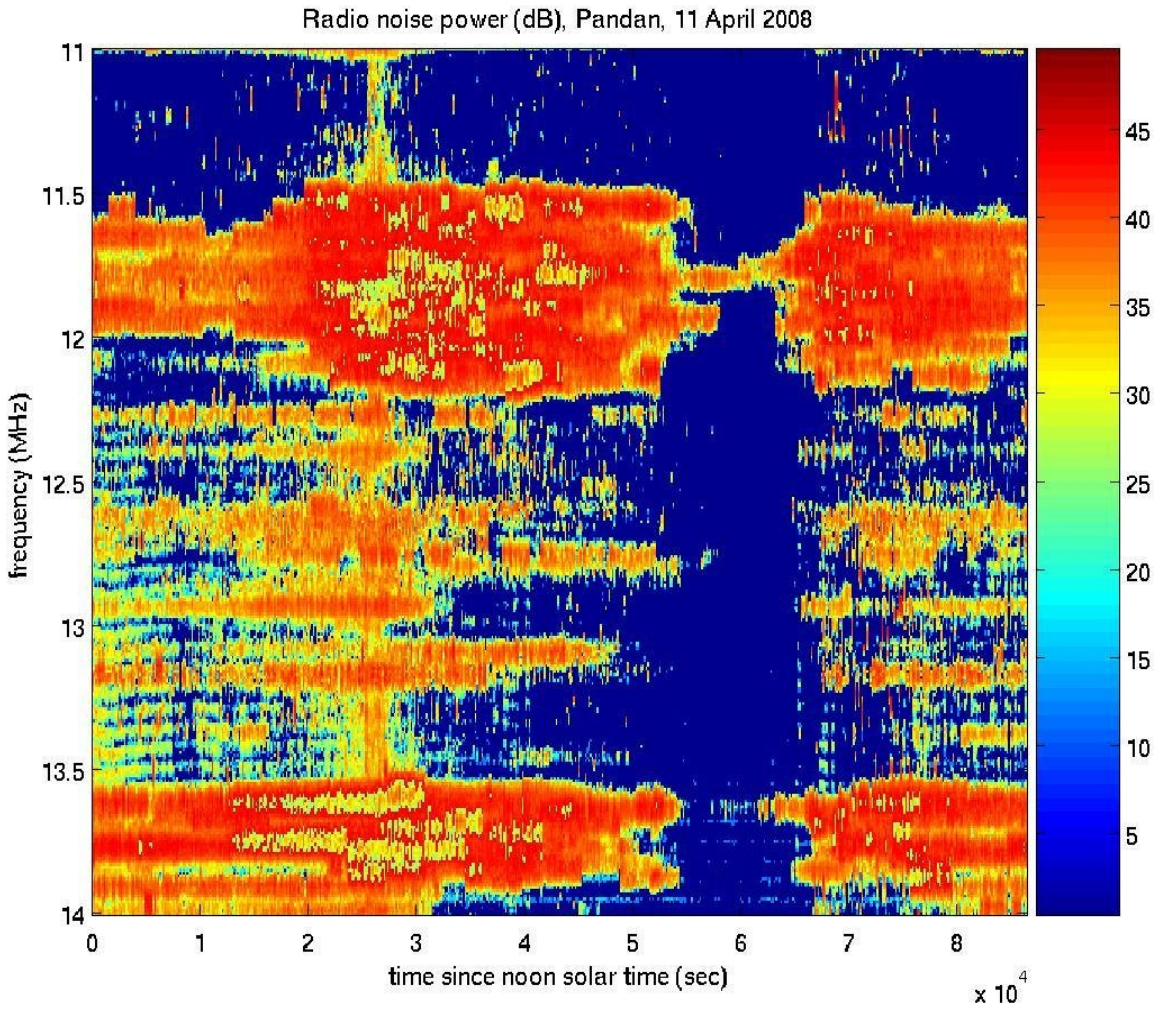


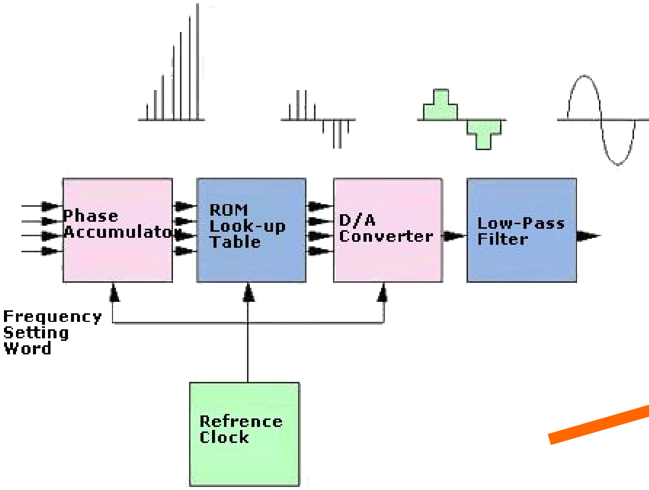
Caveat 1: Geometric Dilution Of Precision (GDOP)



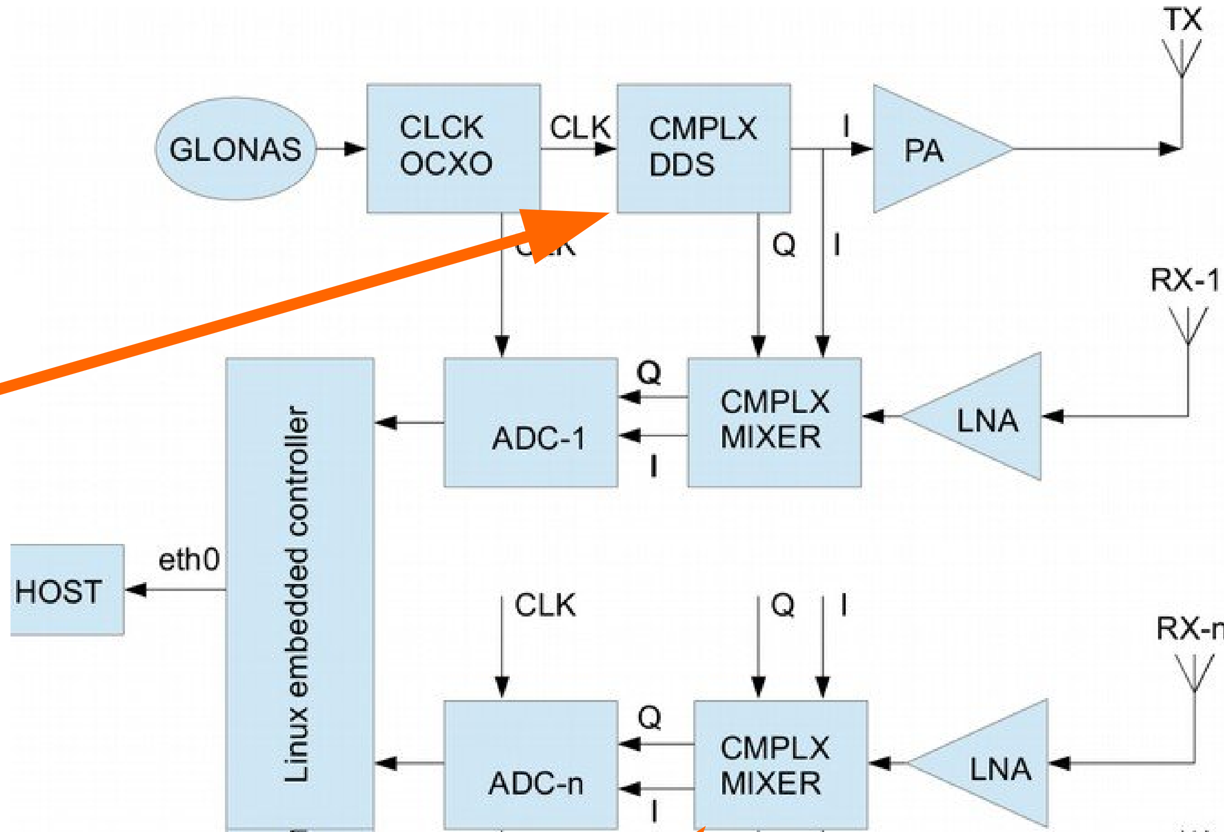
Caveat 2: interference from ionosphere-reflected transmitters







Direct Digital Synthesizer



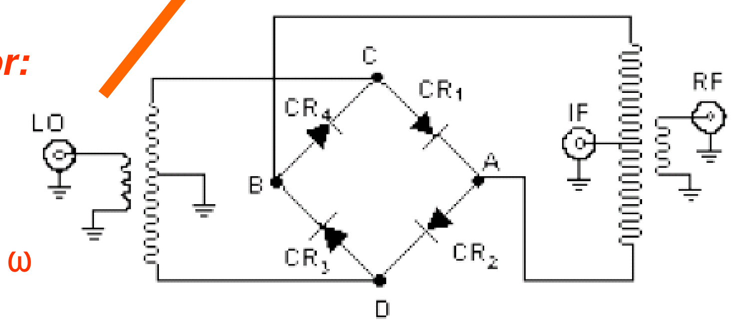
Homodyne HF radars principle of operation

Double-Balanced Mixer/quadrature detector:

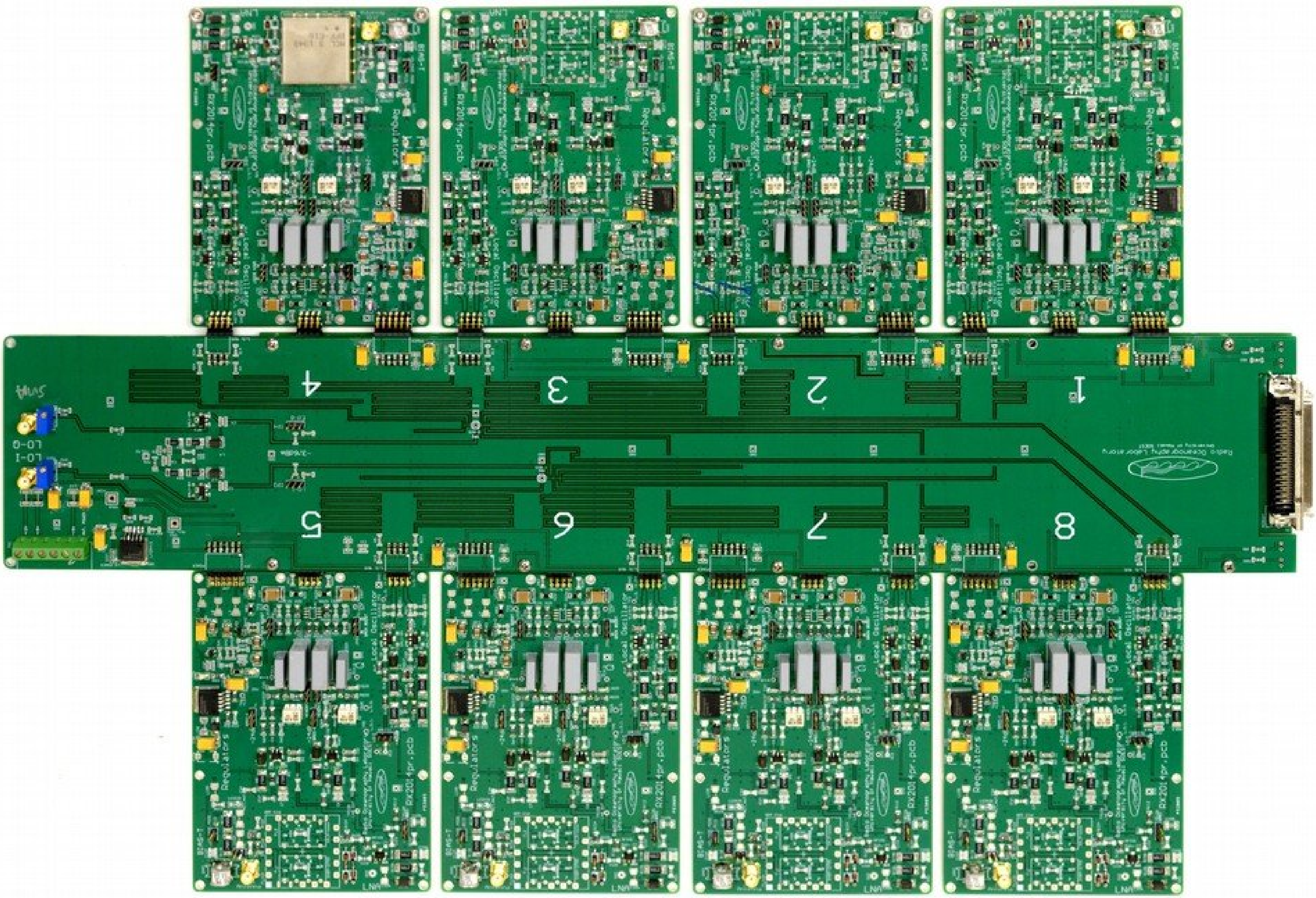
I: $2 \sin x \sin y = \cos(x-y) - \cos(x+y)$

Q: $2 \sin x \cos y = \sin(x-y) + \sin(x+y)$

if $x = (\omega + \Delta\omega)\, t$ **and** $y = \omega\, t$ **then** $x - y = \Delta\omega\, t$

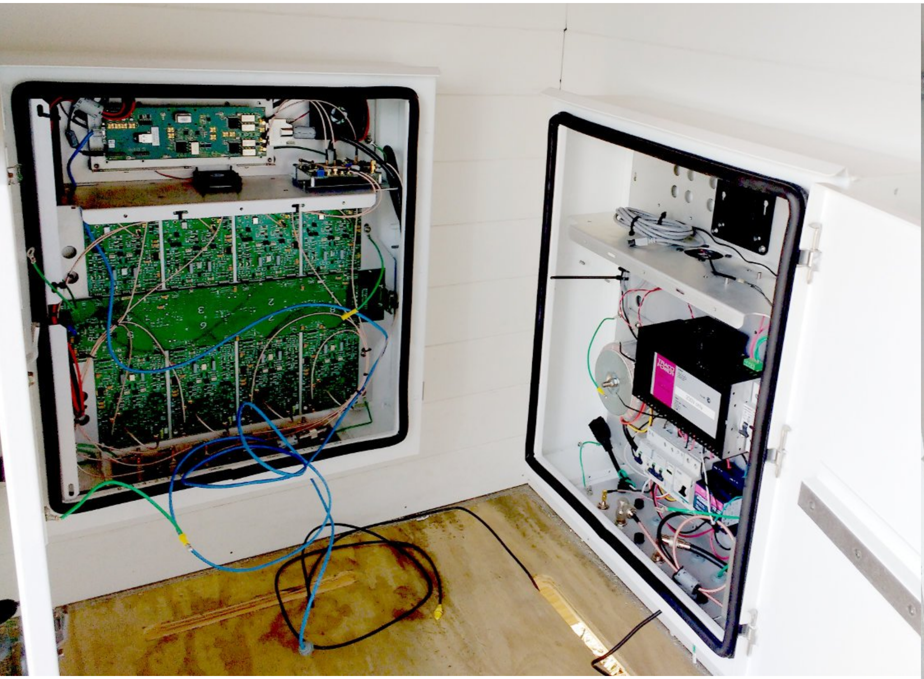


MK-III receiver engine (University of Hawaii)



University of Hawaii HFR (100 built):

- all-in-one, 24V solar/wind ready
- passively cooled, no A/C
- one 2.5” 4Tb drive = 4 years raw data
- all components outsourced
- mostly commercial off-the-shelf
- qty 40 cost about $36,000



Processing HF Radar data for currents:

