HF RADAR Tutorial

Principles of Operation, Data Products & State-of-the-Art

Chad Whelan

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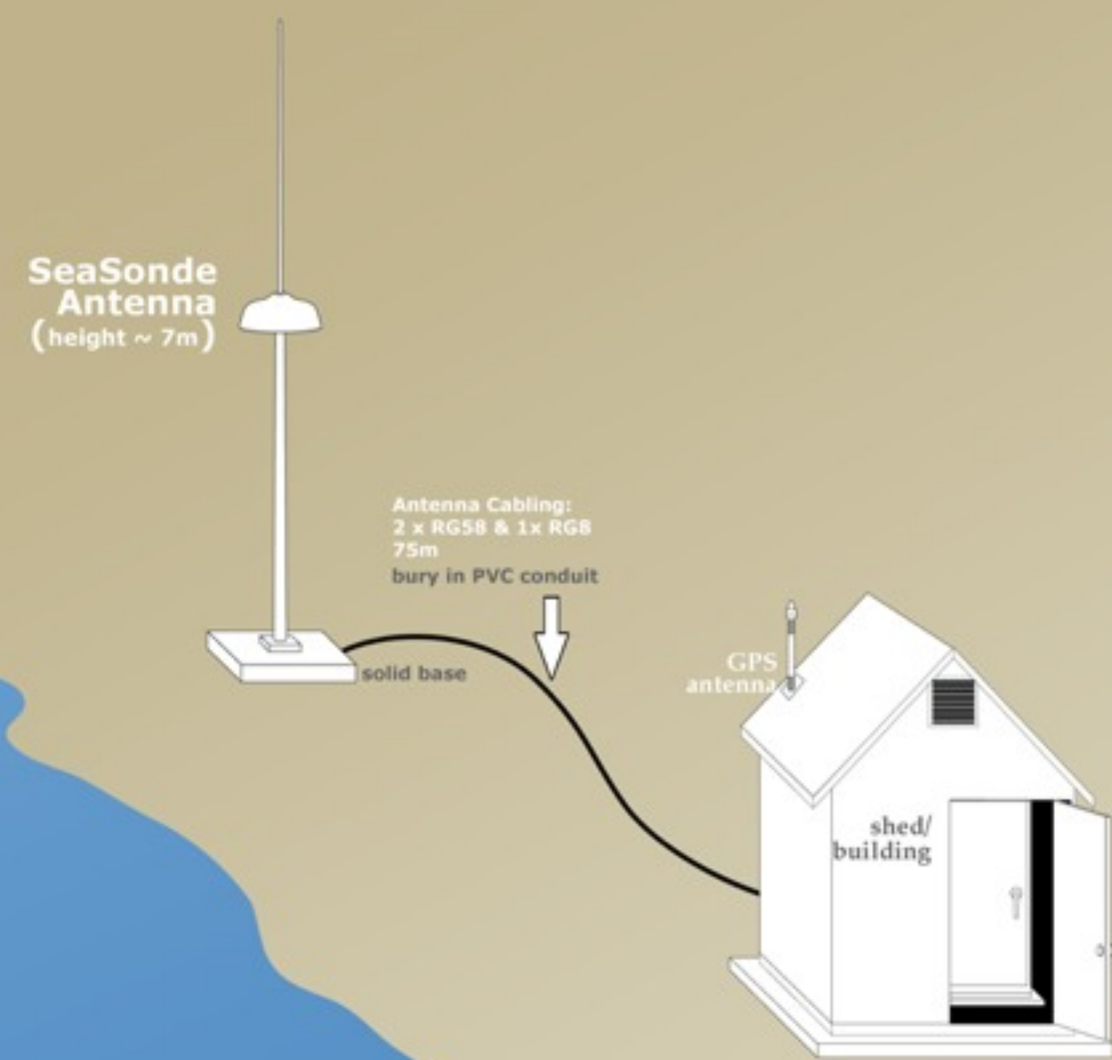
HF RADAR Tutorial
Bergen, Norway
June 10, 2013

SeaSonde Site Layout

Climate-Controlled Shelter with Power, Communications

> 11 MHz:
Single T/R antenna

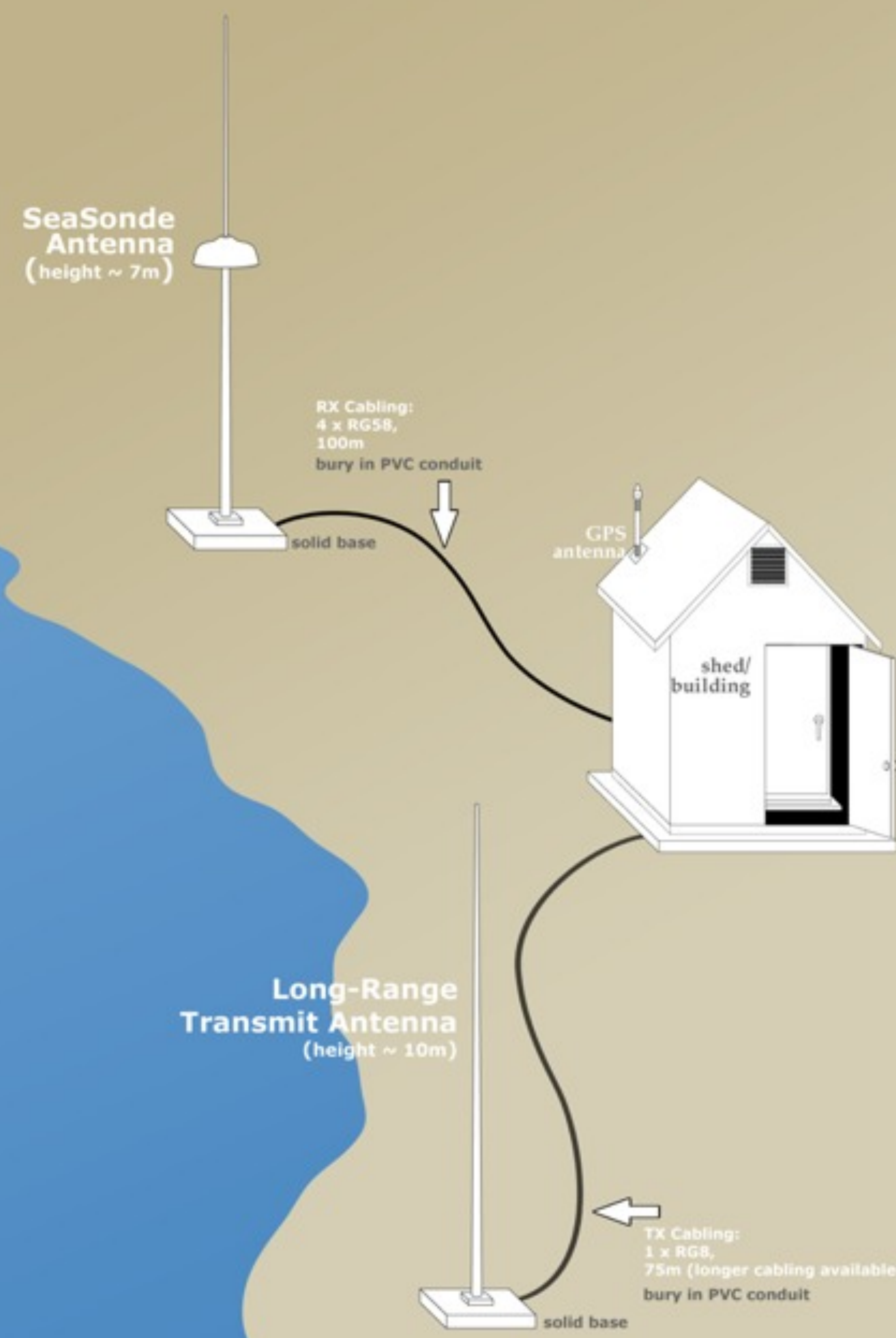


SeaSonde Site Layout

Climate-Controlled Shelter with Power, Communications

> 11 MHz:
  Single T/R antenna

< 11 MHz:
  Separate T & R antennas



Compact Omnidirectional Antenna

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7.6 m

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Compact Electronics

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#1


Cintra

Low Power (<200 Watts)


HELITRANS

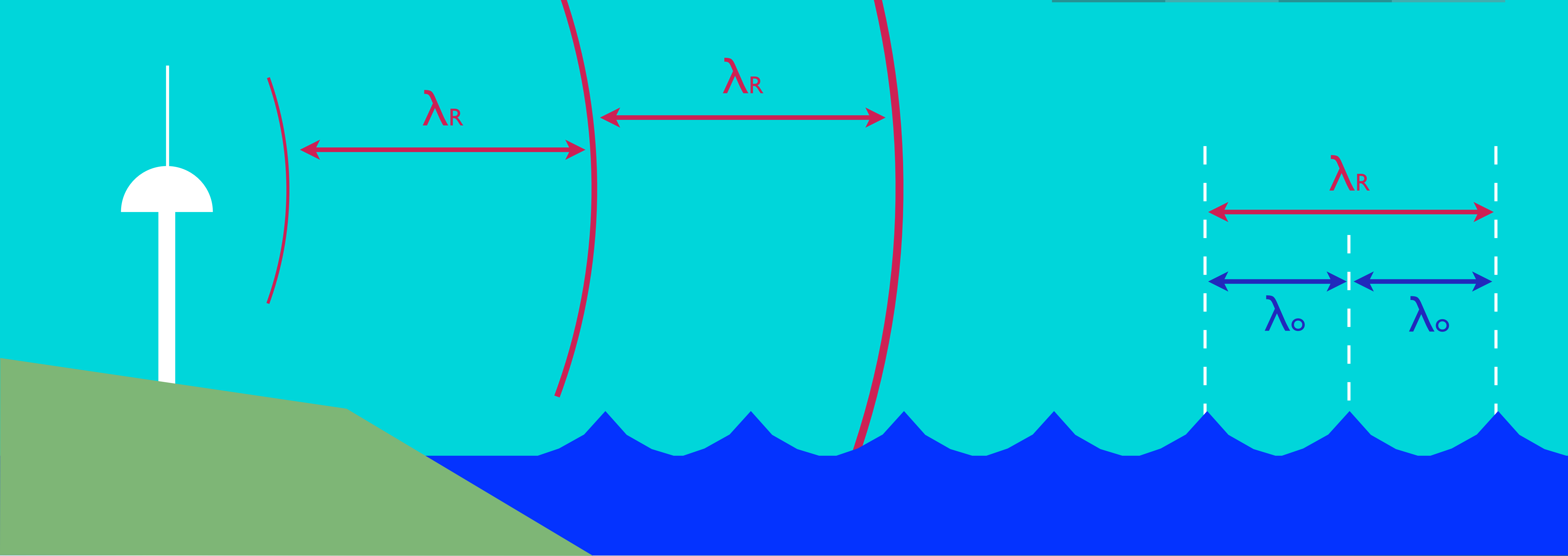
How Does It Work?