1. time series of digitized received antennas
2. range-resolving Fourier transform
3. Doppler-resolving Fourier transform
4. azimuth-resolving beam-forming transform
5. Doppler-shift tracking of Bragg echoes

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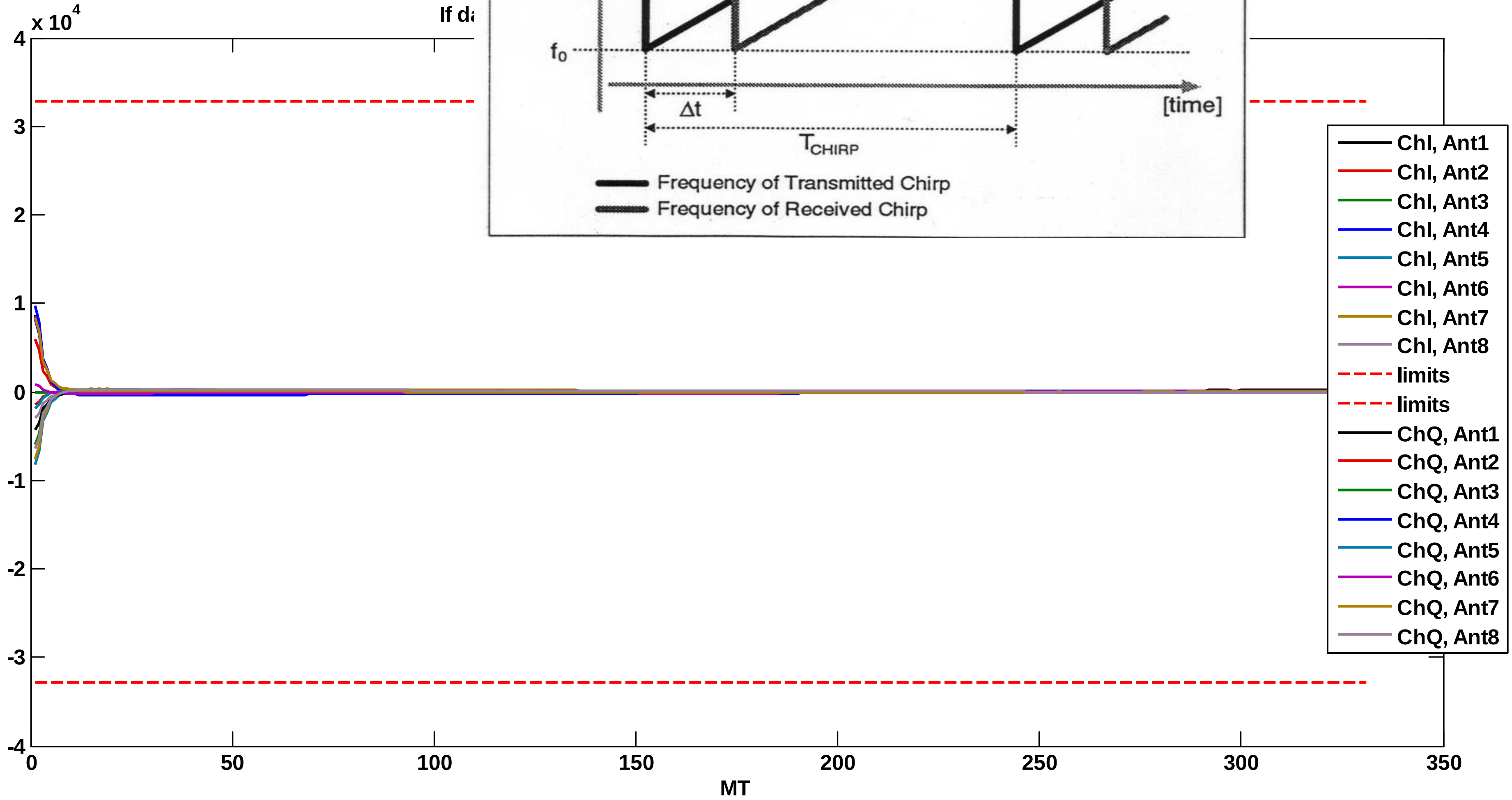

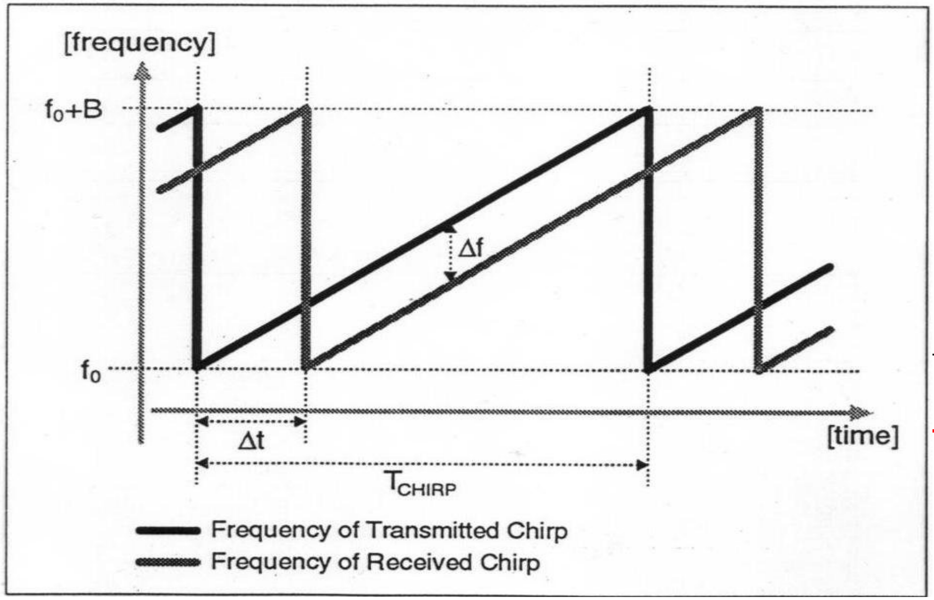

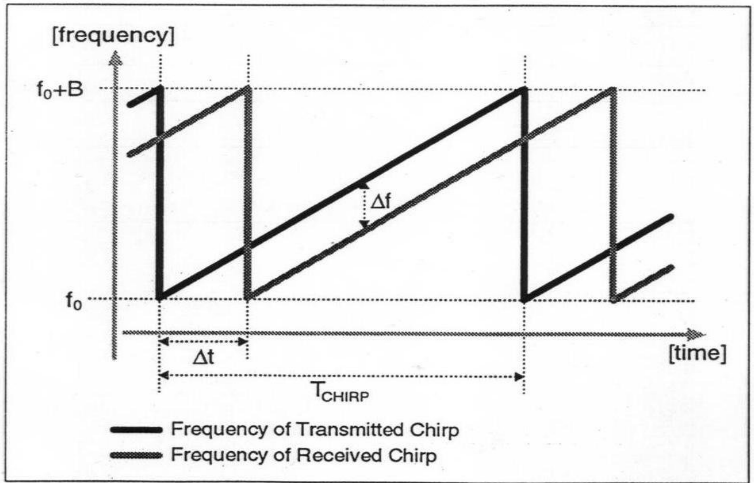

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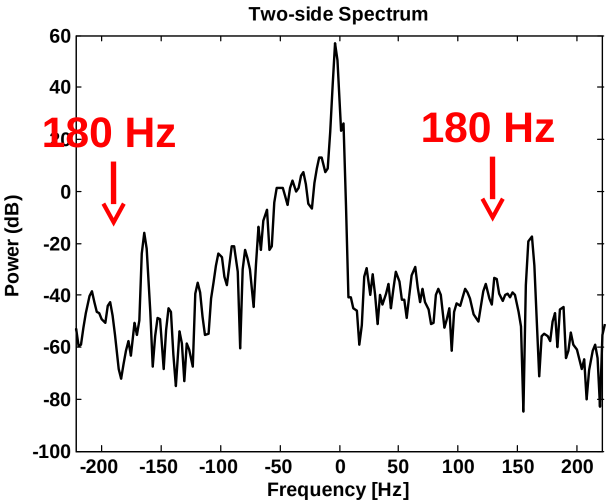

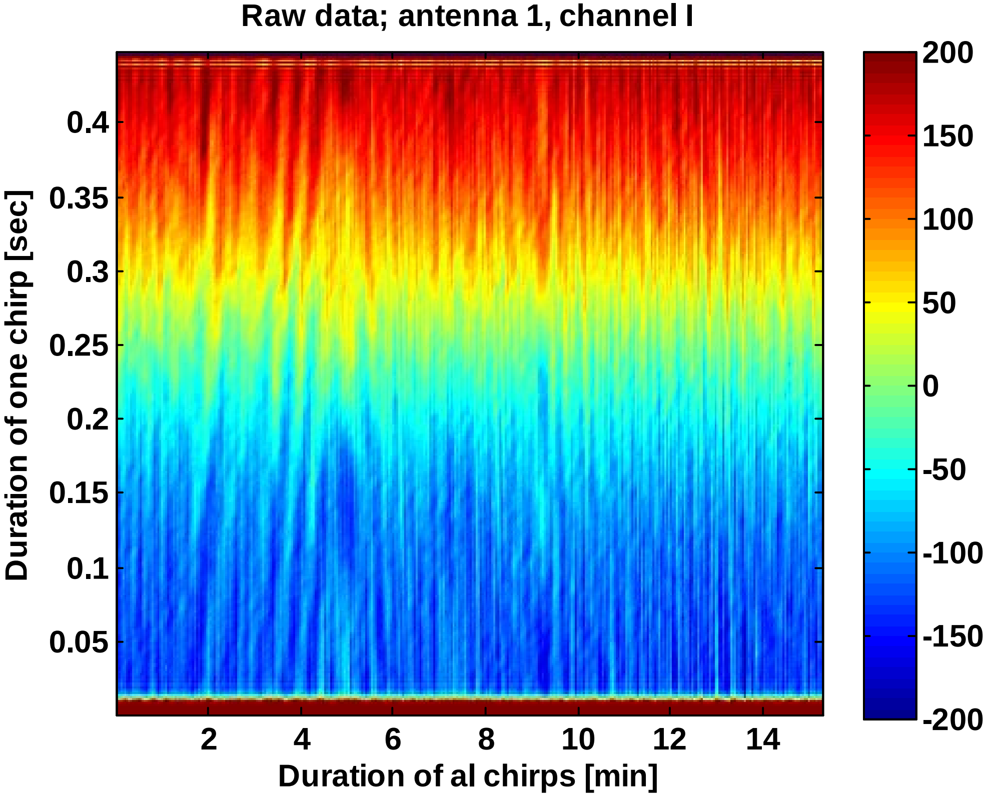

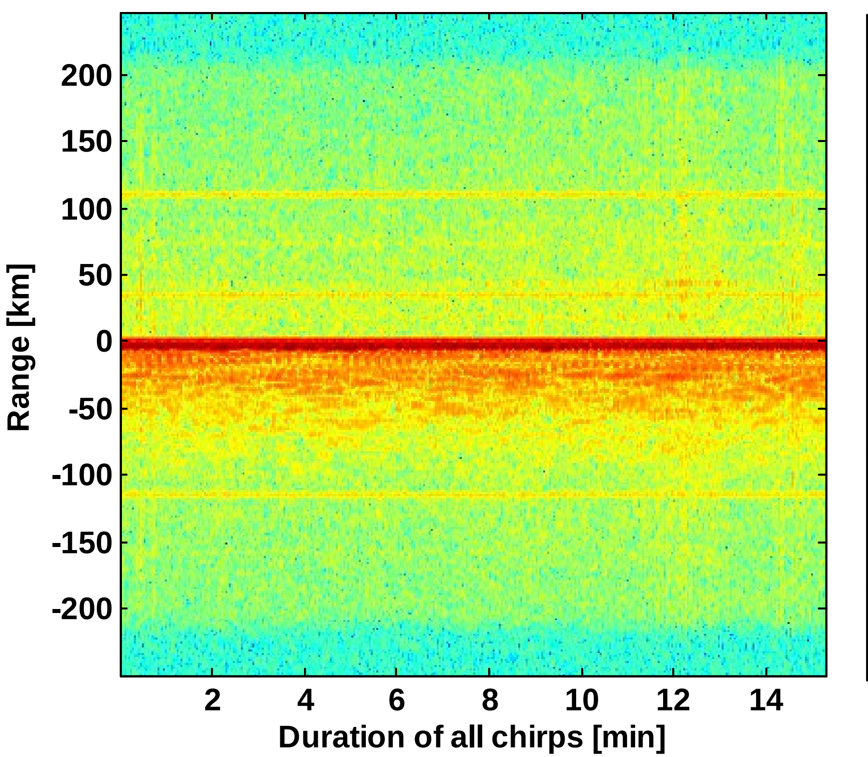

Time Series

Range-resolving FFT

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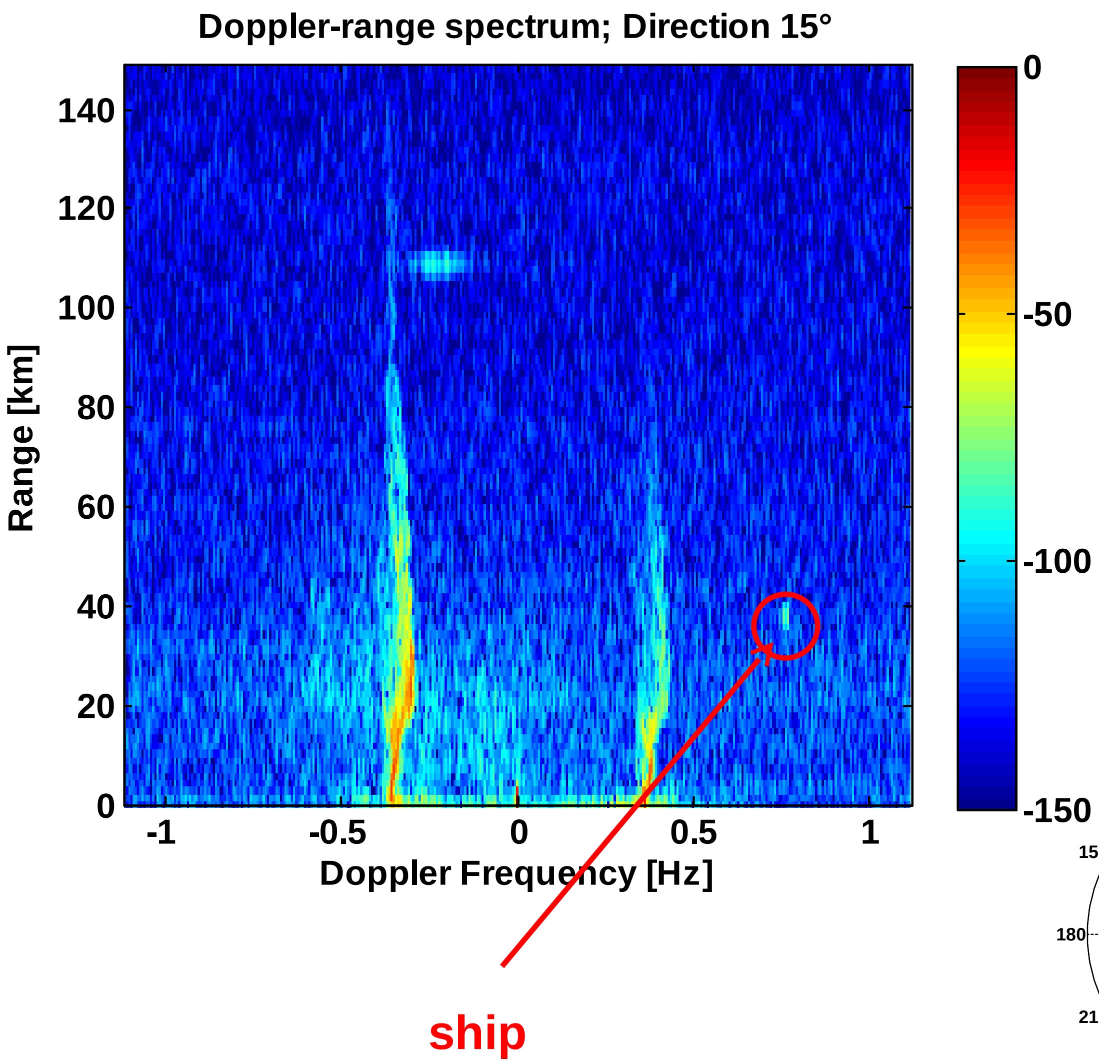
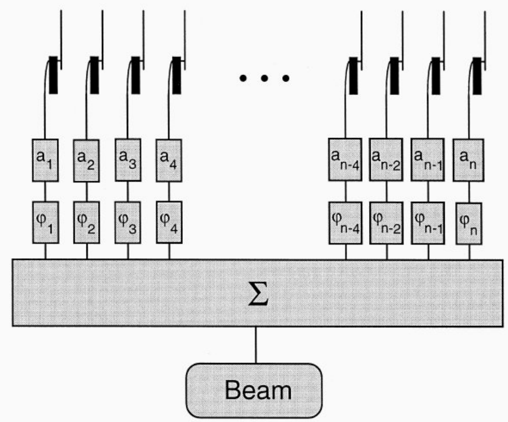
Doppler-resolving FFT and beamforming





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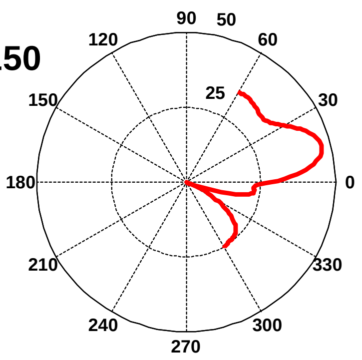

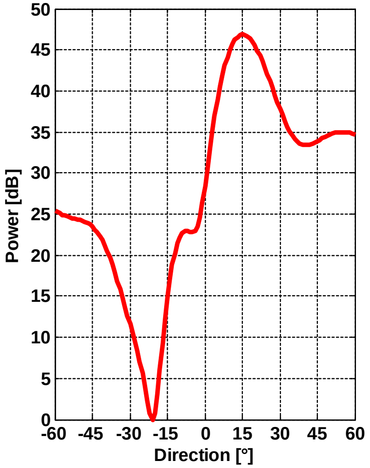

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Radial currents

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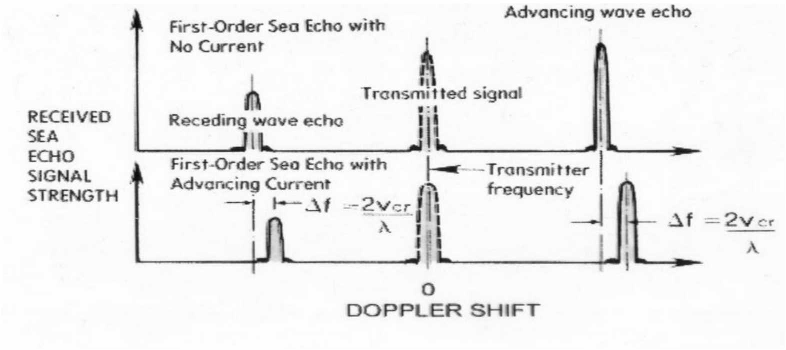
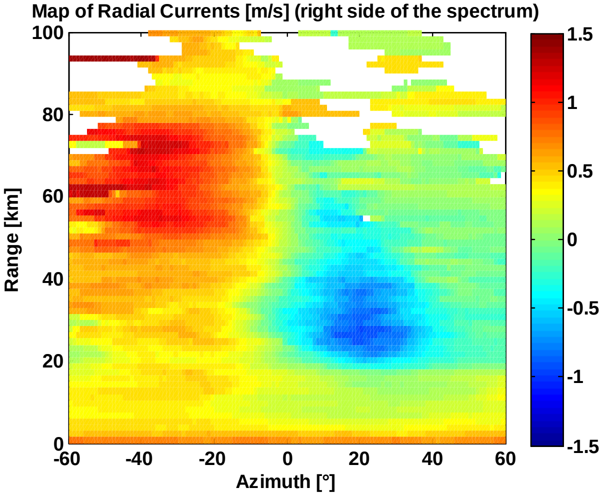
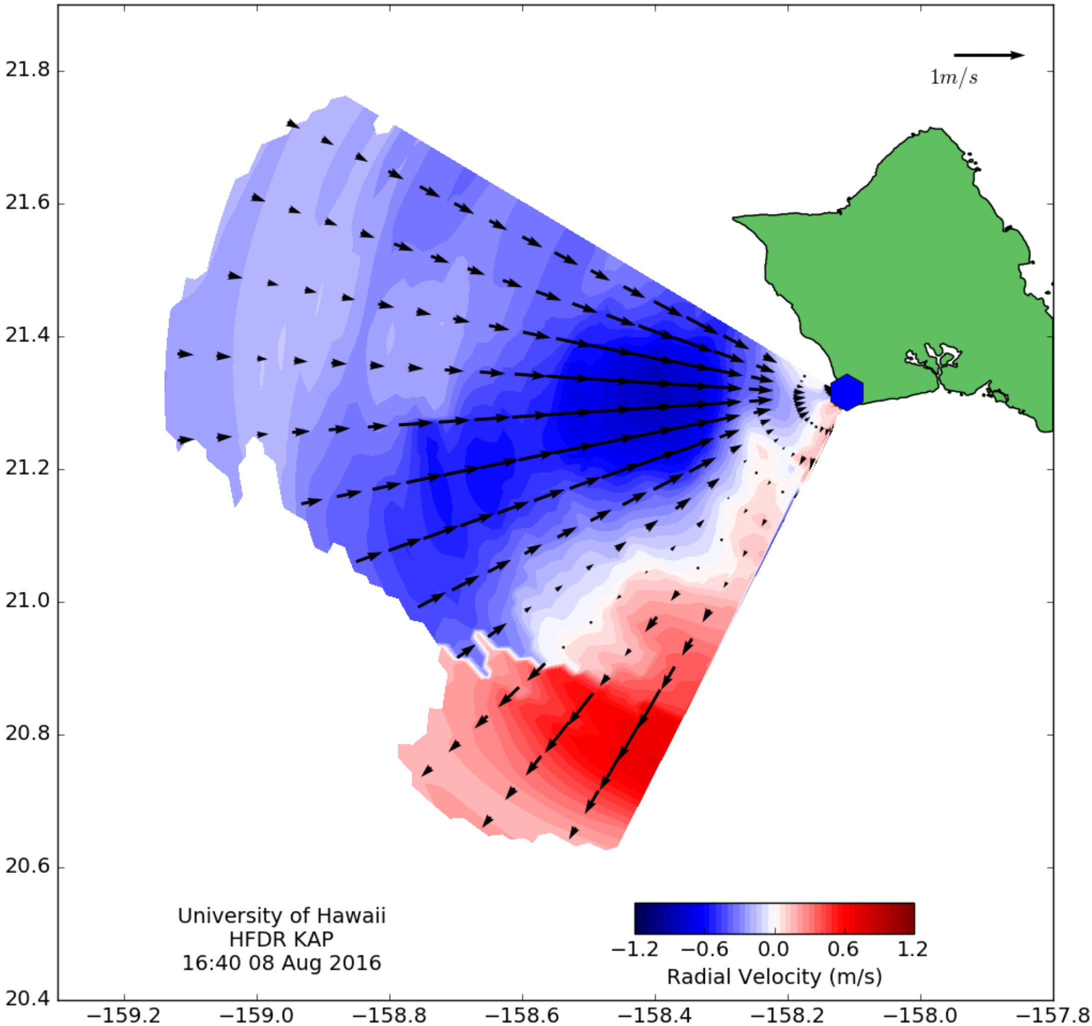






Low frequency flow in Panay Strait

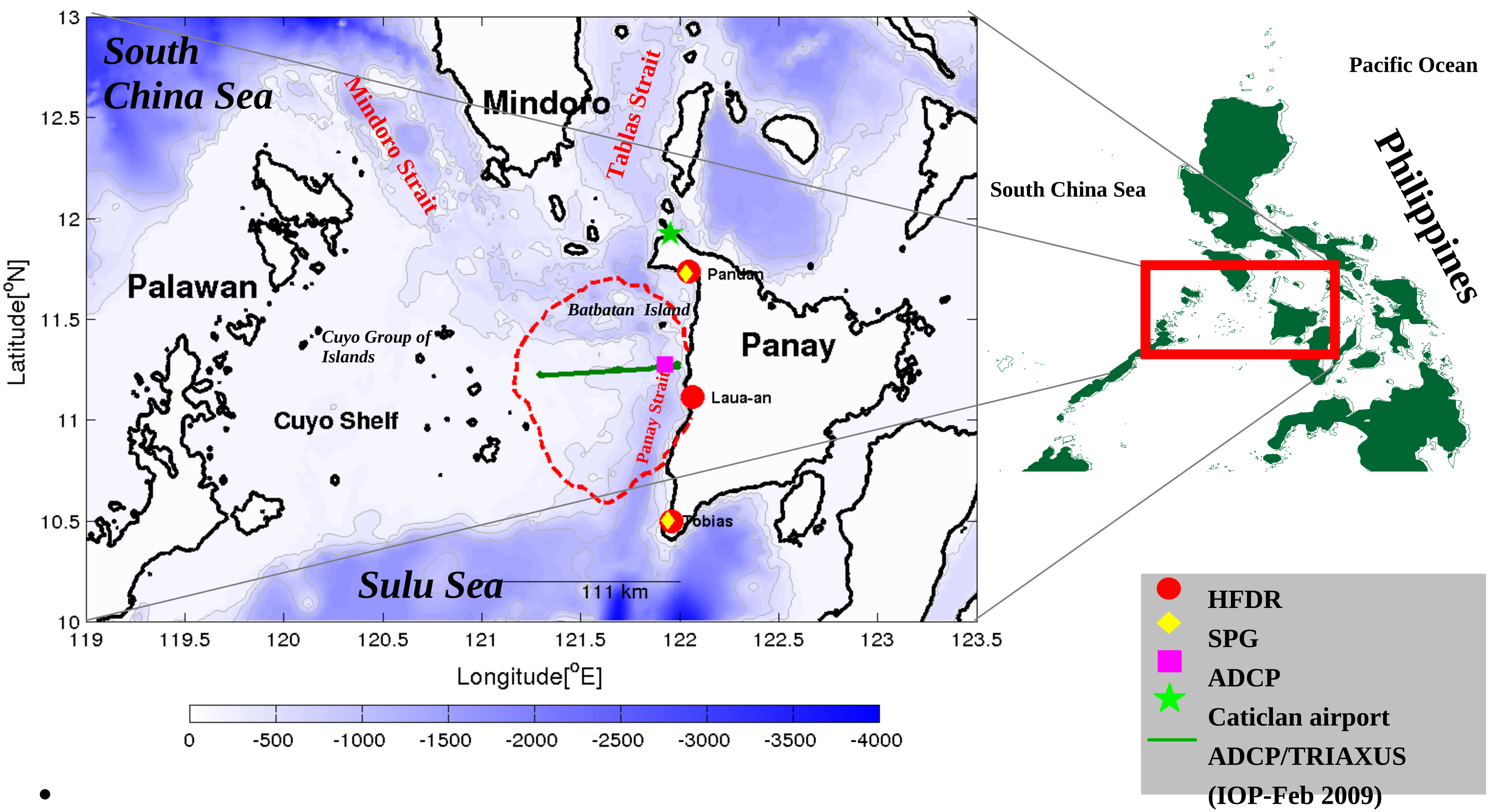
Ph.D. dissertation

Charina Repollo, U.P. Diliman

- characterize the dominant surface and subsurface flows
- assess the wind contribution on the onset and growth of cyclonic eddy
- describe the influence of eddy on biology

Philippine Straits Dynamics Experiment (2008)

Mindoro-Panay Strait: a branch of Indonesian Through-Flow



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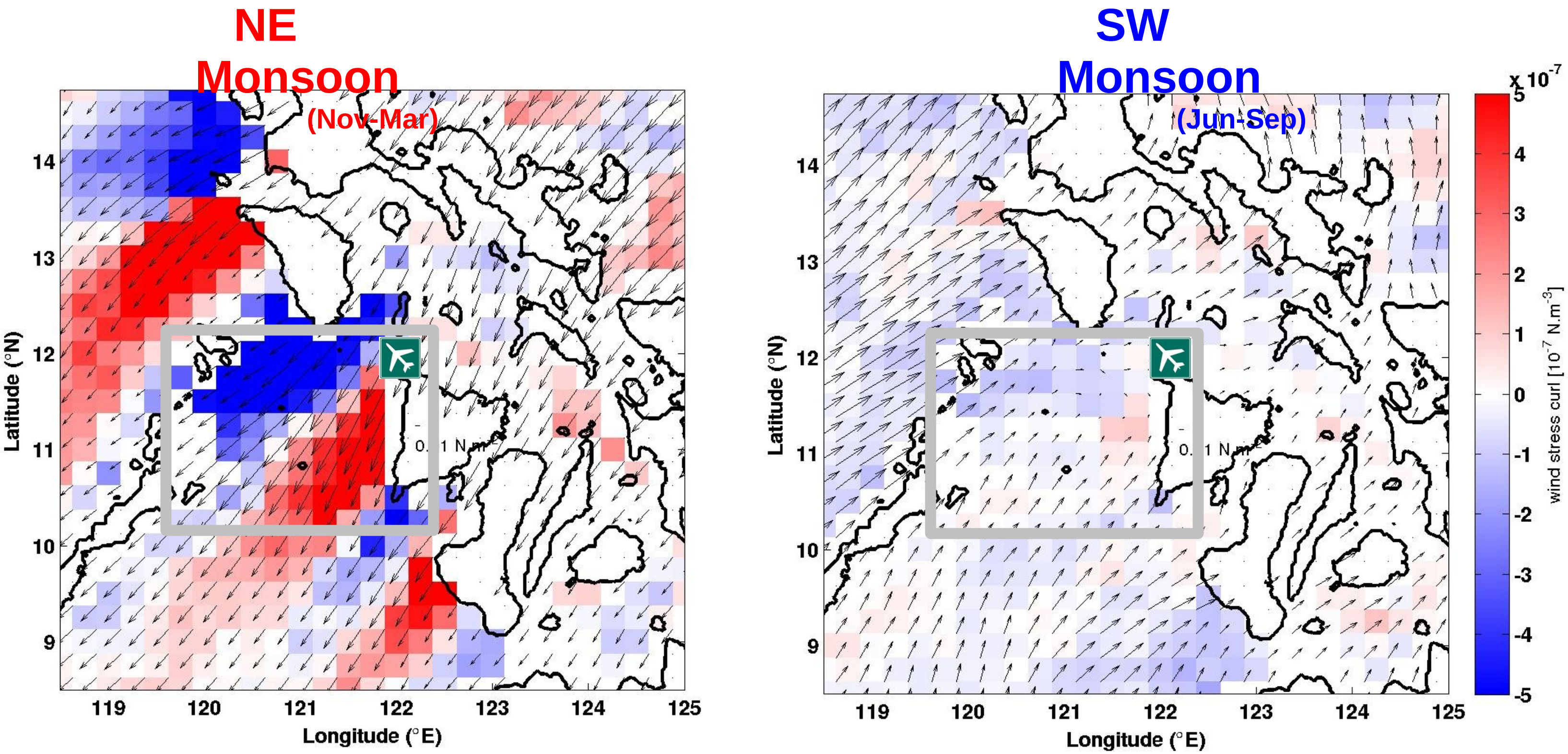
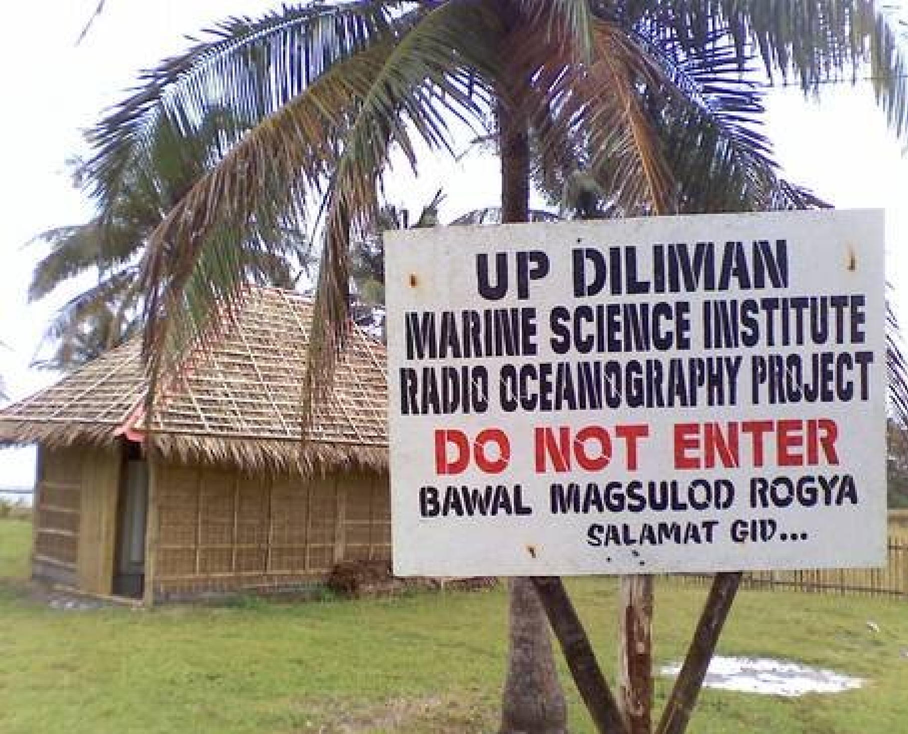
Wind stress and curl