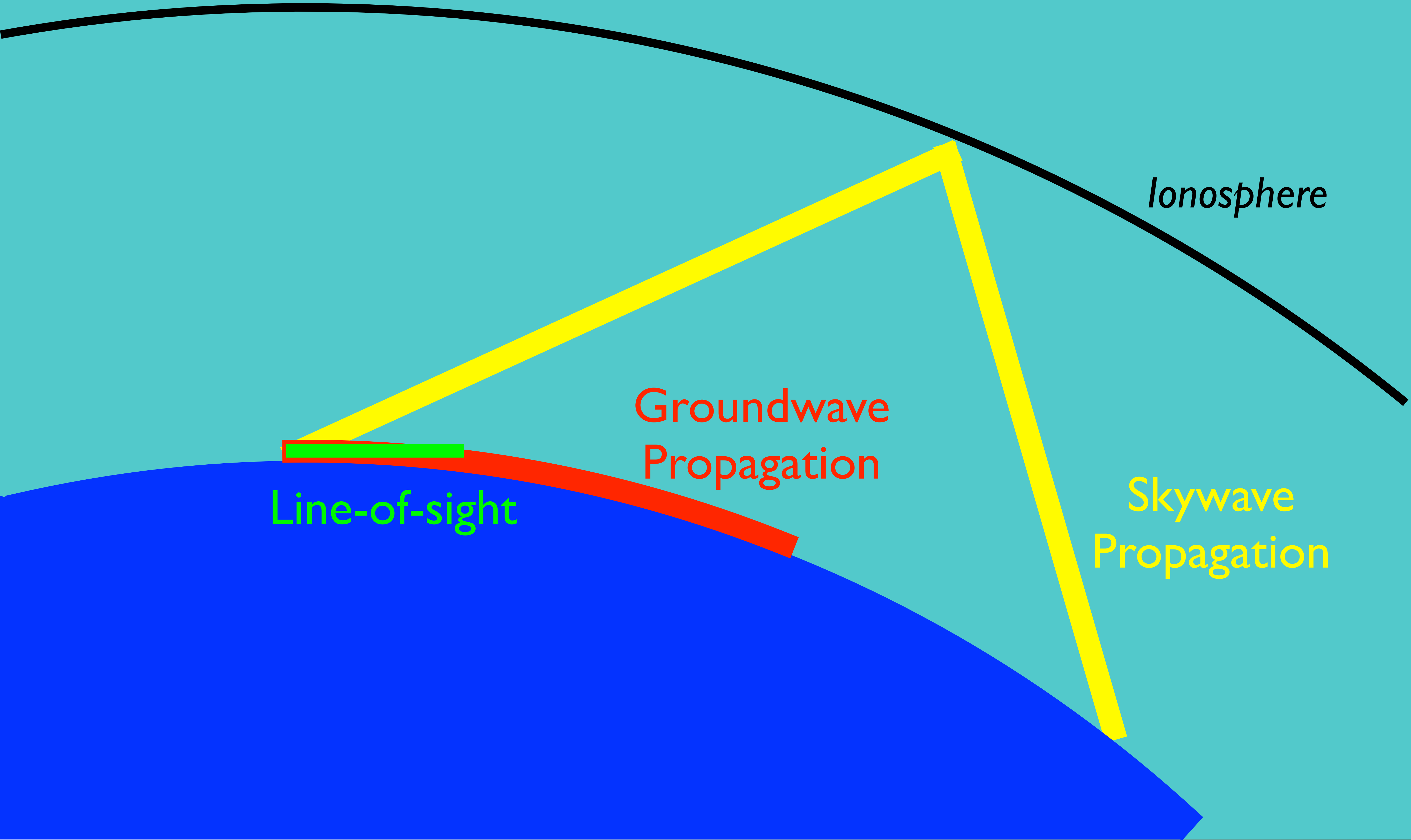
SeaSonde is a Doppler Radar

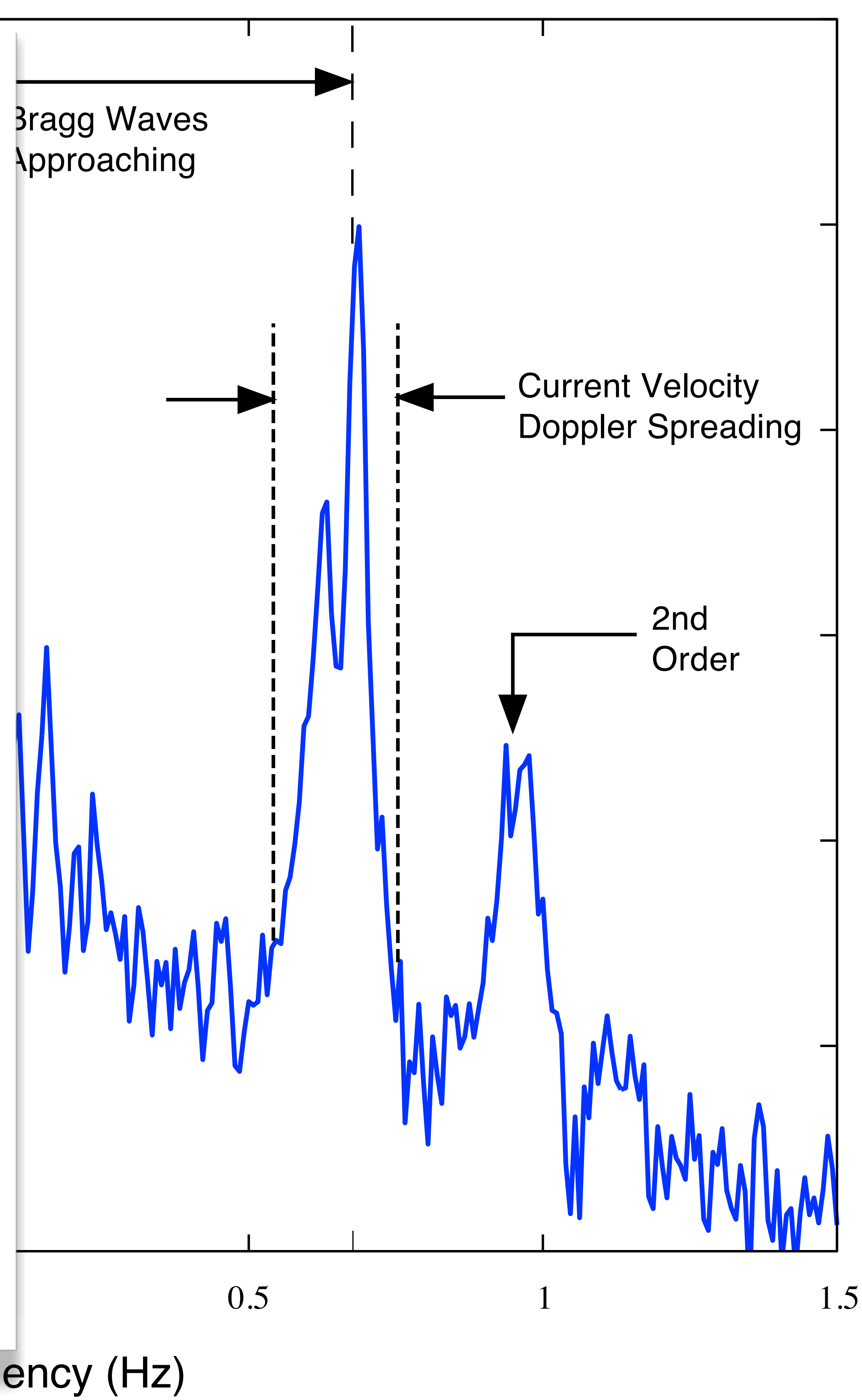
Measures velocity of target towards or away from the Radar

Bragg Scattering

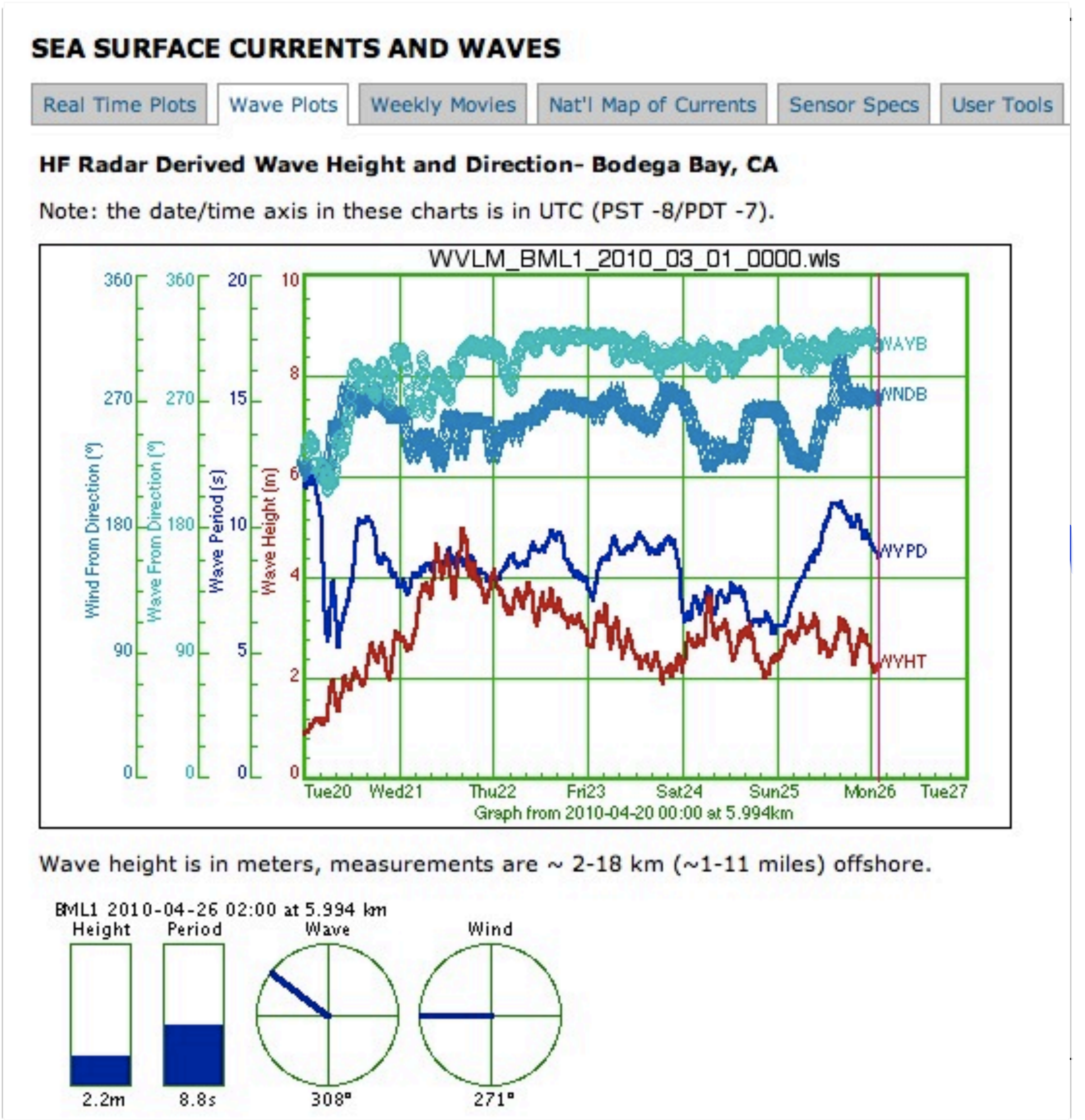
Freq mhz	λ_R meters	λ_O meters	T_O seconds
5	60	30.0	4.4
13	23	11.5	2.7
25	12	6.0	2.0
42	7	3.6	1.5