(QuikSCAT satellite radar)



Pronounced seasonal cycle

- **NE monsoon, strong wind stress curl in the lee of Panay Island**
- **SW monsoon, curl dipoles absent with random wind direction**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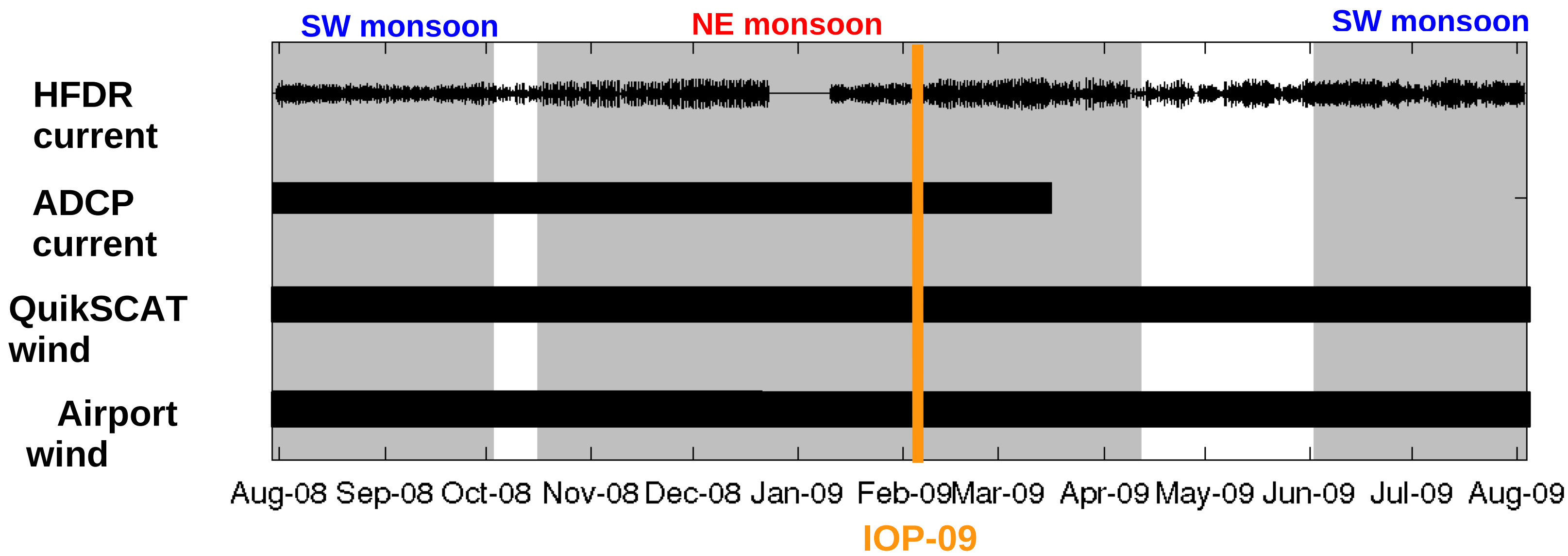
RADIO OCEANOGRAPHY PROJECT
DO NOT ENTER
BAWAL MAGSULOD ROGYA
SALAMAT GID...

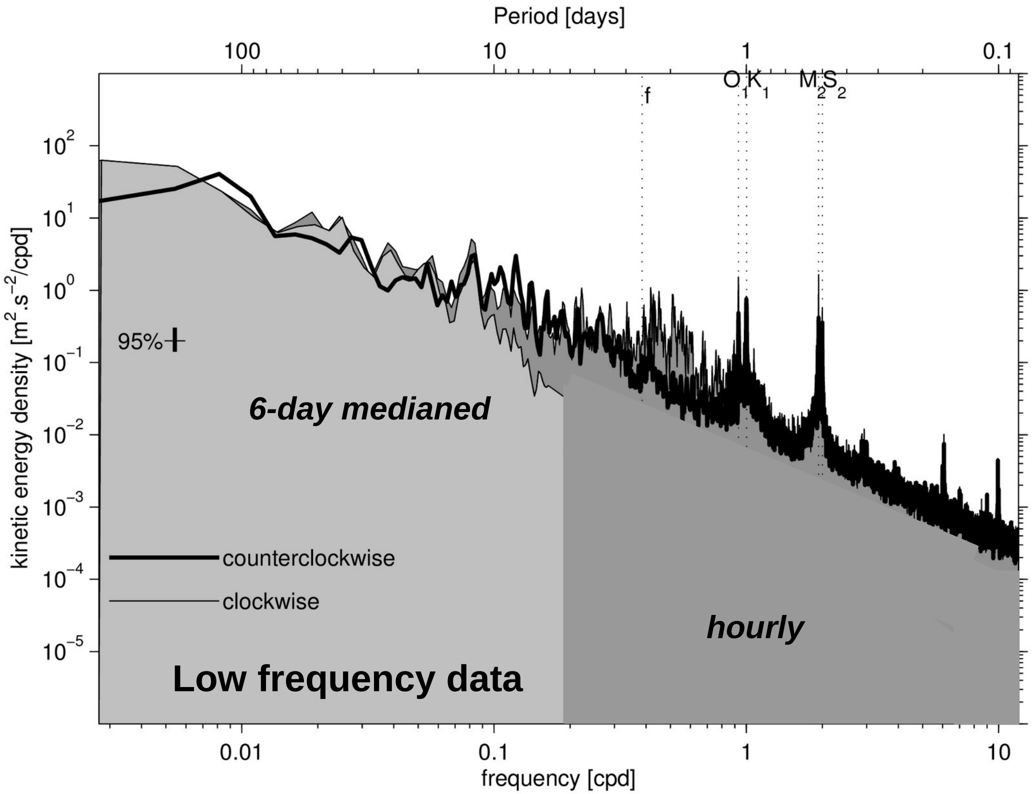


Data



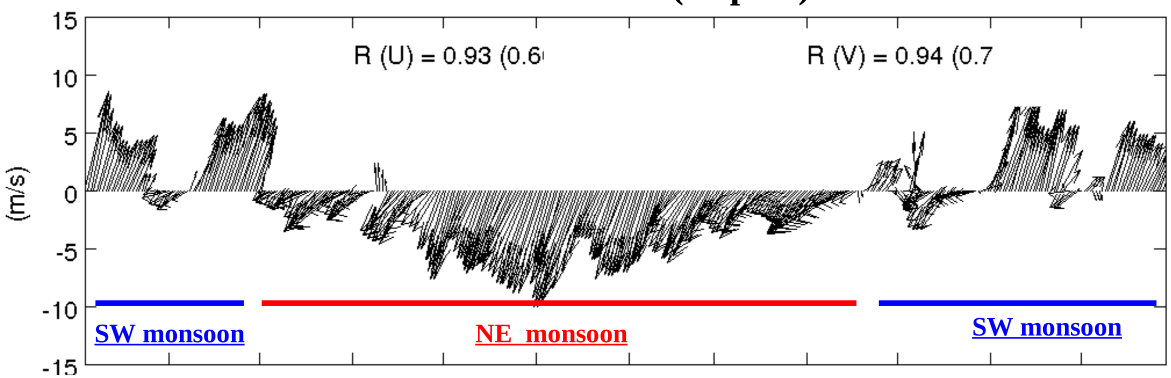
Low-frequency time series obtained by

- **removing the tides (*t-tide*)**
- **6-day running median**

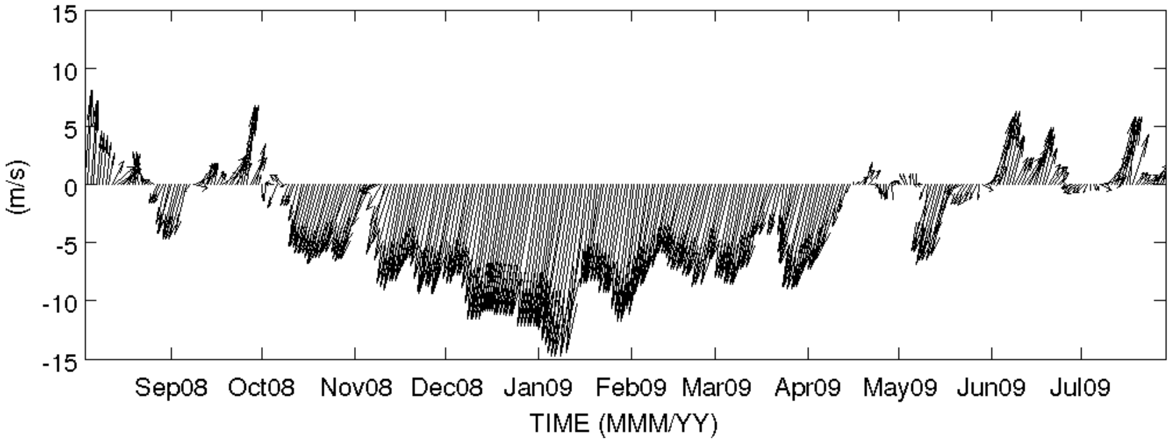


Local wind

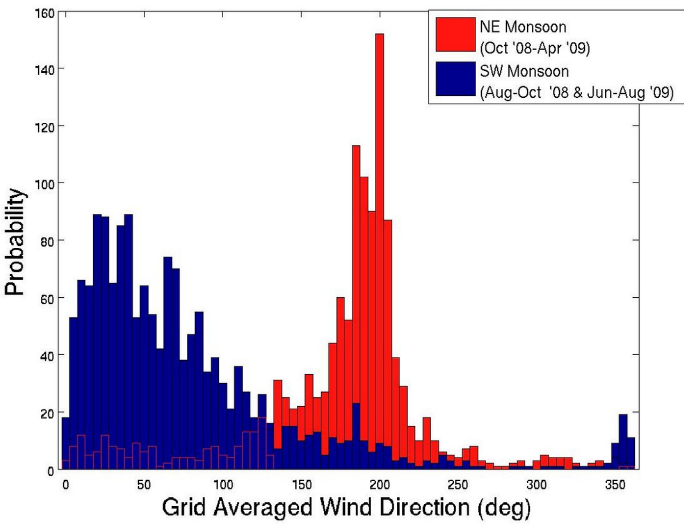
observed wind (airport)

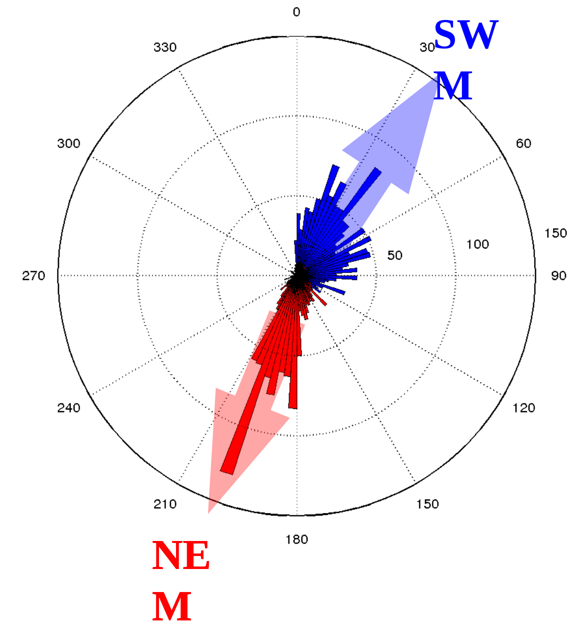


satellite-derived wind (QuikSCAT)

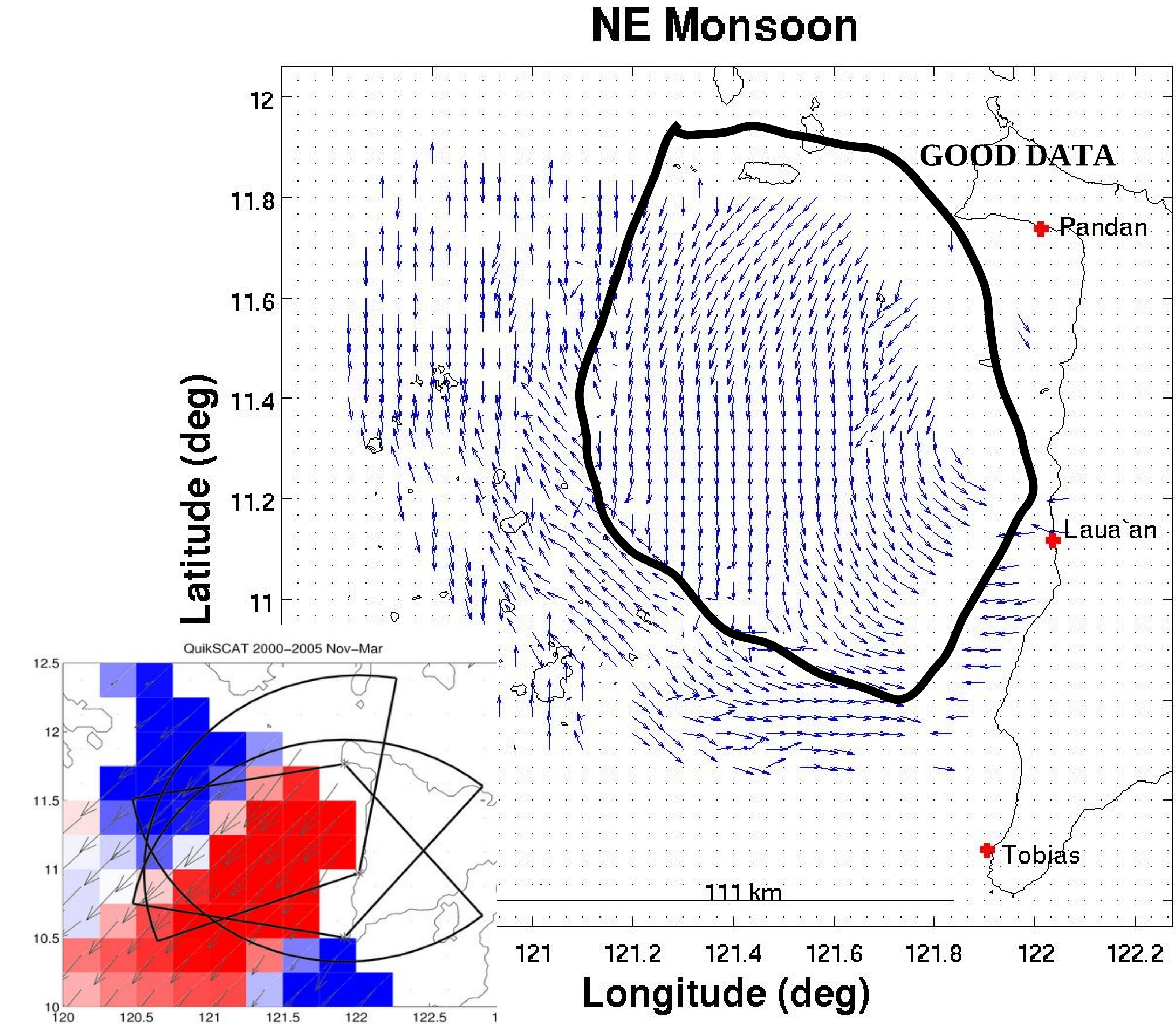


HFDR wind direction



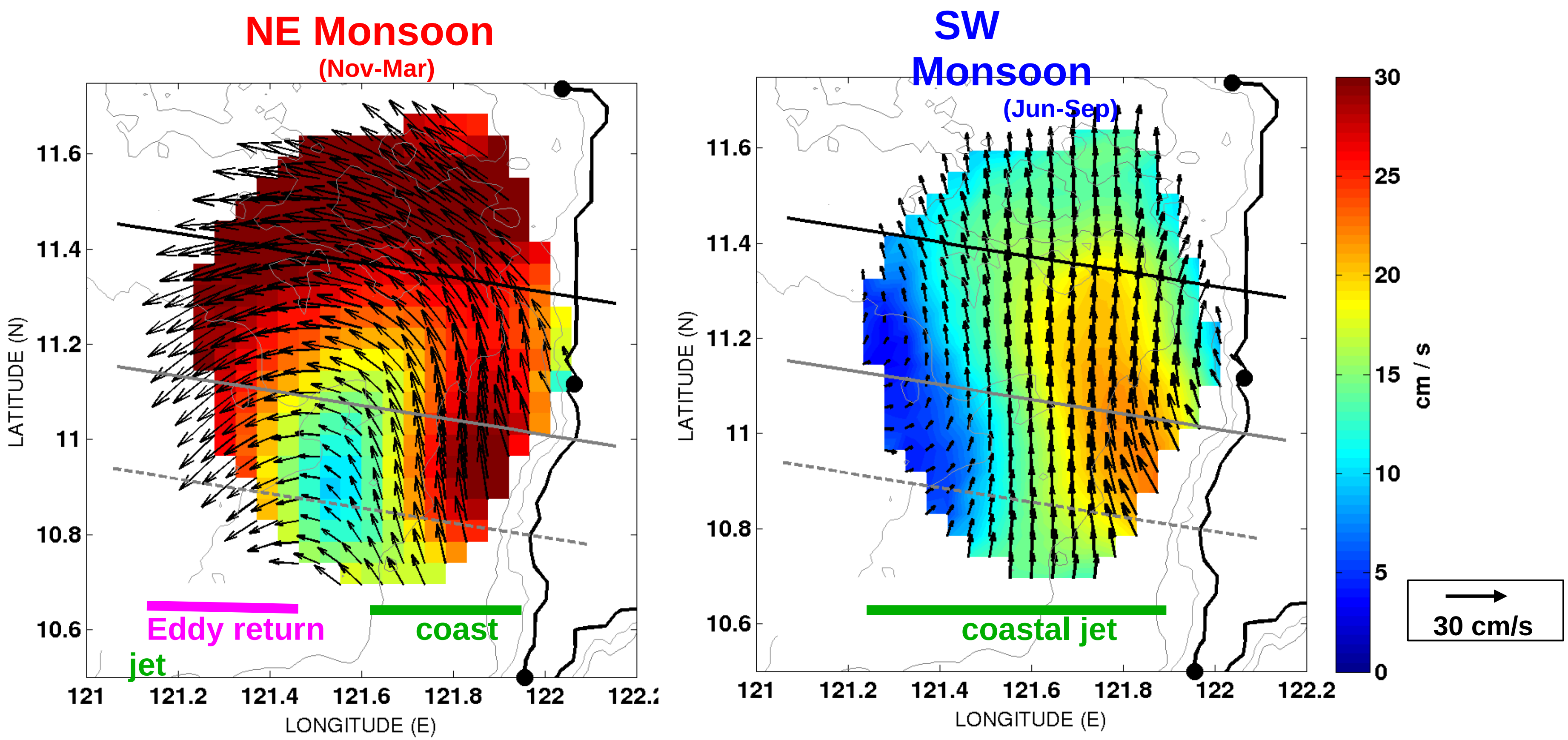


- Observed and satellite-derived winds well-correlated
- Persistent northeasterly wind Oct - April
- Variable southwesterly wind May - Sep
- Well-defined transition periods, October and April



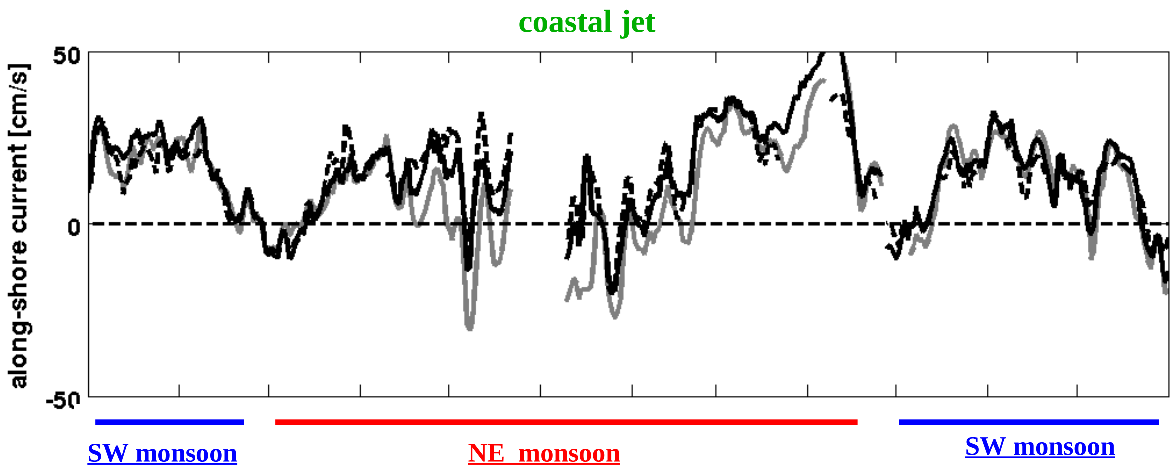
NE Monsoon
GOOD DATA
Pandan
Laua`an
Tobias
111 km
Latitude (deg)
Longitude (deg)
12
11.8
11.6
11.4
11.2
11
121
121.2
121.4
121.6
121.8
122
122.2
QuikSCAT 2000-2005 Nov-Mar
12.5
12
11.5
11
10.5
10
120
120.5
121
121.5
122
122.5

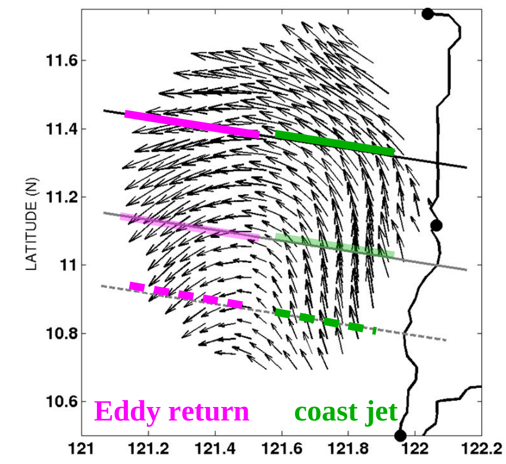
Surface flow (HFDR)

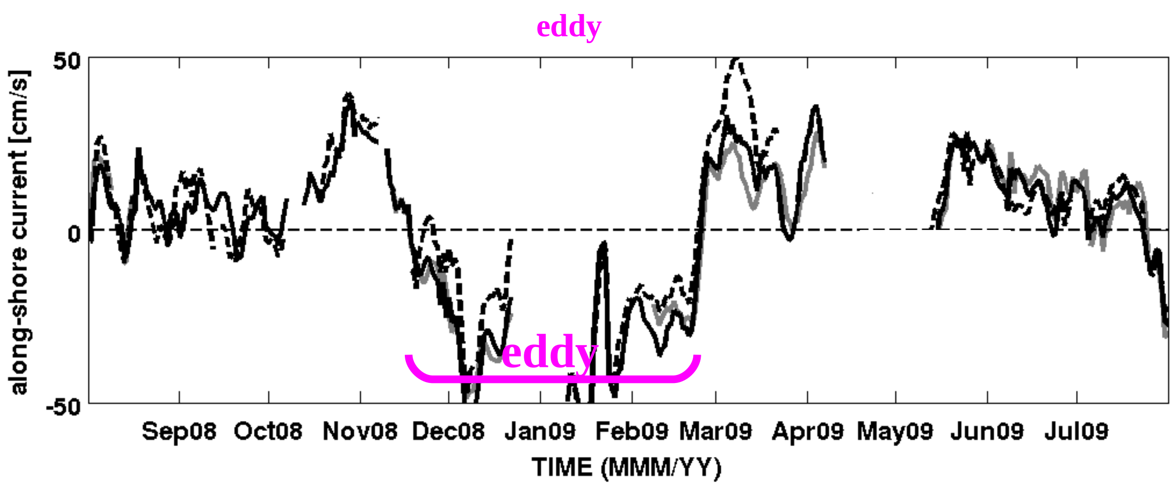


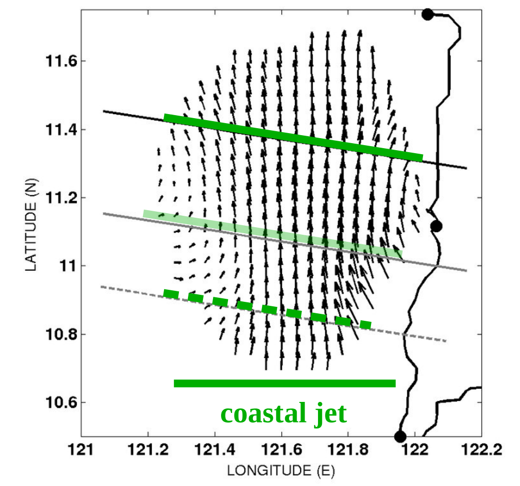
- coastal jet – northward alongshore flow from the coast to the center of the eddy
- eddy – southward return flow from the center of the eddy to the west

. Coastal jet and cyclonic eddy





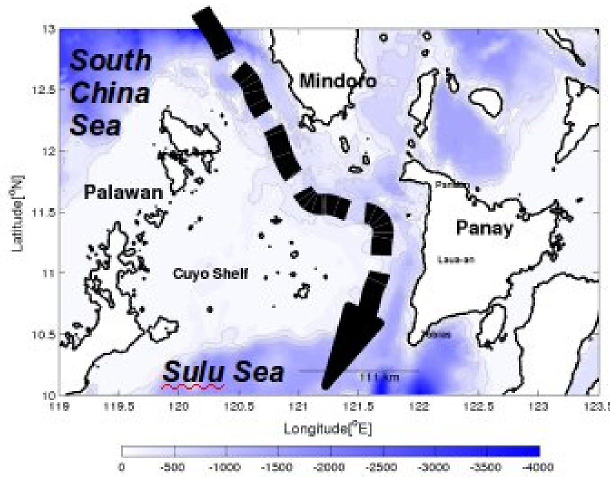


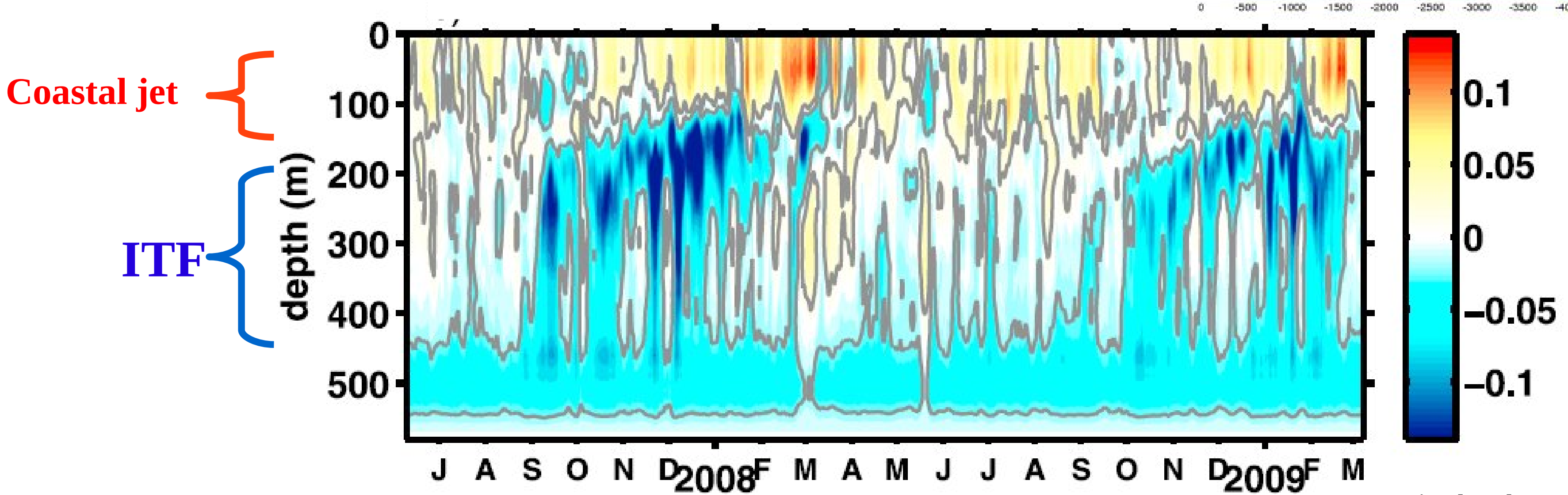


- **coastal jet is permanent**
- **cyclonic eddy is distinctly seasonal, NE monsoon**
- **well-defined transition periods, October and April**
- **intermittent variation of coastal jet concurrent with the eddy formation**

- **Where is the Indonesian Through-Flow?**

(moves water from West Philippines Sea to Sulu Sea)