Ionosphere
Groundwave Propagation
Line-of-sight
Skywave Propagation

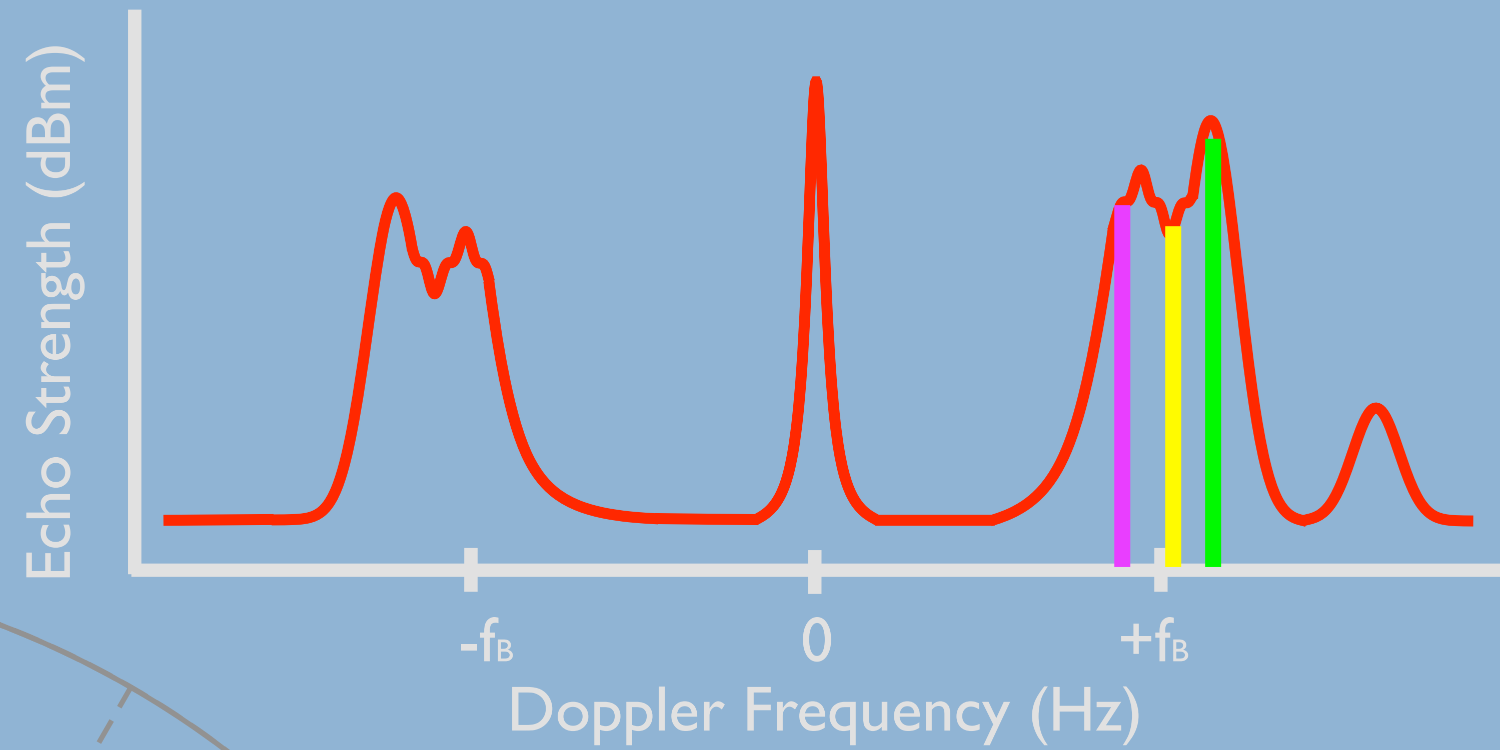


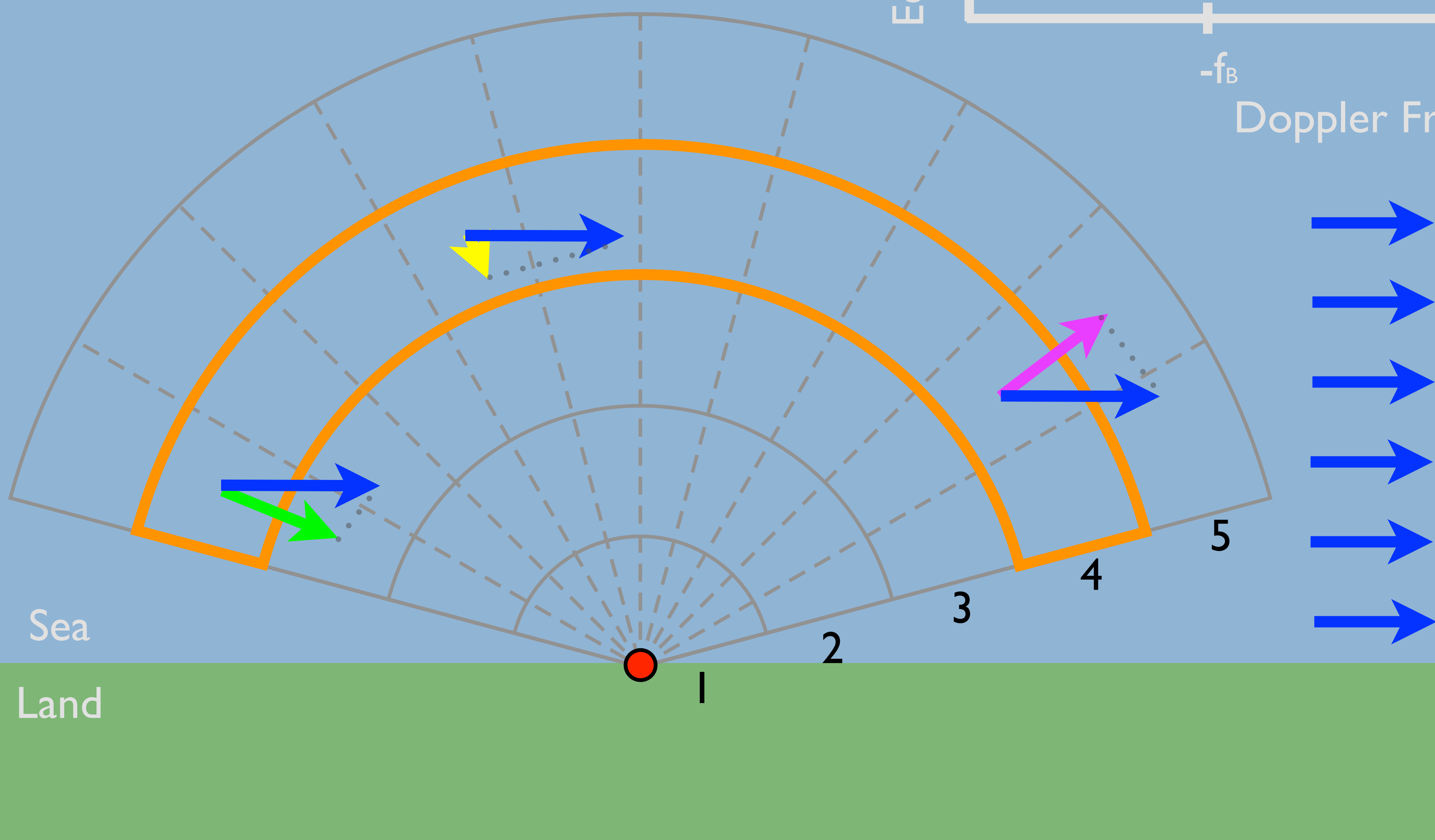
-100
Bragg Waves
Approaching
Current Velocity
Doppler Spreading
2nd
Order
0.5
1
1.5
Doppler Frequency (Hz)



SEA SURFACE CURRENTS AND WAVES
Real Time Plots
Wave Plots
Weekly Movies
Nat'l Map of Currents
Sensor Specs
User Tools
HF Radar Derived Wave Height and Direction- Bodega Bay, CA
Note: the date/time axis in these charts is in UTC (PST -8/PDT -7).
WVLM_BML1_2010_03_01_0000.wls
Wind From Direction (°)
Wave From Direction (°)
Wave Period (s)
Wave Height (m)
WAVB
WNDB
WVPD
WVHT
Tue20
Wed21
Thu22
Fri23
Sat24
Sun25
Mon26
Tue27
Graph from 2010-04-20 00:00 at 5.994km
Wave height is in meters, measurements are ~ 2-18 km (~1-11 miles) offshore.
BML1 2010-04-26 02:00 at 5.994 km
Height
Period
Wave
Wind
2.2m
8.8s
308°
271°

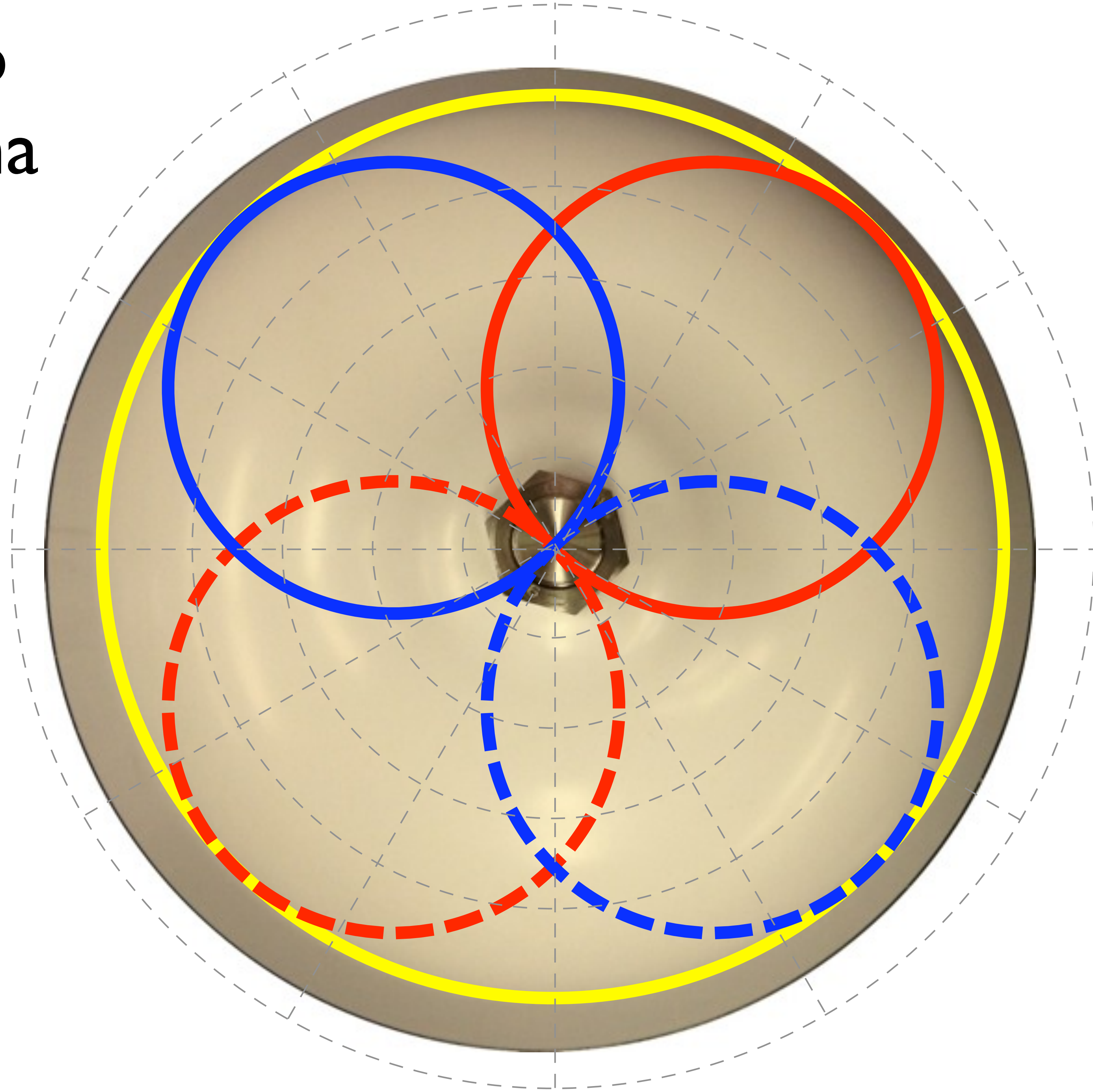
Radial Currents

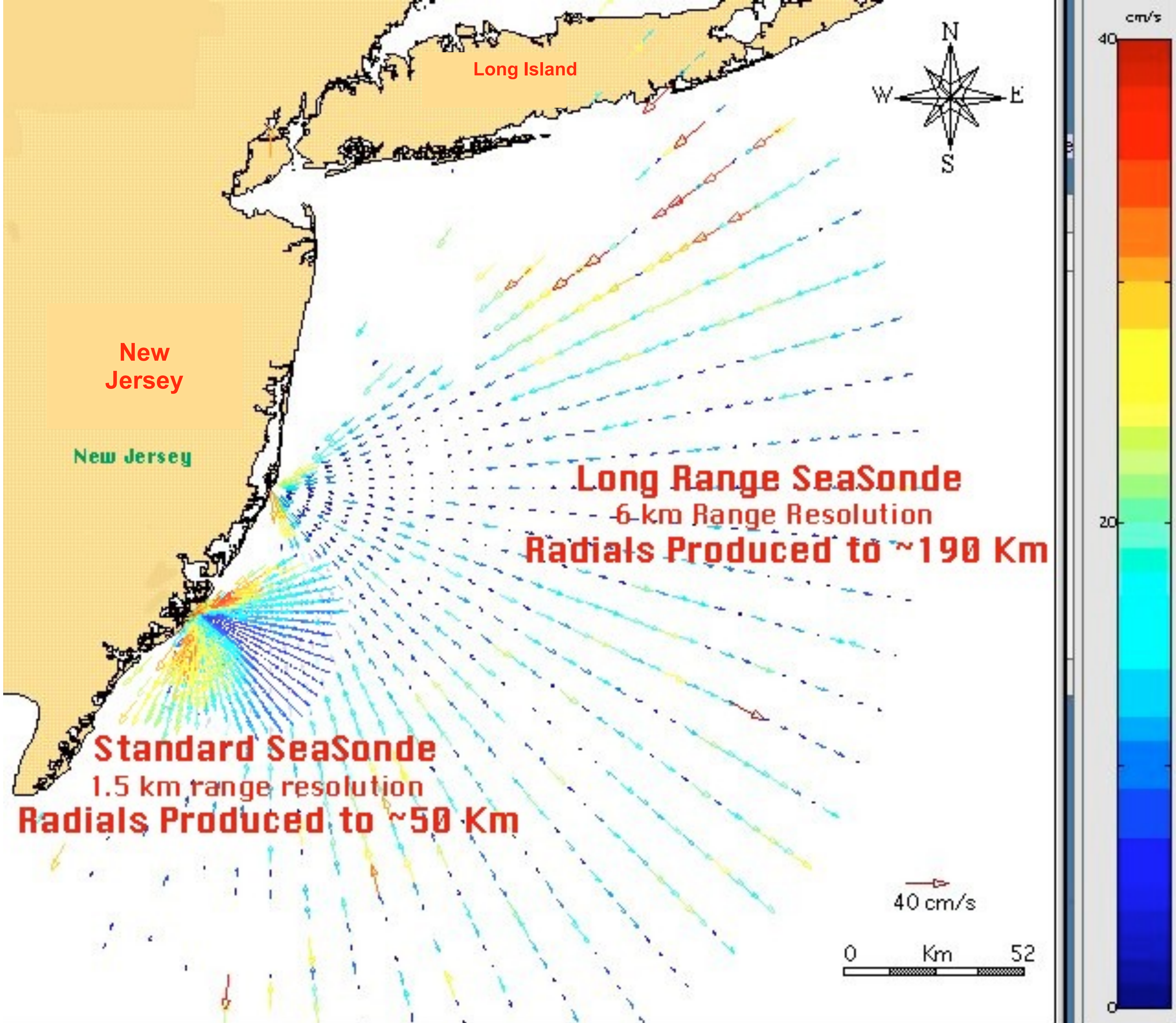




Compact Crossed Loop Omnidirectional Antenna

- *3 co-located antennas*
- *Unique combination of amplitude & phase for each antenna = 6 parameters for each bearing*
- *MUSIC Direction Finding on each Doppler bin*



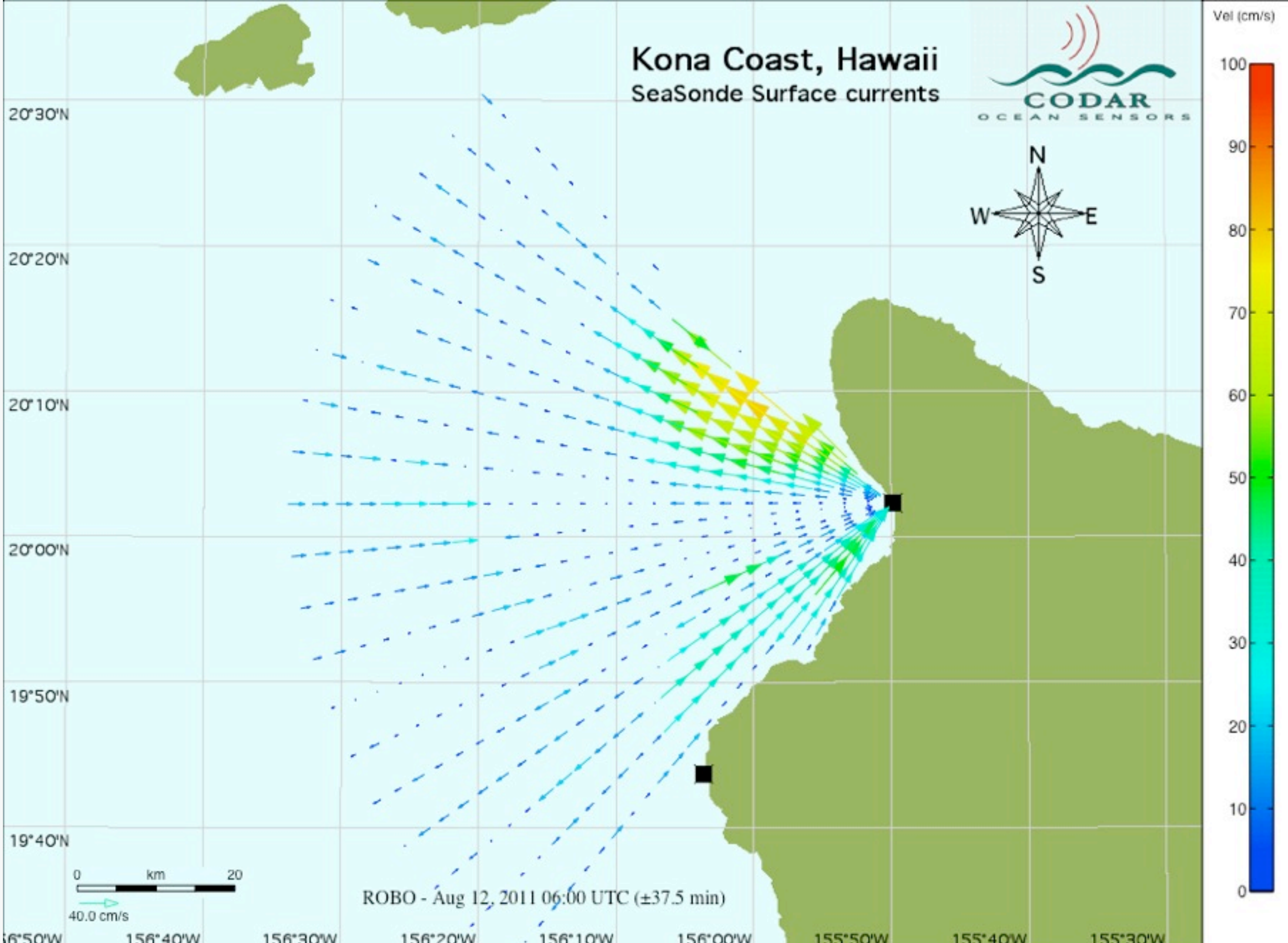

Long Island
N
W
E
S
New Jersey
New Jersey
Long Range SeaSonde
6 km Range Resolution
Radials Produced to ~190 Km
Standard SeaSonde
1.5 km range resolution
Radials Produced to ~50 Km
40 cm/s
0
Km
52
cm/s
40
20
0

Considerations for Choosing Frequency

Freq. (MHz)	Ants	Radar λ (m)	Ocean λ (m)	Current Depth (m)	Max Speed (m/s)	Range (km)	Range Res. (km)	Sat. $H_{1/3}$ (m)
4.5	2	67.3	33.6	2.0	6.5	160-220	3-6	25
5.3	2	57.0	28.5	2.0	6.0	150-200	6	24
9.3	2	32.2	16.1	1.6	4.5	90-130	3-6	19
13.5	1	22.2	11.1	1.3	3.7	60-90	3	13
16.2	1	18.6	9.3	1.0	3.4	45-65	1.5	11
24.5	1	12.2	6.1	0.7	2.8	30-50	1	7
26.2	1	11.4	5.7	0.6	2.7	25-45	1	6
39.3	1	7.6	3.8	0.3	2.2	15-25	0.3	3
42.3	1	7.1	3.6	0.3	2.1	15-25	0.3	3

Factors Affecting Performance

- HF Radio Noise Sources
  - Man Made Broadcasts
  - Natural Sources (Auroral, Lightning, etc.)
- Shallow Water
- Local Wave Climate
  - Fetch Limitations
  - Saturation at Higher Frequencies
- Very Strong or Very Weak Range of Currents
- Site Conditions (Antenna Interactions, Propagation Loss)
- Salinity



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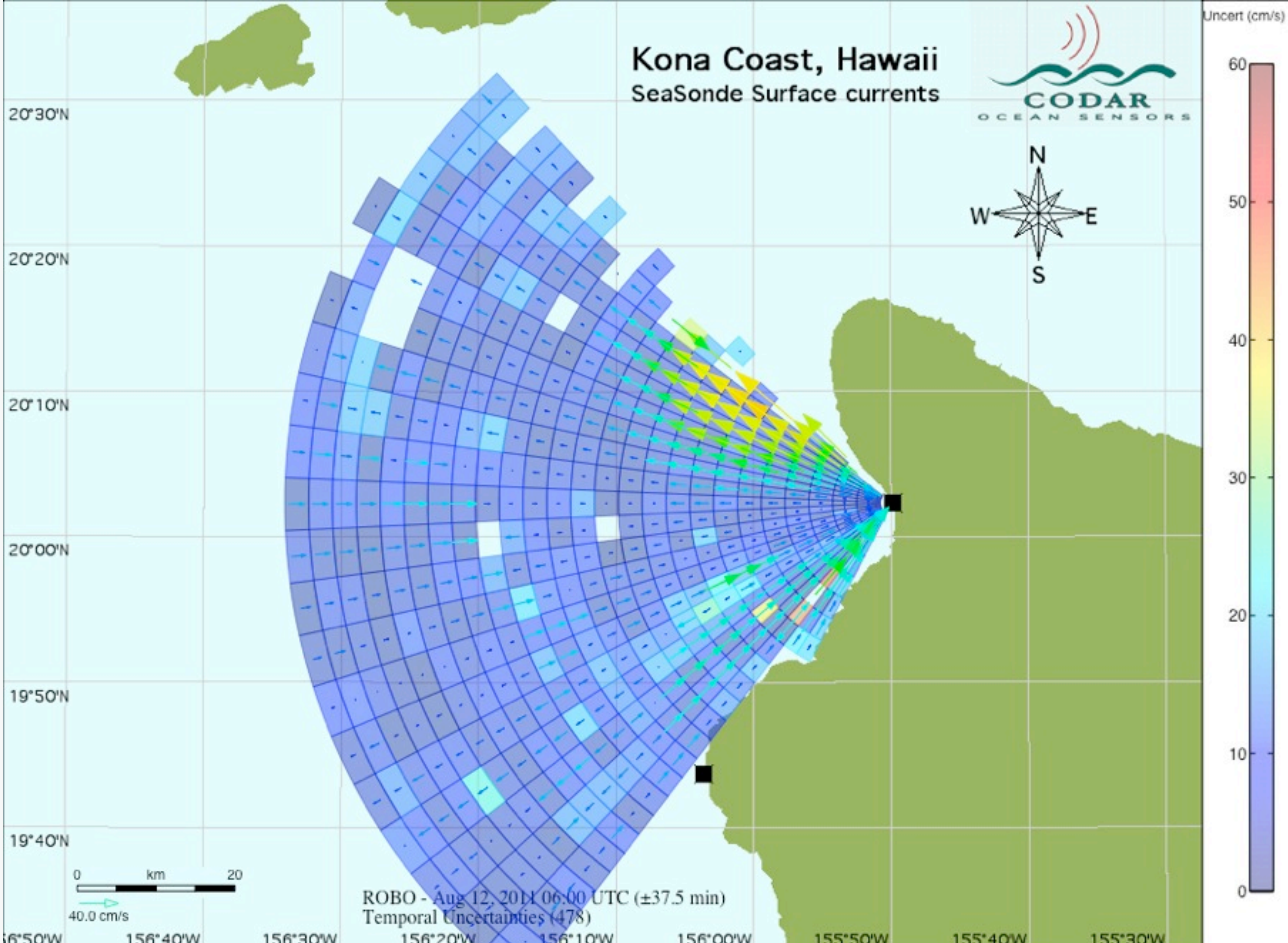