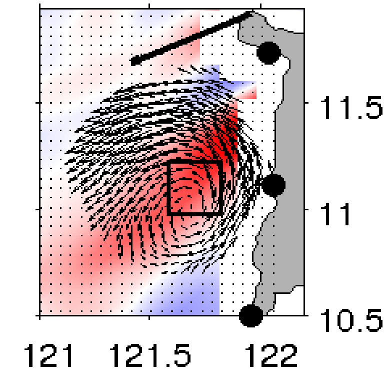
Sprintal et al., 2012

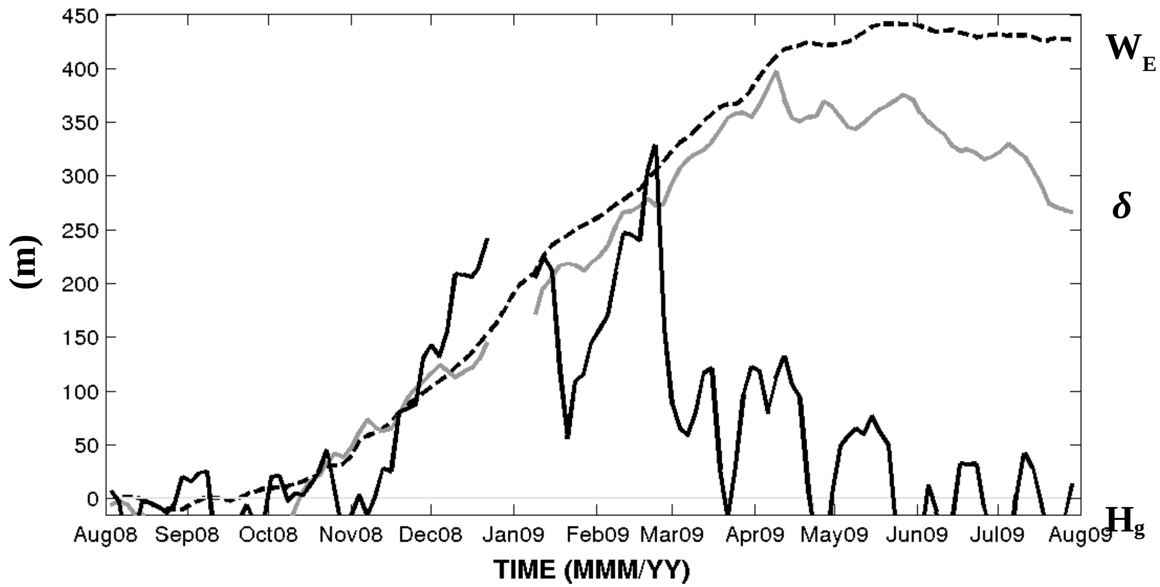
Vertical distribution of transport per unit depth (Sv m^{-1}) to Panay sill depth

- **Indonesian Through-Flow (ITF) is subsurface, under locally forced northward coastal jet**

- # Time integral

Cumulative effect of wind stress curl generates divergence, permanently lifting the thermocline and increases vorticity





W_E - wind stress curl

δ - divergence

H_g - vorticity

$\int_0^T W_E$ **(COAMPS)** **W_E – Ekman pumping velocity**

$H_E \int_0^T \delta$ **(HFDR)** **H_E – Ekman depth, best fit = 32 m**

H_g **(HFDR)** **H_g – thermocline height**

$$H_G = \frac{\zeta f L_G^2}{g'}$$

ζ - vorticity

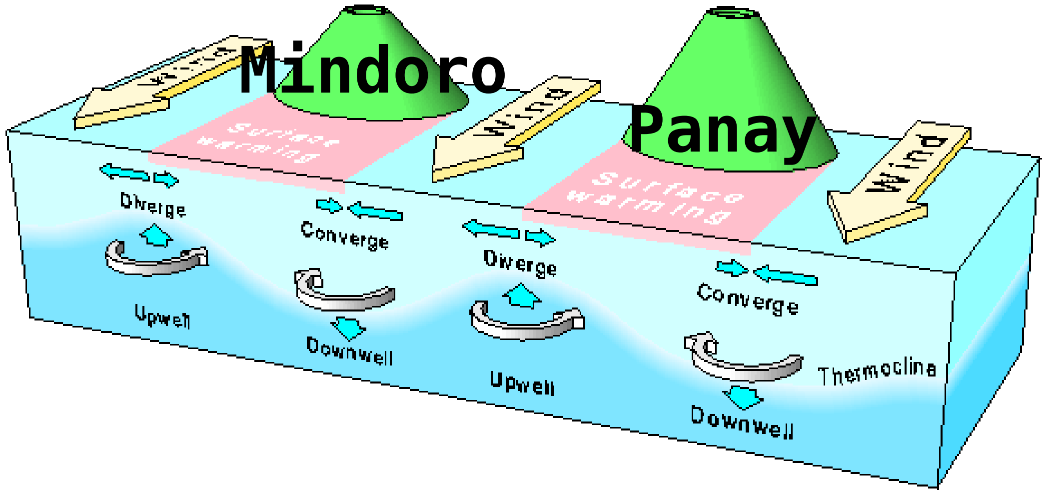
f - Coriolis parameter

L_G - radius the eddy, best fit=100km

g' - reduced gravity

Conclusions

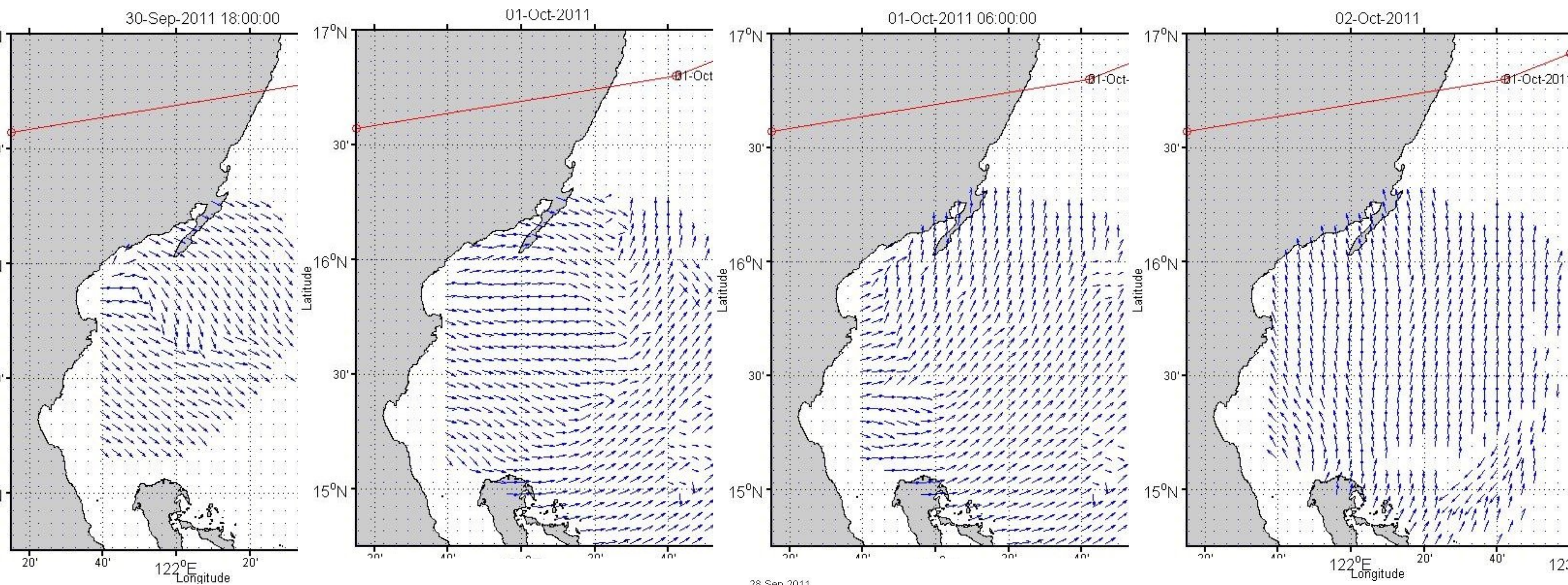
- **Conceptual diagram showing Ekman pumping in the lee of islands**
  1. **wind intensifies between islands**
  2. **wind stress variations form positive wind stress curl in the lee of Panay**
  3. **induces divergent surface currents**
  4. **which in turn uplift thermocline**
  5. **pressure gradient spins-up eddy in geostrophic balance**

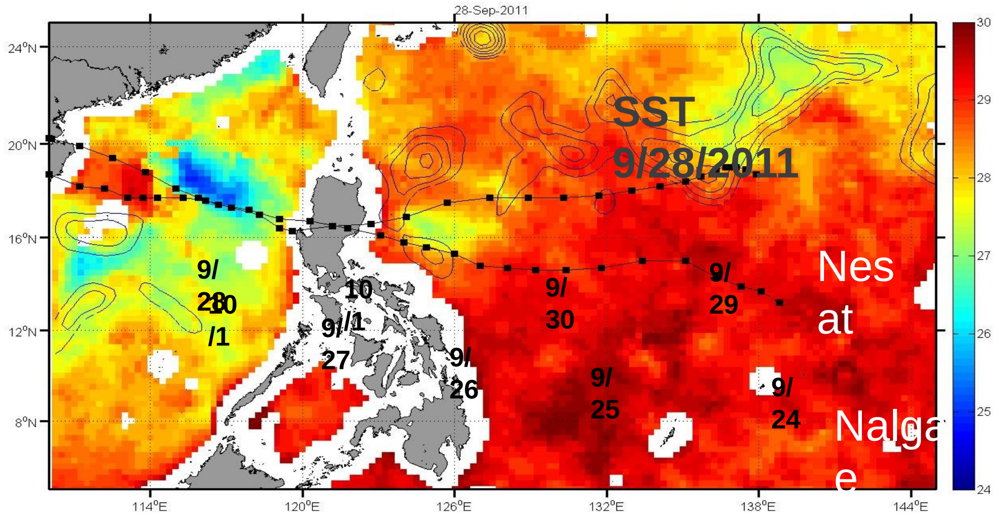


- **mechanism of cumulative wind stress curl to eddy kinetic energy**

OKMC

Wind direction from HFDR during typhoon passages (Ian Fernandez, UP-MSI)





Observations of the Luzon Strait through High-frequency Doppler Radar Scatterometers

Authors

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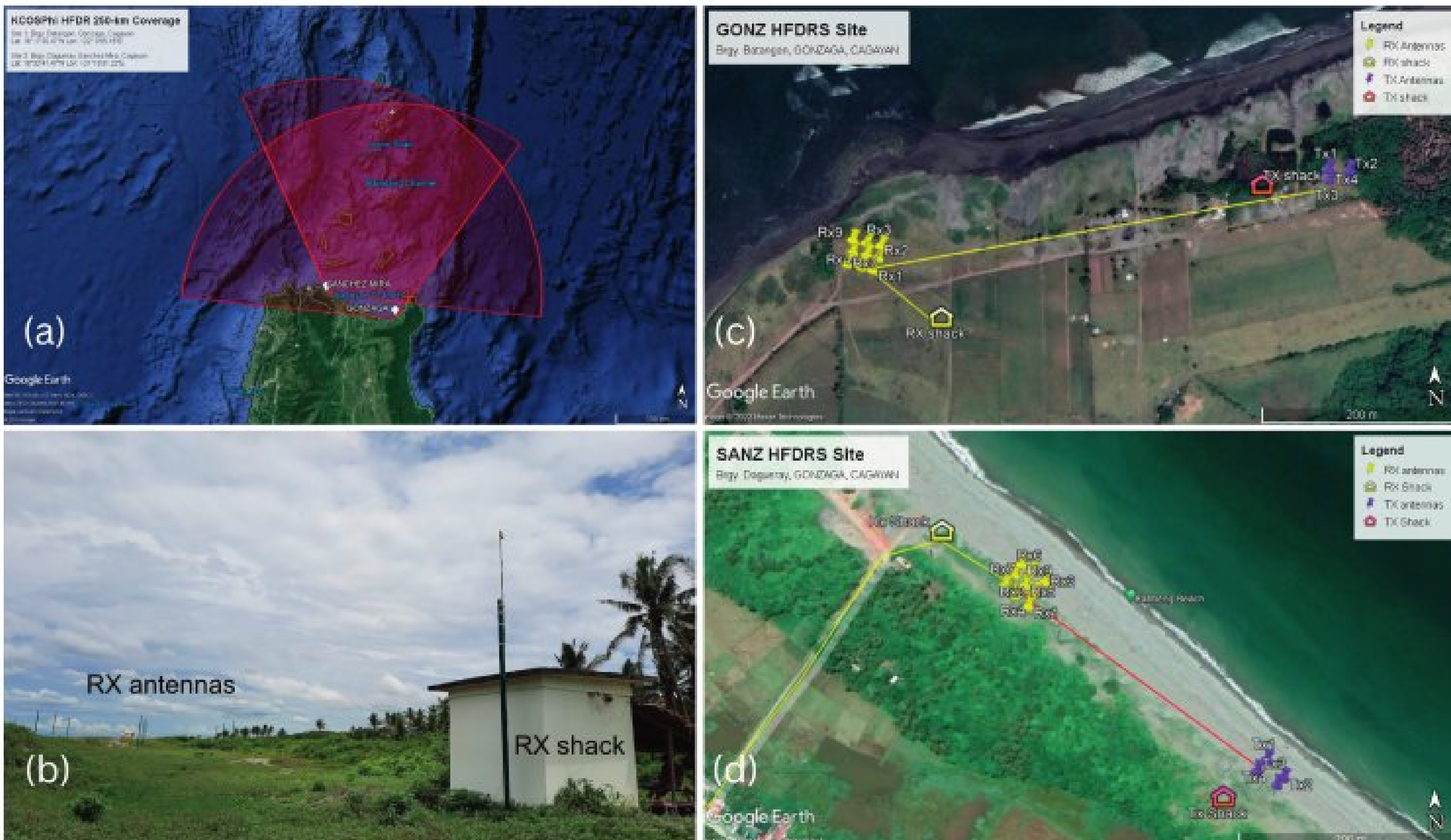
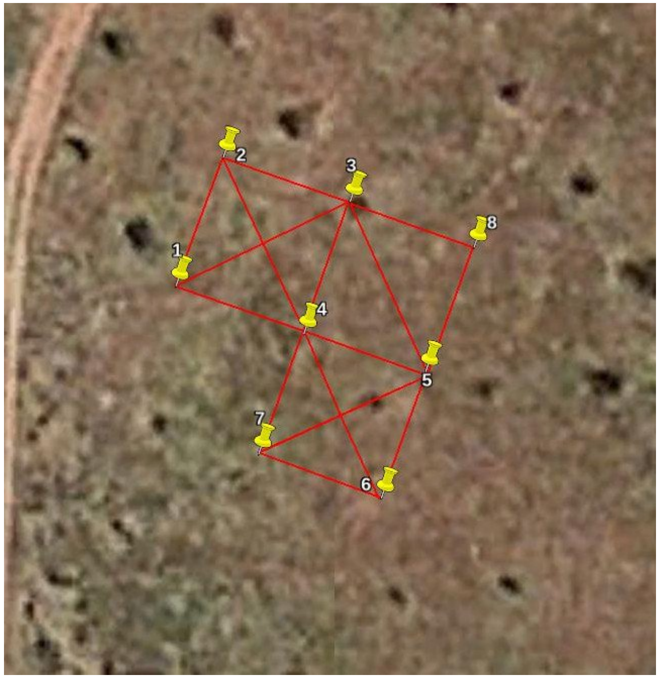
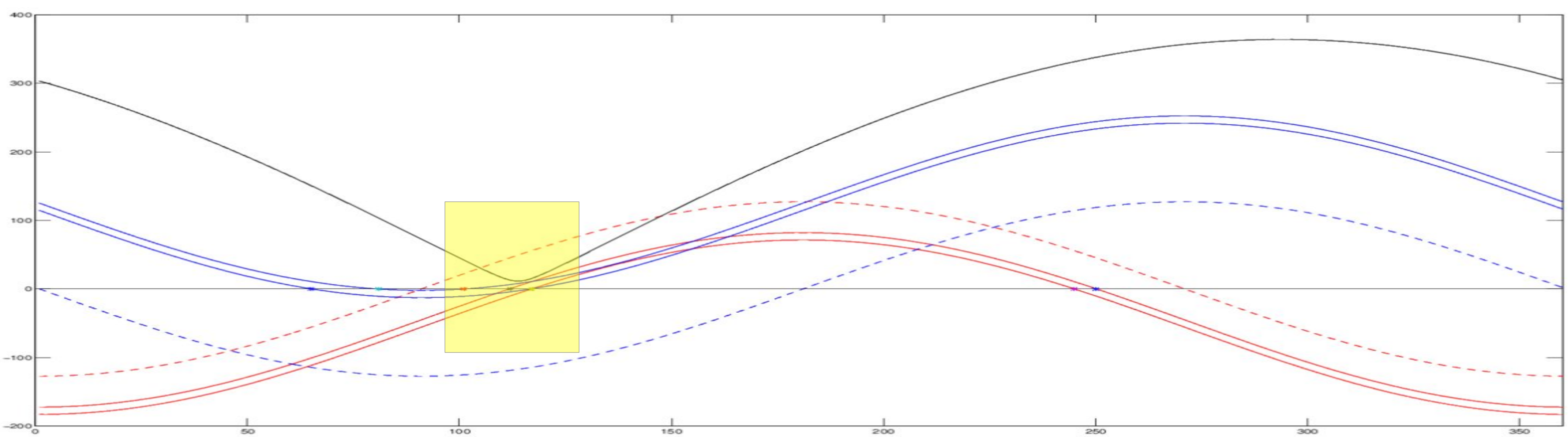
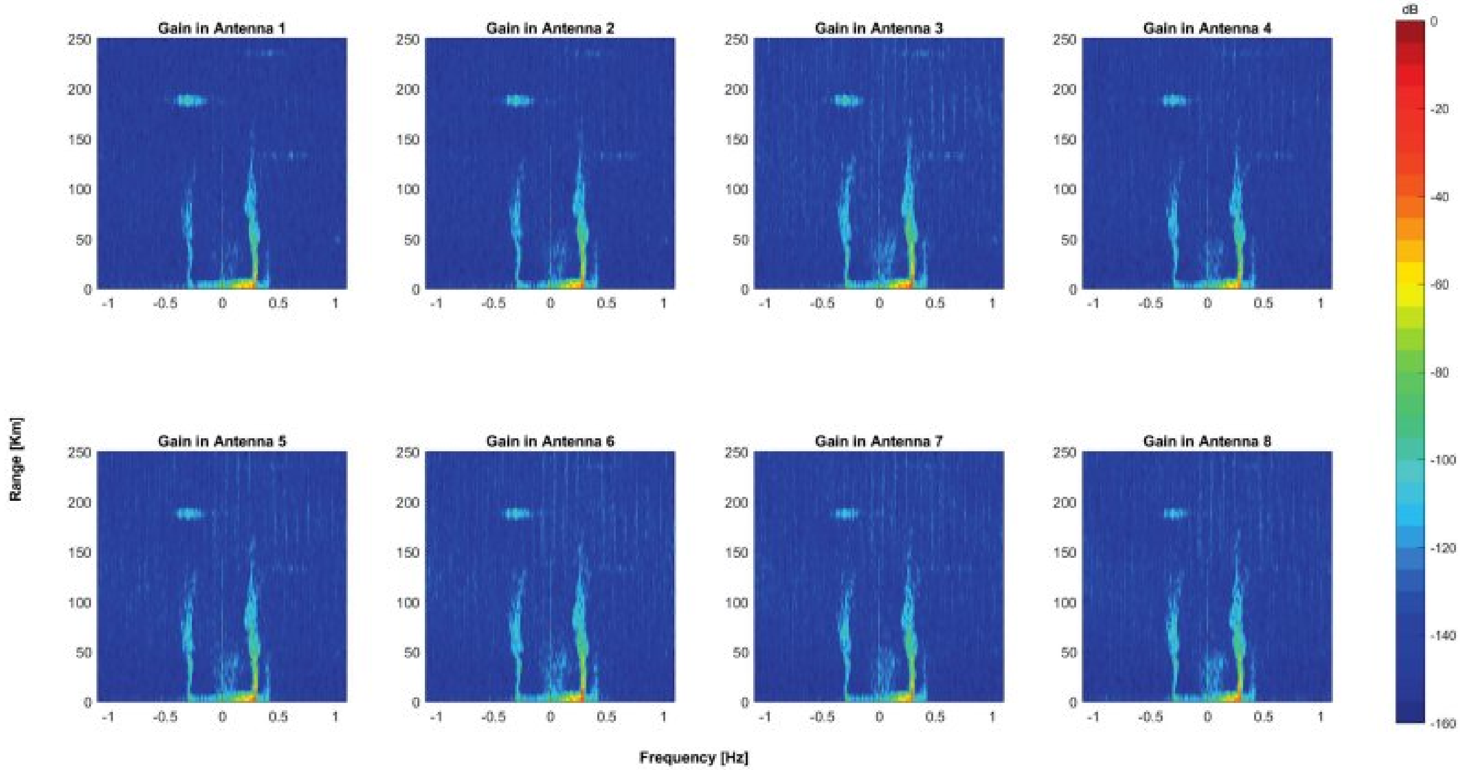


Figure 3. (a) Location of the two HF radar sites in Cagayan and the estimated coverage of the HF radar, (b) Set-up in SANZ site showing the RX shack and eight RX antennas, TX antennas not shown. Aerial view of the HF radar sites in (c) Gonzaga, Cagayan, and (d) Sanchez-Mira Cagayan

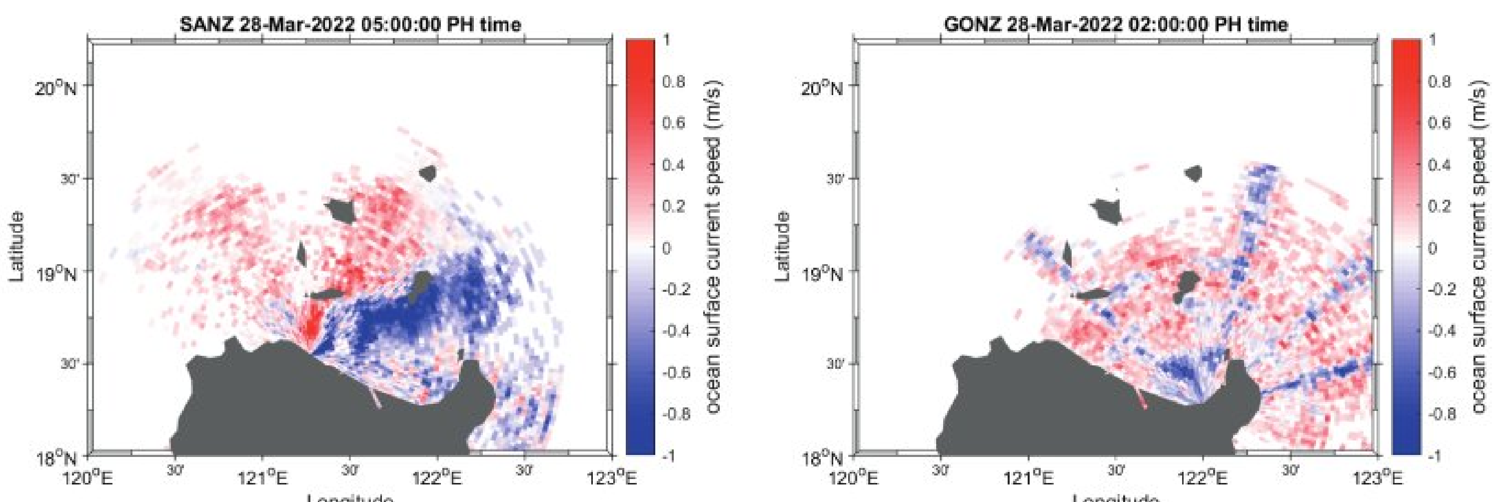
Novel array configuration: 3^2-1 grid for direction finding

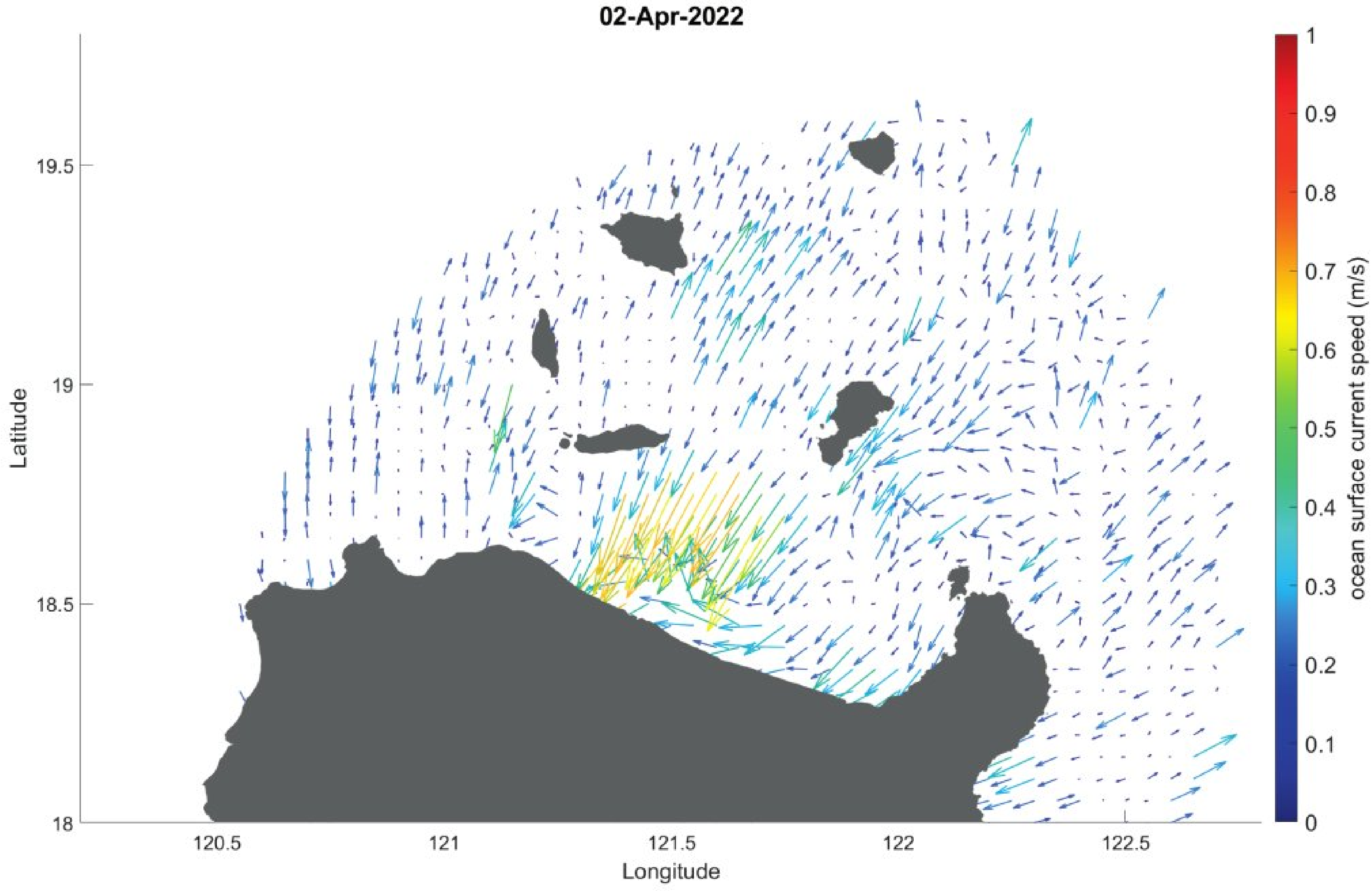






FILE: 20220910600_gonz.mat 01-Apr-2022 14:00:00





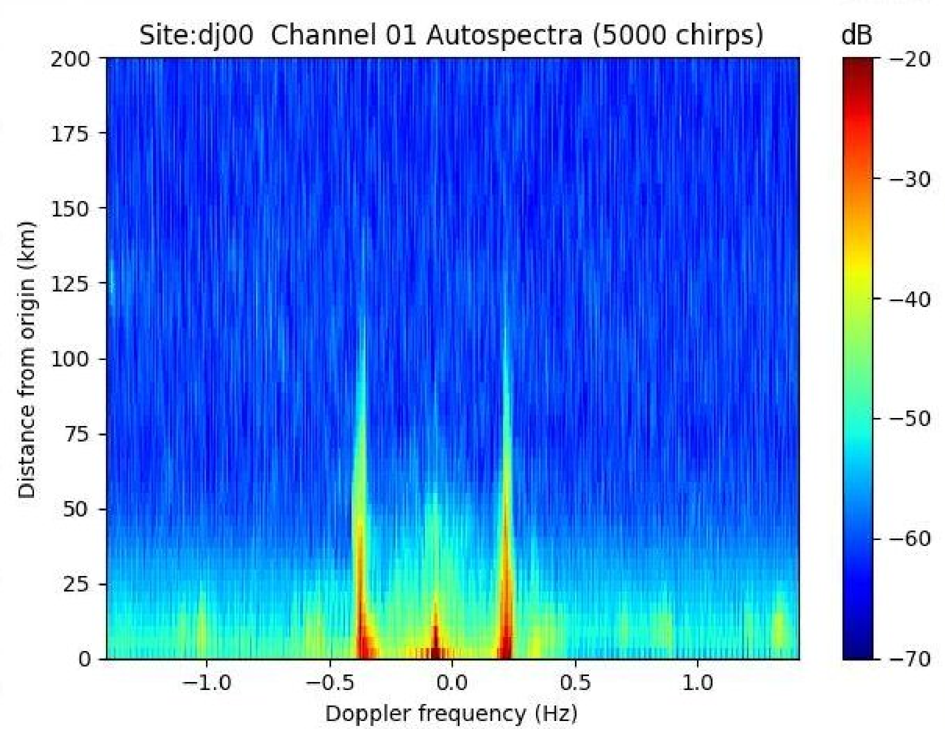
02-Apr-2022
19.5
19
18.5
18
120.5
121
121.5
122
122.5
Longitude
Latitude
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ocean surface current speed (m/s)

Recent development:
all-constellations GNSS synchronization:

- use best PPS timing board on the market: U-Blox F9T
- tested ±7 ns PPS jitter on fixed position
- firmware modules implemented in FPGA controller
  - ntp server on local network good to 1 ms
  - iterative clock-remapping of OCXO to 1 mHz using dedicated DDS by counting clock cycles between PPS
  - code to start chirp and ADC on exact PPS

- clock stability to 0.01 mHz maintained

  by chip-scale Microsemi Rb clock



- *Applications:*

  1: distant TX and RX without cable connection

  (allowing single-antenna TX)