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Example Radial Vector File

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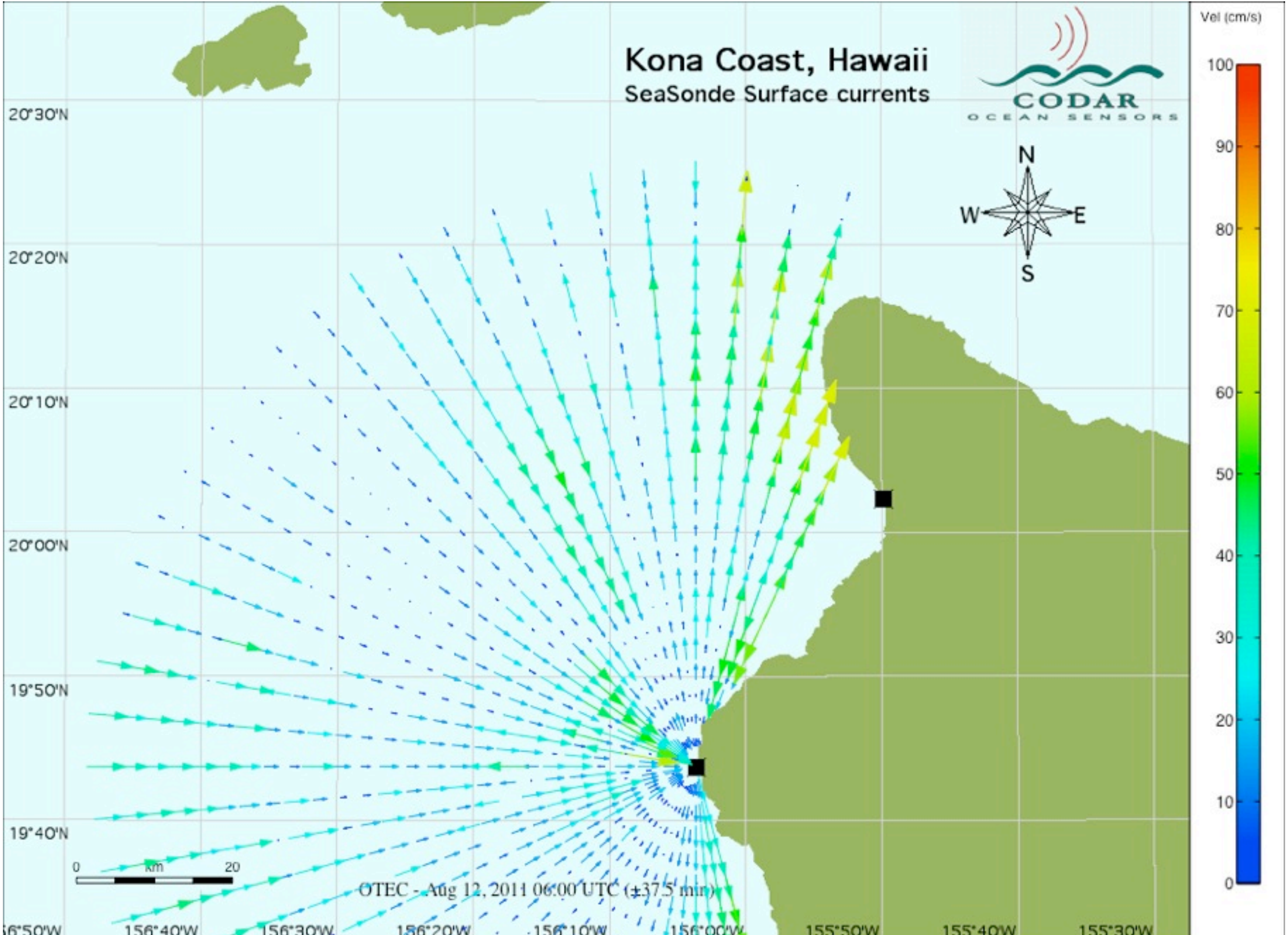
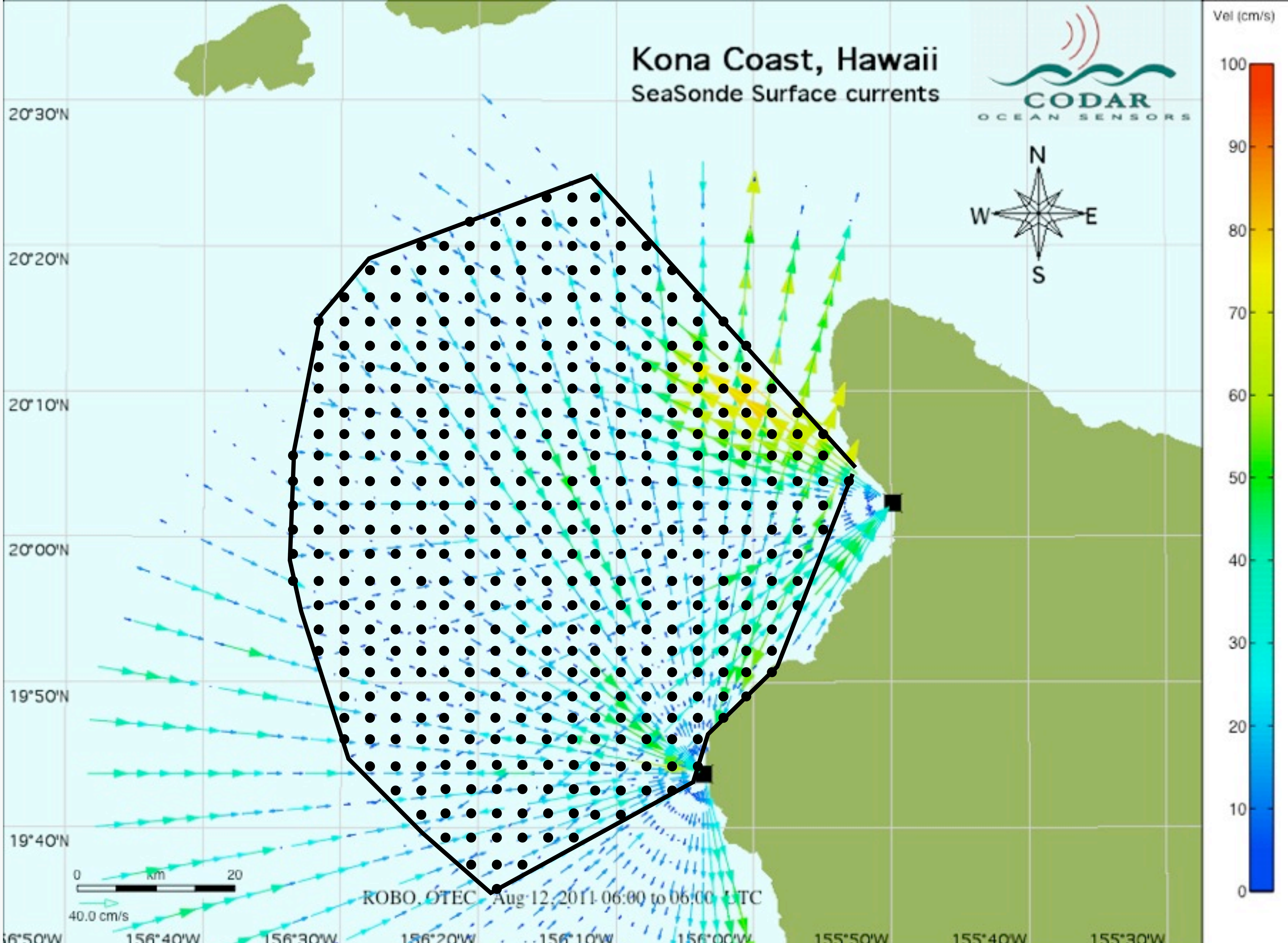
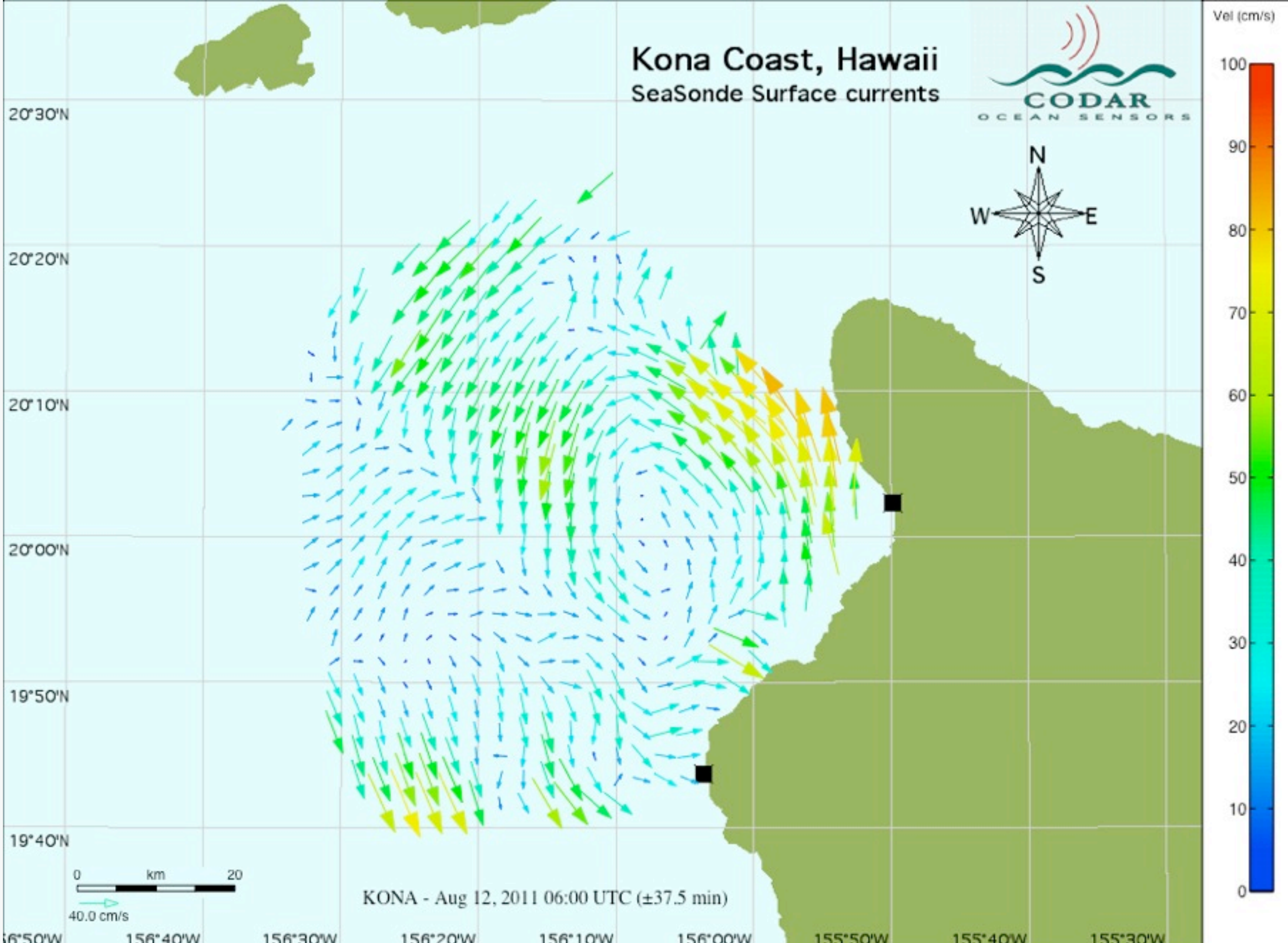
%CTF: 1.00
%FileType: LLUV rdls "RadialMap"
%LLUVSpec: 1.14  2010 07 18
%UUID: 6849889E-2746-4FDD-86A3-D9E4CEAE4BA7
%Manufacturer: CODAR Ocean Sensors. SeaSonde
%Site: OTEC ""
%TimeStamp: 2011 08 12  03 00 00
%TimeZone: "UTC" +0.000 0 "Atlantic/Reykjavik"
%TimeCoverage: 75.000 Minutes
%Origin:  19.7288833 -156.0604833
%GreatCircle: "WGS84" 6378137.000  298.257223562997
%GeodVersion: "CGEO" 1.57  2009 03 10
%LLUVTrustData: all %% all lluv xyuv rbvd
%RangeStart: 1
%RangeEnd: 25
%RangeResolutionKMeters: 3.022400
%AntennaBearing: 315.0 True
%ReferenceBearing: 0 True
%AngularResolution: 5 Deg
%SpatialResolution: 5 Deg
%PatternType: Ideal
%PatternDate: 2009 04 30  22 21 12
%PatternResolution: 1.0 deg
%TransmitCenterFreqMHz: 13.450000
%DopplerResolutionHzPerBin: 0.003906250
%FirstOrderMethod: 0
%BraggSmoothingPoints: 4
%CurrentVelocityLimit: 120.0
%BraggHasSecondOrder: 0
%RadialBraggPeakDropOff: 158.490
%RadialBraggPeakNull: 63.100
%RadialBraggNoiseThreshold: 3.000
%PatternAmplitudeCorrections: 1.0000  1.0000
%PatternPhaseCorrections: 205.00  205.00
%PatternAmplitudeCalculations: 16.8800  7.3200
%PatternPhaseCalculations: 0.00  -16.22
%RadialMusicParameters: 40.000 20.000 2.000
%MergedCount: 7
%RadialMinimumMergePoints: 2
%FirstOrderCalc: 0
%MergeMethod: 1 MedianVectors
%PatternMethod: 1 PatternVectors
%TransmitSweepRateHz: 2.000000
%TransmitBandwidthKHz: -49.629688
%SpectraRangeCells: 127
%SpectraDopplerCells: 512
%TableType: LLUV RDL9
%TableColumns: 18
%TableColumnTypes: LOND LATD VELU VELV VFLG ESPC ETMP MAXV MINV ERSC ERTC XDST YDST RNGE BEAR VELO HEAD SPRC
%TableRows: 1075
%TableStart:
%%   Longitude   Latitude    U comp   V comp  VectorFlag    Spatial    Temporal     Velocity     Velocity  Spatial  Temporal  X Distance  Y Distance   Range   Bearing   Velocity  Direction    Spectra
%%     (deg)       (deg)     (cm/s)   (cm/s)  (GridCode)    Quality     Quality      Maximum      Minimum    Count    Count       (km)        (km)       (km)    (True)    (cm/s)     (True)    RngCell