Recent development:
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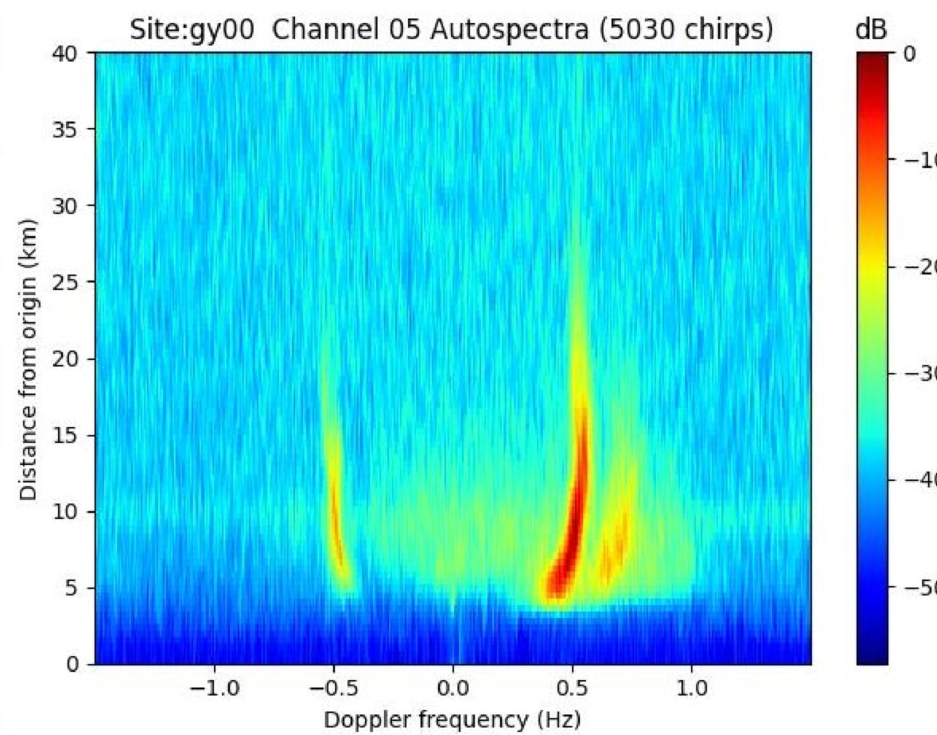


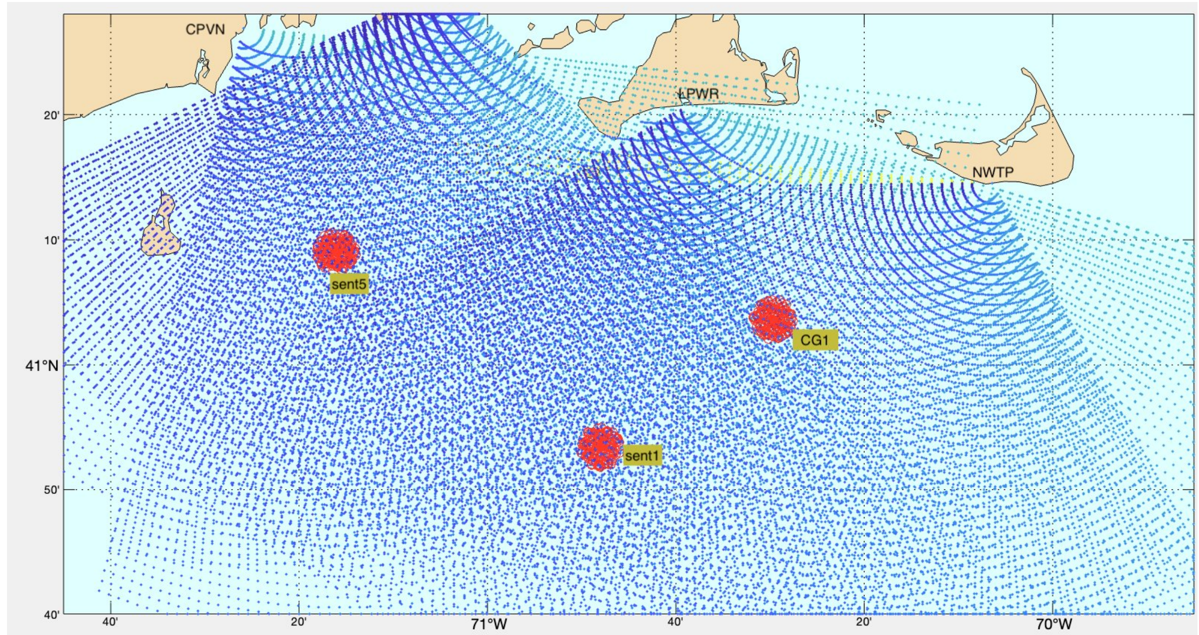
- *Applications:*

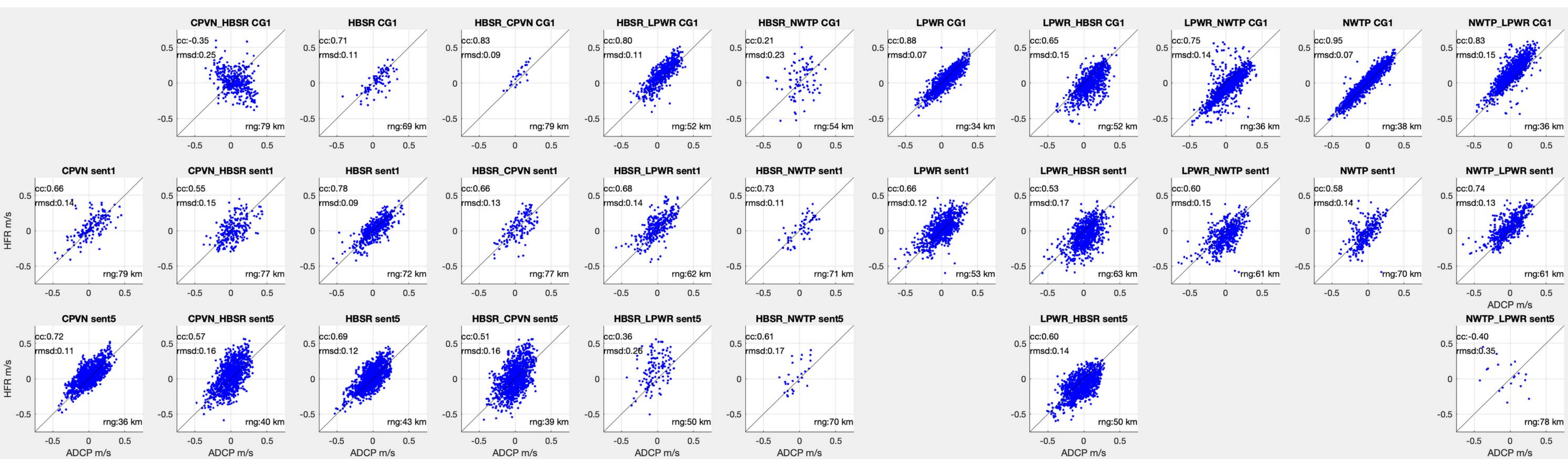
  2: multi-static operation for simultaneous

  elliptical and circular solutions (here:

  8.5 km between TX and RX)

New England operational GNSS-synchronized multi-static array (LPWR/NWTP are atomic)





Space weather applications (ONR)

- use opportunistic well-known HFDR signal for ionospheric studies
- passive high-bandwidth receivers installed Palau, Taiwan, Philippines
- detect many chirping transmitters, few identified
- trend-setting paper by Scripps' group

Deployable Vector Sensor Antenna Array

-

Observations of Ionospheric Clutter at Near Equatorial High Frequency Radar Stations

by Thomas M. Cook *,†, Eric J. Terrill, Carlos Garcia-Moreno and Sophia T. Merrifield

Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92039, USA

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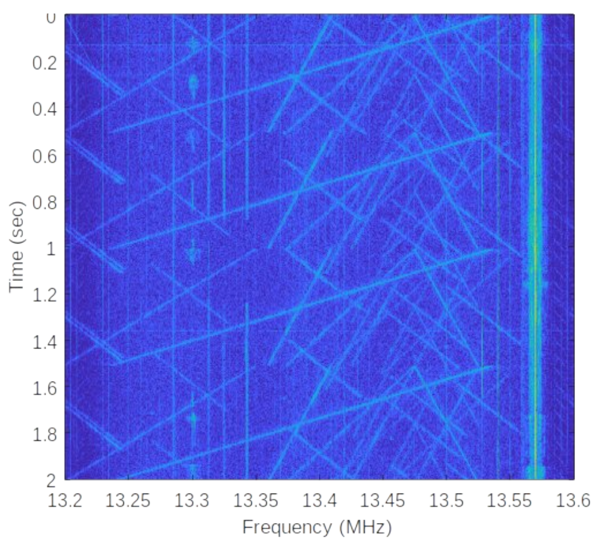
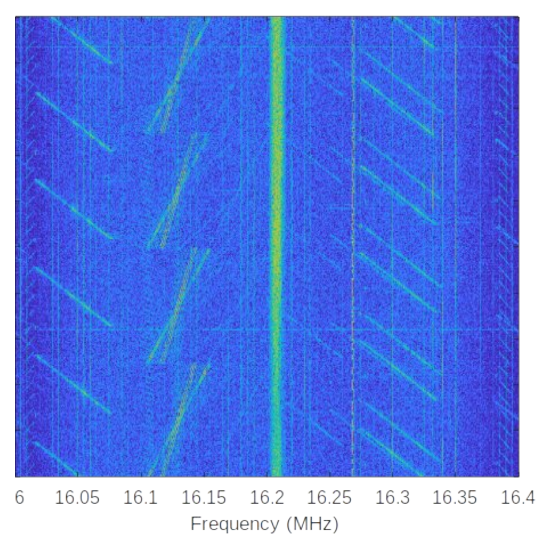
† Current Address: Ocean Modeling Laboratory, SRI International, Ann Arbor, MI 48105, USA.

Remote Sens. **2023**, *15*(3), 603; https://doi.org/10.3390/rs15030603





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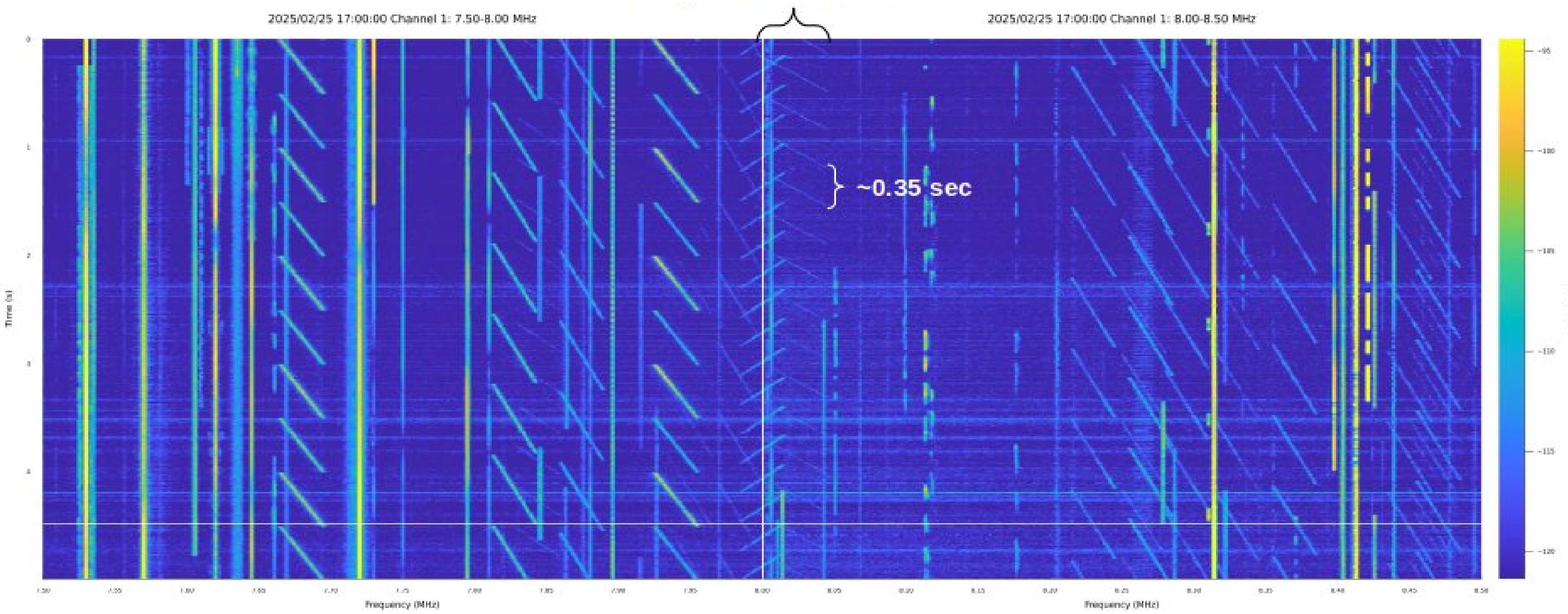
Deployable Vector Sensor Antenna Array

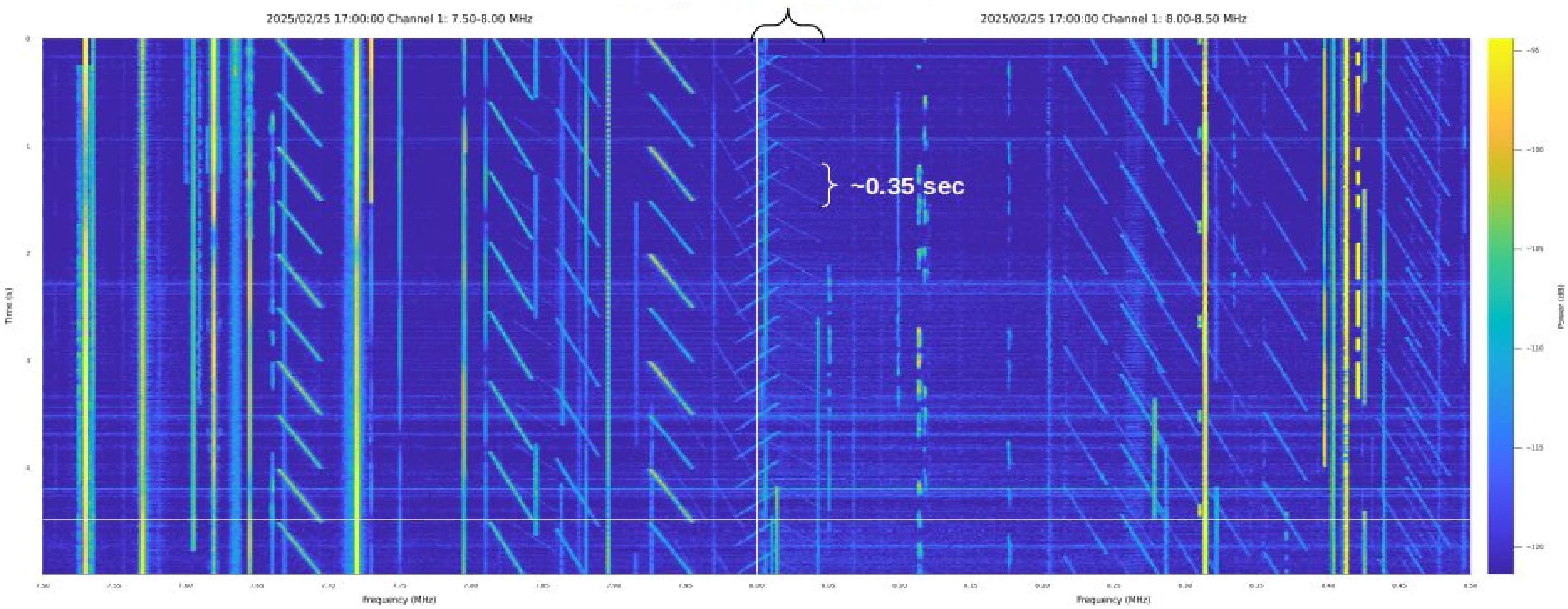
-

MIT Lincoln Lab’s MODI receiver on Palau:



Future developments:

- are we seeing the end of *homodyne* HF radars?
- are software-defined HF radars next?
- potential for using opportunistic well-known HFDR signals for transmitter-less multi-frequency passive receiver radars



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