  -156.0604833  19.7561857   0.000   -9.957          0    999.000      18.527        9.957        9.957        1        7      0.0000      3.0224    3.0224     0.0      9.957     180.0          1
  -156.0579700  19.7560818  -0.536   -6.122          0      6.294      16.393       14.313       -5.290        7        5      0.2634      3.0109    3.0224     5.0      6.145     185.0          1
  -156.0554757  19.7557708  -3.047  -17.275          0      8.421      16.317       39.208       -6.380        4        6      0.5248      2.9765    3.0224    10.0     17.542     190.0          1
```

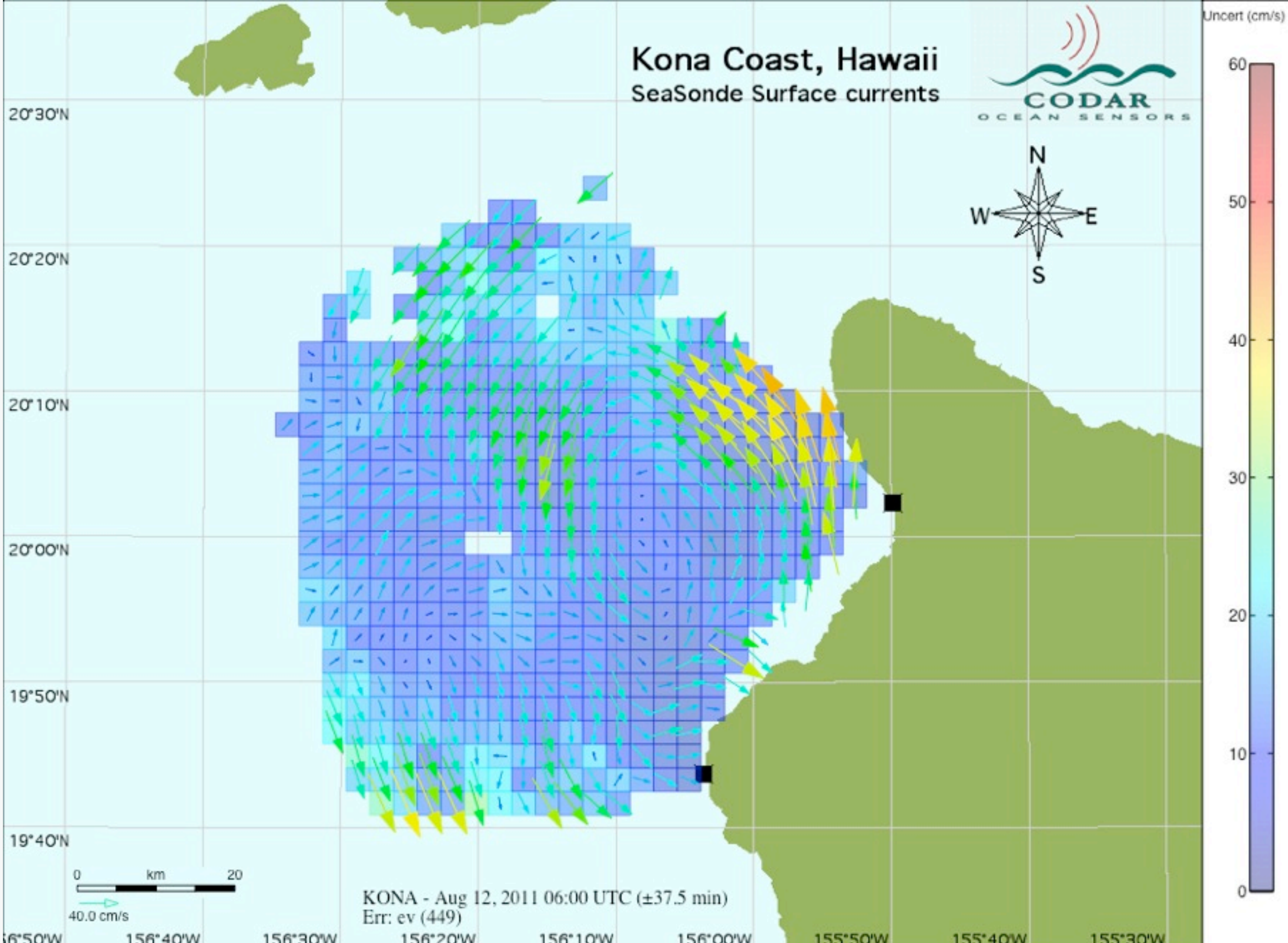
SeaSonde QA/QC

Antenna Pattern Measurement/Calibration
1st Order Bragg Identification Algorithms
Vessel Echo Detection & Removal
Ionospheric Echo Detection & Rejection
Burst Noise (Lightning) Removal
Outlier Removal
Radio Signal Interference Rejection Per-Doppler
Solution SNR thresholds
MUSIC parameter thresholding


Kona Coast, Hawaii
SeaSonde Surface currents
CODAR
OCEAN SENSORS
N
W
E
S
Vel (cm/s)
100
90
80
70
60
50
40
30
20
10
0
20°30'N
20°20'N
20°10'N
20°00'N
19°50'N
19°40'N
0
km
20
OTEC - Aug 12, 2011 06:00 UTC (±37.5 min)
156°40'W
156°30'W
156°20'W
156°10'W
156°00'W
155°50'W
155°40'W
155°30'W


Kona Coast, Hawaii
SeaSonde Surface currents
CODAR
OCEAN SENSORS
N
W
E
S
Vel (cm/s)
100
90
80
70
60
50
40
30
20
10
0
20°30'N
20°20'N
20°10'N
20°00'N
19°50'N
19°40'N
0
km
20
40.0 cm/s
ROBO, OTEC Aug 12, 2011 06:00 to 06:00 UTC
156°50'W
156°40'W
156°30'W
156°20'W
156°10'W
156°00'W
155°50'W
155°40'W
155°30'W


Kona Coast, Hawaii
SeaSonde Surface currents
CODAR
OCEAN SENSORS
N
W
E
S
Vel (cm/s)
100
90
80
70
60
50
40
30
20
10
0
20°30'N
20°20'N
20°10'N
20°00'N
19°50'N
19°40'N
0
km
20
40.0 cm/s
KONA - Aug 12, 2011 06:00 UTC (±37.5 min)
156°40'W
156°30'W
156°20'W
156°10'W
156°00'W
155°50'W
155°40'W
155°30'W


Kona Coast, Hawaii
SeaSonde Surface currents
CODAR
OCEAN SENSORS
N
W
E
S
Uncert (cm/s)
60
50
40
30
20
10
0
20°30'N
20°20'N
20°10'N
20°00'N
19°50'N
19°40'N
0 km 20
40.0 cm/s
KONA - Aug 12, 2011 06:00 UTC (±37.5 min)
Err: ev (449)
156°40'W
156°30'W
156°20'W
156°10'W
156°00'W
155°50'W
155°40'W
155°30'W

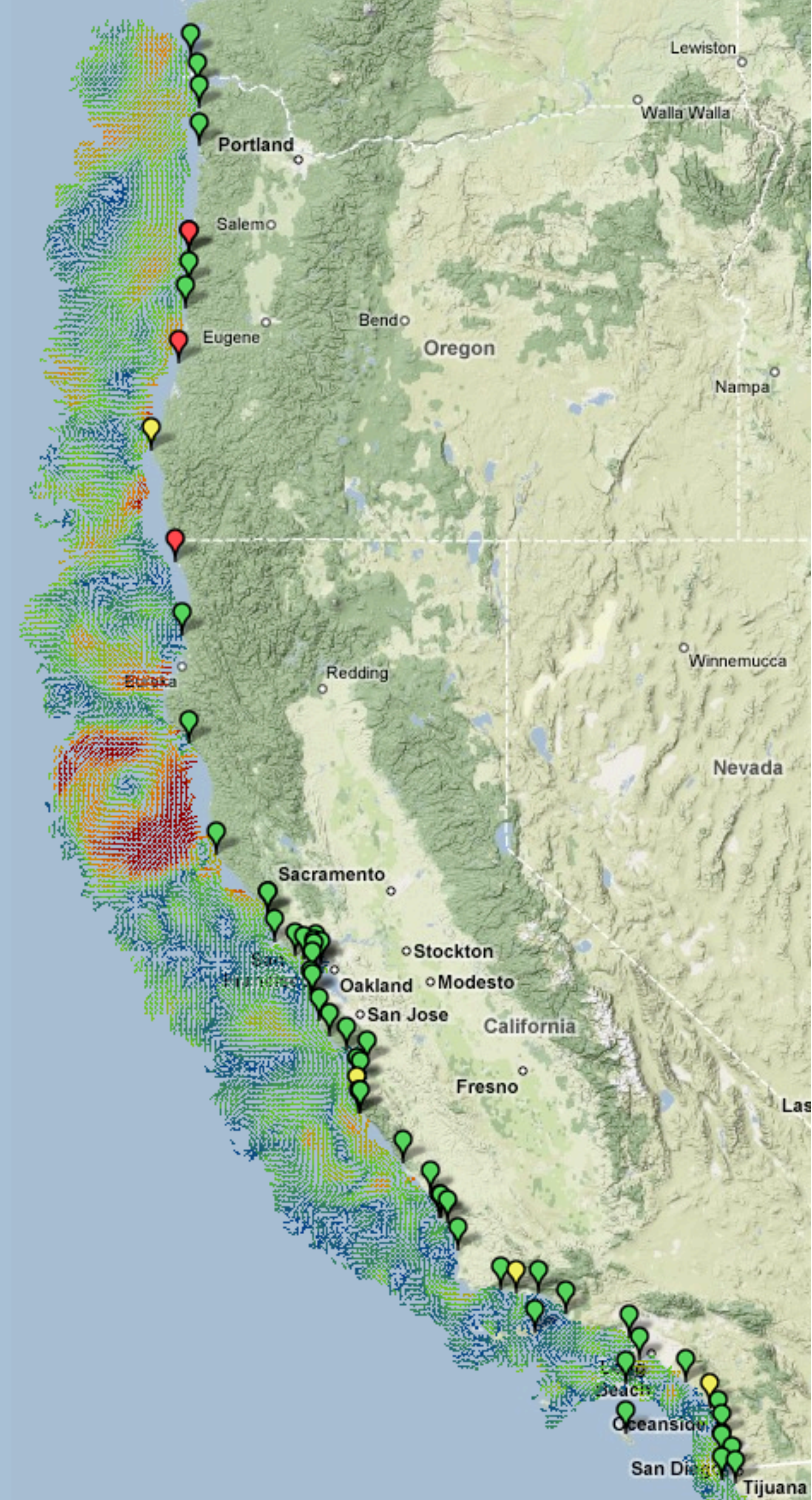
Example Total Vector File

```
%CTF: 1.00
%FileType: LLUV tots "CurrentMap"
%LLUVSpec: 1.15  2010 11 23
%UUID: 19B1A3E9-5810-424D-AE90-15814E0FB313
%Manufacturer: CODAR Ocean Sensors. SeaSonde
%Site: KONA ""
%TimeStamp: 2011 08 12  06 00 00
%TimeZone: "UTC" +0.000 0 "Atlantic/Reykjavik"
%TimeCoverage: 75.000 Minutes
%Origin:  20.0193538 -156.3350283
%GreatCircle: "WGS84" 6378137.000  298.257223562997
%GeodVersion: "CGEO" 1.57  2009 03 10
%LLUVTrustData: all %% all lluv xyuv rbvd
%CombineMethod: 1
%GridAxisOrientation: 0.0 True
%GridCreatedBy: SeaDisplay 5.1.5
%GridVersion: 4
%GridTimeStamp: 4  2010 12 01  00 00 00
%GridLastModified: 2011 08 24  17 32 59
%GridAxisOrientation: 0.0 DegNCW
%GridAxisType: 6
%GridSpacing: 3.000 km
%AveragingRadius: 4.000 km
%DistanceAngularLimit: 20.0
%CurrentVelocityLimit: 200.0 cm/s
%% SiteSource # Name  Lat          Lon     Coverage(s) RngStep(km)  Pattern AntBearing(NCW)
%SiteSource:  1 ROBO  20.0380167 -155.8309667   75.00     3.022 Meas     305.0  Radial
%SiteSource:  2 OTEC  19.7288833 -156.0604833   75.00     3.022 Ideal    315.0  Radial
%TableType: LLUV TOT4
%TableColumns: 20
%TableColumnTypes: LOND LATD VELU VELV VFLG UQAL VQAL CQAL XDST YDST RNGE BEAR VELO HEAD S1CN S2CN S3CN S4CN S5CN S6CN
%TableRows: 454
%TableStart:
%%   Longitude   Latitude   U comp   V comp  VectorFlag  U StdDev   V StdDev  Covariance  X Distance  Y Distance    Range  Bearing  Velocity  Direction  Site Contributers
%%     (deg)       (deg)    (cm/s)   (cm/s)  (GridCode)   Quality    Quality    Quality      (km)        (km)       (km)   (True)    (cm/s)    (True)    #1  #2  #3  #4  #5  #6
  -156.5645561  20.1276008  10.255   11.078          0     7.020     10.570    -63.400    -24.0000     12.0000   26.8328   296.6    15.096      42.8     2   3   0   0   0   0
  -156.5355901  19.9108430   7.408   14.071          0     3.540     16.500     25.930    -21.0000    -12.0000   24.1868   240.3    15.902      27.8     2   4   0   0   0   0
  -156.5356243  19.9379424  10.923   -2.944          0     4.120     19.490     51.850    -21.0000     -9.0000   22.8473   246.8    11.313     105.1     2   3   0   0   0   0
  -156.5356586  19.9650417  15.062    7.129          0     3.450     14.150     10.360    -21.0000     -6.0000   21.8403   254.1    16.664      64.7     2   4   0   0   0   0
  -156.5356929  19.9921409  14.219   10.698          0     2.920     12.010     -2.130    -21.0000     -3.0000   21.2132   261.9    17.794      53.0     2   3   0   0   0   0
  -156.5357273  20.0192400  16.729    7.306          0     3.180     12.240    -17.780    -21.0000      0.0000   21.0000   270.0    18.255      66.4     2   4   0   0   0   0
  -156.5357617  20.0463391  17.123    1.180          0     3.090     13.360    -13.190    -21.0000      3.0000   21.2132   278.1    17.164      86.1     2   3   0   0   0   0
  -156.5357961  20.0734380  17.086    5.003          0     6.410     12.730    -58.690    -21.0000      6.0000   21.8403   285.9    17.803      73.7     2   4   0   0   0   0
  -156.5358306  20.1005369  17.345   13.885          0     6.350     10.030    -51.700    -21.0000      9.0000   22.8473   293.2    22.218      51.3     2   2   0   0   0   0
  -156.5358651  20.1276357  12.495    6.871          0     5.420      9.580    -41.520    -21.0000     12.0000   24.1868   299.7    14.260      61.2     3   4   0   0   0   0
  -156.5358997  20.1547344  10.975   -2.427          0     6.680     14.240    -68.080    -21.0000     15.0000   25.8070   305.5    11.240     102.5     2   2   0   0   0   0
  -156.5359343  20.1818331   0.188   -8.537          0     7.330     12.540    -73.330    -21.0000     18.0000   27.6586   310.6     8.539     178.7     2   2   0   0   0   0
  -156.5359690  20.2089316   5.800   -3.909          0     9.410     10.650    -90.720    -21.0000     21.0000   29.6985   315.0     6.994     124.0     2   3   0   0   0   0
  -156.5067922  19.7753748  17.080  -43.486          0     9.500     22.410    181.760    -18.0000    -27.0000   32.4500   213.7    46.720     158.6     2   4   0   0   0   0
  -156.5068214  19.8024746  14.937  -36.198          0     7.570     23.640    110.380    -18.0000    -24.0000   30.0000   216.9    39.159     157.6     2   3   0   0   0   0
  -156.5068506  19.8295744  12.339  -26.007          0     6.310     19.430     50.700    -18.0000    -21.0000   27.6586   220.6    28.786     154.6     2   5   0   0   0   0
```

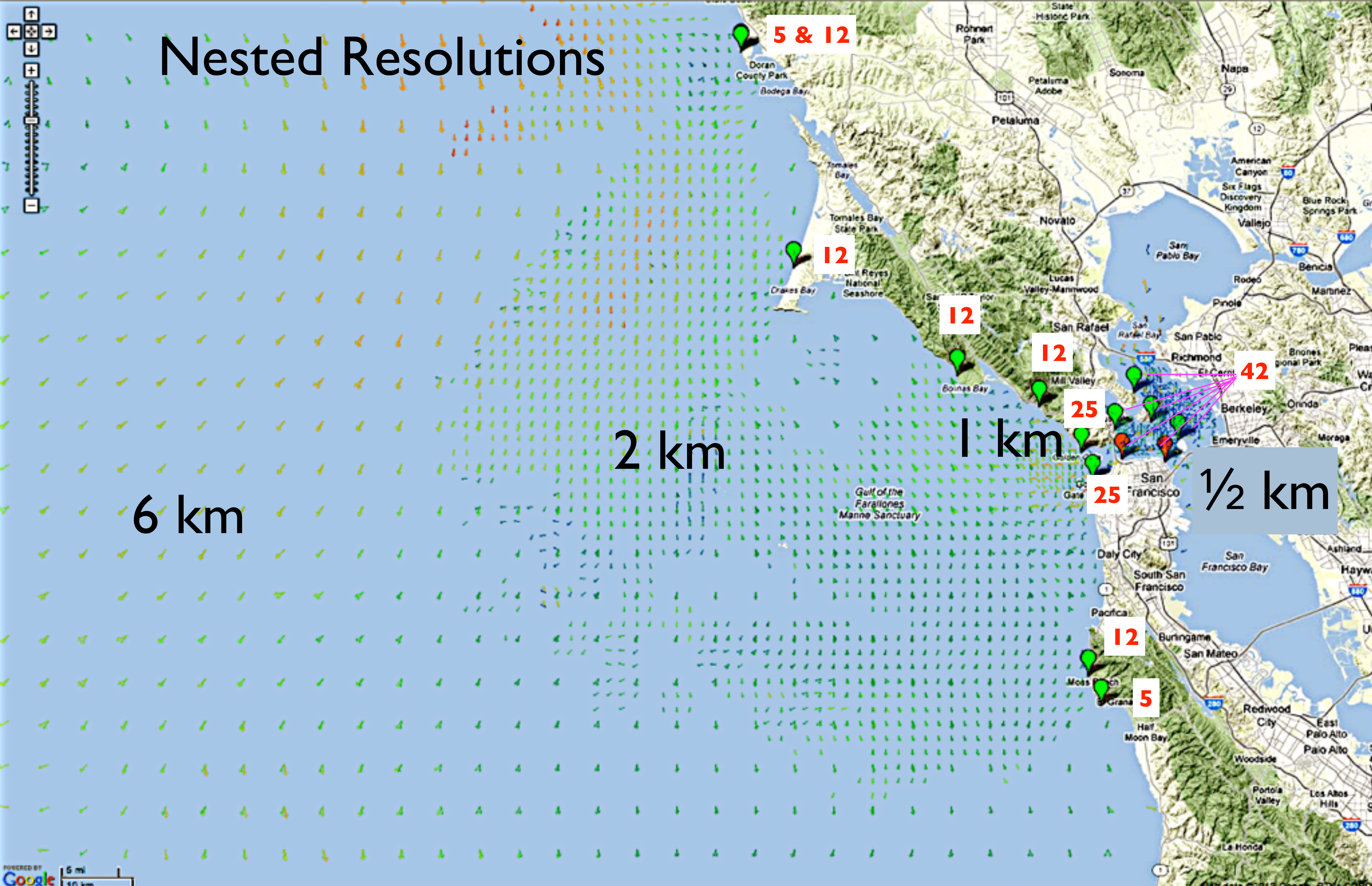
Regional/National Networks

Case Study: U.S. West Coast

- 60+ SeaSondes
- Mixed frequencies: 5, 13, 25, 42
- Nested Resolutions
- >2000 km of coastline covered



Nested Resolutions



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Validations

Lipa et al (2009), HF Radar Bistatic Measurement of Surface Current Velocities: Drifter Comparisons and Internal Radar Consistency Checks, Remote Sensing, vol. 1, pp. 1190-2111.

Ohlmann, C., P. White, L. Washburn, E. Terrill, B. Emery and M. Otero, 2007: Interpretation of Coastal HF Radar-Derived Surface Currents with High-Resolution Drifter Data, J. Atmospheric and Oceanic Technology, vol. 24, pp. 666-680.

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Barrick, D., P. Lilleboe, B. Lipa, L. Pederson, and J. Issacson (1999), Circulation Mapping in Complex Waterways. Sea Technology, Oct., pp. 19-21.

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Validations

Hubbard, M., D. Barrick, N. Garfield, J. Pettigrew, C. Ohlmann, and M. Gough. "*A New Method for Estimating High-Frequency Radar Error Using Data from Central San Francisco Bay.*" *Ocean Science Journal, 1-12 (2013)*

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Ullman, D., et. al. (June 2003), *"Use of Coastal Ocean Dynamics Application Radar (CODAR) Technology in U.S. Coast Guard Search and Rescue Planning", U.S. Coast Guard Research and Development Center Report No. CG-D-09-03.*

Network Monitoring
&
Data Management

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Bergen, Norway
June 10, 2013

SeaSonde Radial Site RATH

- Status
- Details
- Radials
- Ellipticals
- Waves
- Spectra
- Diags
- Logs
- Archives
- Settings

Alerts

Nothing To Report (for 1 hour 46 mins).

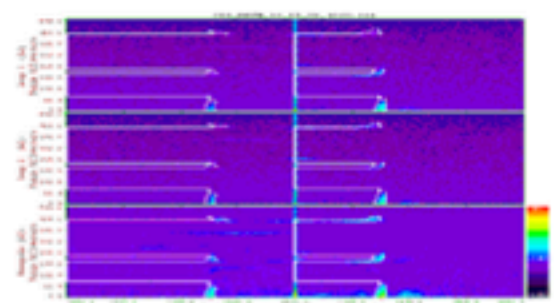
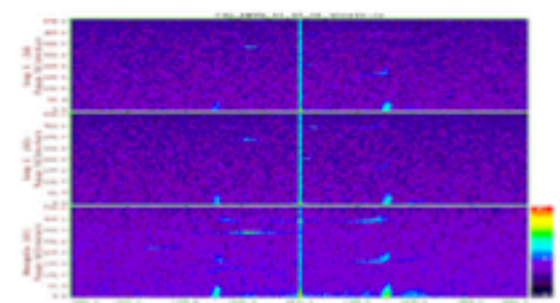
Site RATH

RATH Strathmere, NJ Rutgers-BPU 13MHz CODAR Site
SeaSonde Standard Range
Located 39°11.921'N,074°39.151'W, **Bearing** 198.0° NCW
CF 13.450000 MHz, **BW** -49.630 kHz, **GPS Alignment** 26300.0 us
Blanking 668.8us with **Pulse Shaping** with **Blank Delay** 8.6 us
Site Time 2013-06-09 10:33:05 UTC

Radials

2013-06-09 09:00 UTC Meas ±37.5 min.	2013-06-09 09:00 UTC Ideal ±37.5 min.	2013-06-09 09:37 UTC Meas -25.2 hr.
		

Spectra

2013-06-09 10:20 UTC CSS covers ±7.5 min.	2013-06-09 10:24:29 UTC CSQ covers +4.0 min.
	

SeaSonde Radial Site RATH

Admin Sign Out
2013-06-09
10:36:08 GMT

- Status
- Details
- Radials
- Ellipticals
- Waves
- Spectra
- Diags
- Logs
- Archives
- Settings

Site

RATH Strathmere, NJ Rutgers-BPU 13MHz CODAR Site
SeaSonde Standard Range
Located 39°11.921'N,074°39.151'W, **Bearing** 198.0° NCW
CF 13.450000 MHz, **BW** -49.630 kHz, **GPS Alignment** 26300.0 us
Blanking 668.8us with **Pulse Shaping** with **Blank Delay** 8.6 us
Site Time 2013-06-09 10:35:05 UTC

Alerts

Nothing To Report (for 1 hour 48 mins).

Receiver

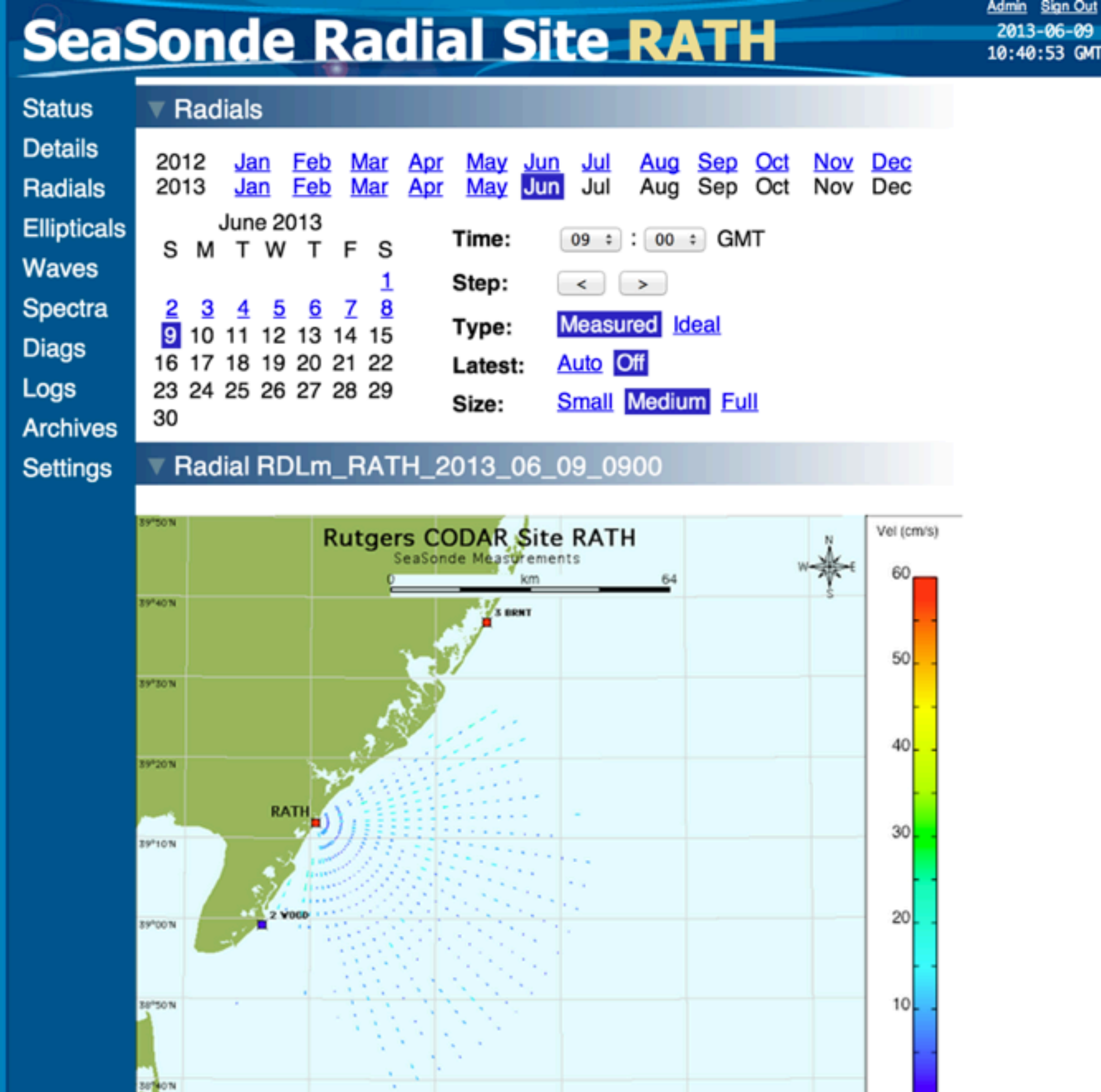
SeaSonde Receiver·SSRX-USB-AWGIII-02011336
CODAR Advanced Waveform Generator III
Firmware Version 3.10 May 5, 2012 Timing 633A Acquisition 9301
Running for 10 hours 18 minutes and 33.0 seconds
Chassis Temperature is 29.1 °C
Humidity 50% with a Dewpoint of 1.2°C
Power Supplies are good at +5.1V, -5.0V and +12.2V

Transmitter

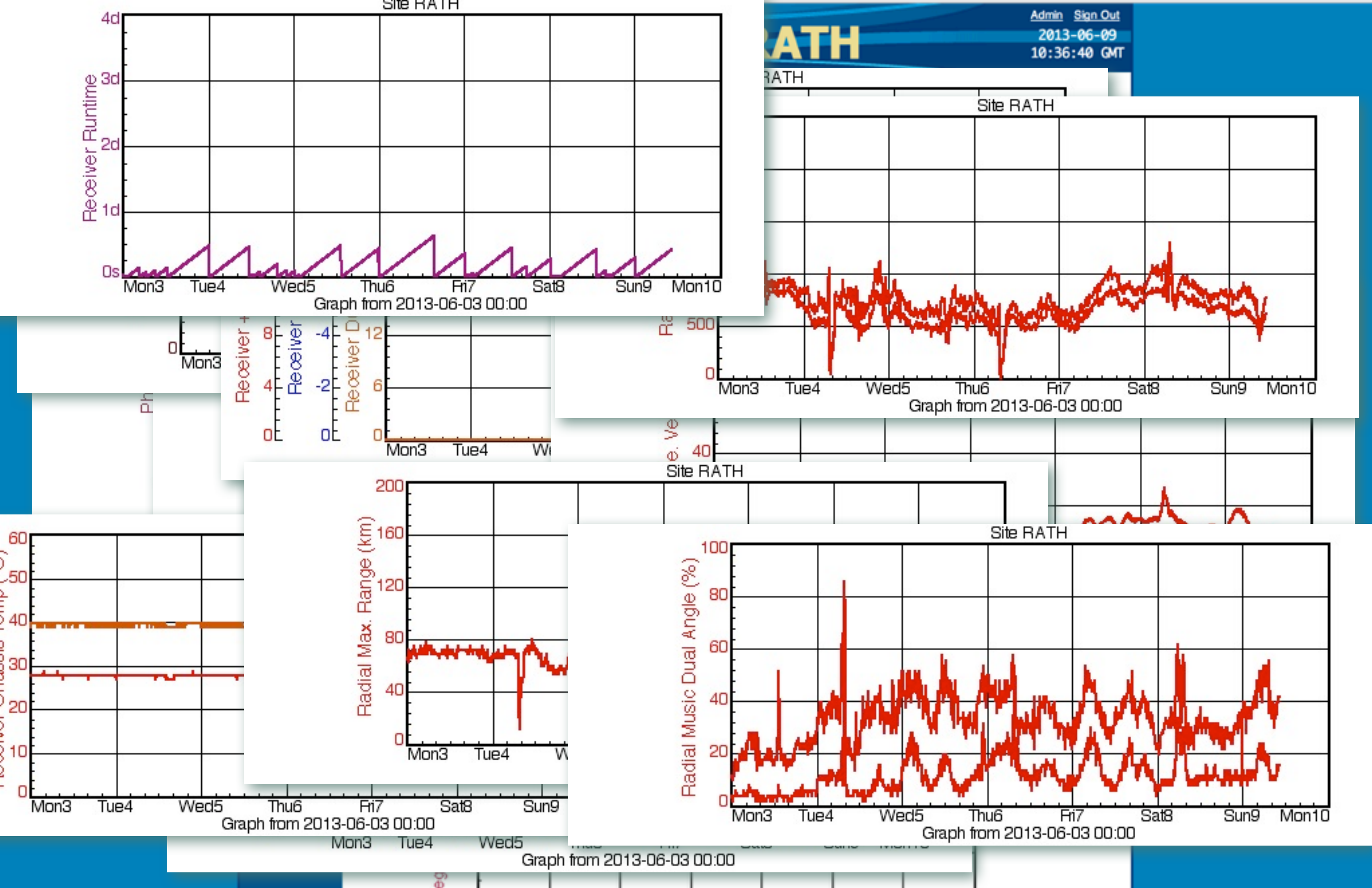
Power 33 Watts Forward, 0 Watt Reflected, VSWR 1.1:1
Chassis Temperature 27.0 °C
Amplifier Temperature 31.0 °C
Power Supplies are good at +5.0V and +24.2V

Data

Logging Range Series at 180 ranges by 512 sweeps.
Logging CrossSpectra at 359 ranges by 512 dopplers
Logging CrossSpectra at 359 ranges by 512 dopplers at 8.0x rate
Logging CrossSpectra at 359 ranges by 256 dopplers at 4.0x rate
Logging CrossSpectra at 359 ranges by 128 dopplers at 2.0x rate
-



SeaSonde Radial Site RATH
Admin Sign Out
2013-06-09
10:40:53 GMT
Status
Details
Radials
Ellipticals
Waves
Spectra
Diags
Logs
Archives
Settings
Radials
2012 Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2013 Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
June 2013
S M T W T F S
1
2 3 4 5 6 7 8
9 10 11 12 13 14 15
16 17 18 19 20 21 22
23 24 25 26 27 28 29
30
Time: 09 : 00 GMT
Step: < >
Type: Measured Ideal
Latest: Auto Off
Size: Small Medium Full
Radial RDLm_RATH_2013_06_09_0900
Rutgers CODAR Site RATH
SeaSonde Measurements
0 km 64
RATH
Vel (cm/s)
60
50
40
30
20
10



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Bergen, Norway
June 10, 2013

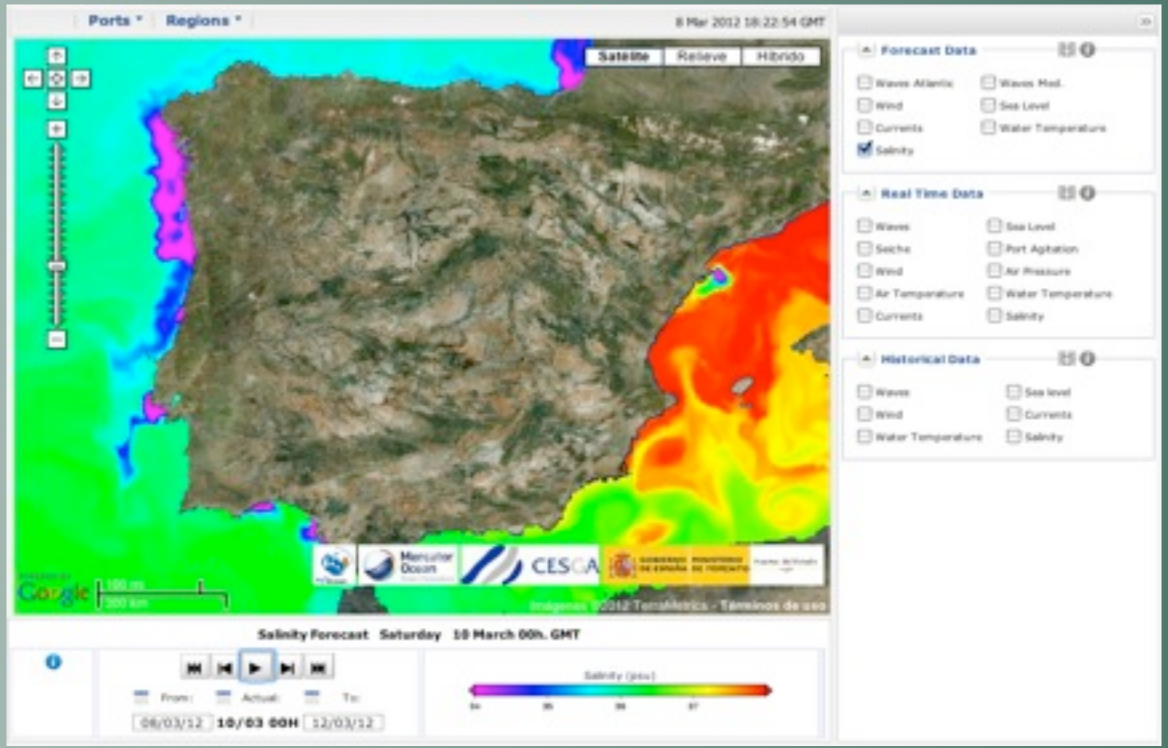
PORTUS
A SeaSonde-centered marine information system

The main aim of PORTUS is to enhance the utility and usability of SeaSonde HF radar data

PORTUS provides a multi-user, easy-to-use geographical interface to foster HF radar data use and data sharing

PORTUS is also able to manage and integrate data from other measurement instruments and models and fuse them with SeaSonde

Surface currents in Algeciras Port



MyOcean Salinity Model in PORTUS

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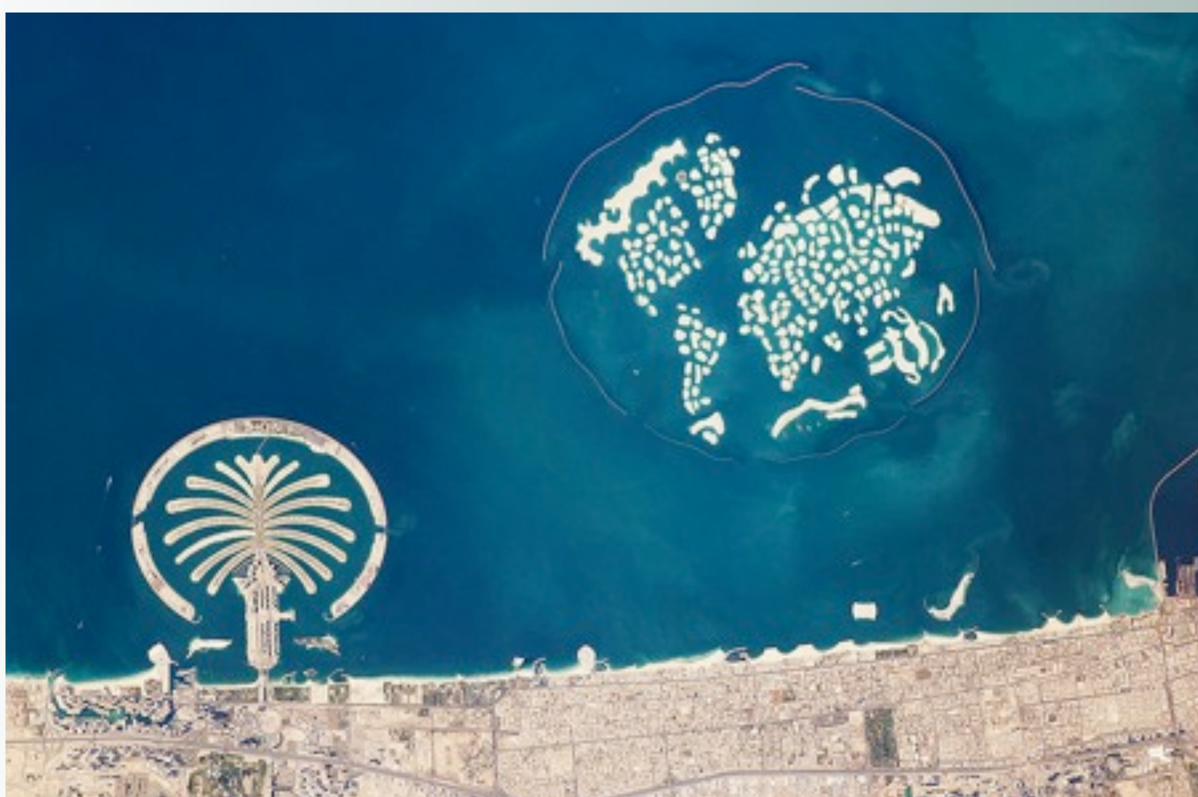
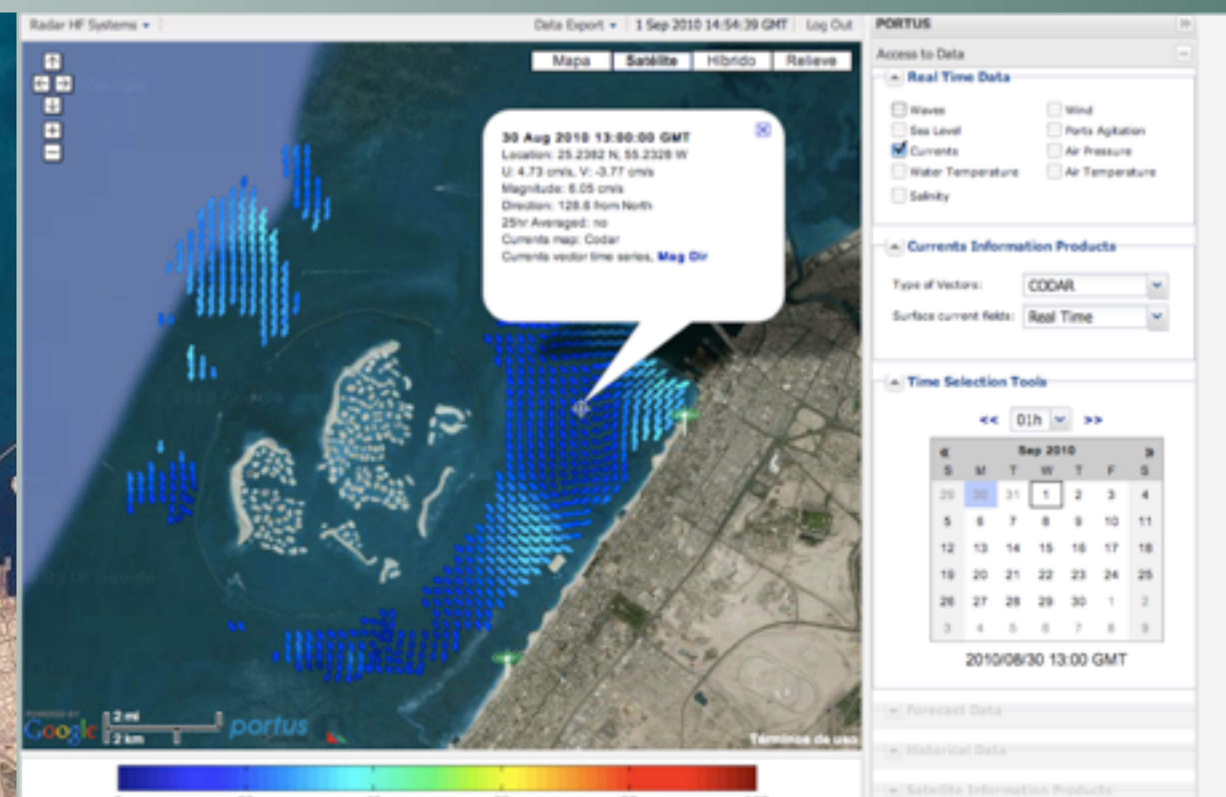
Bergen, Norway
June 10, 2013

General PORTUS features (I)

Reliable and efficient data storage and data management

Powerful and user friendly Google maps based web interface





Dubai SeaSonde HF radar data in PORTUS

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June 10, 2013

General PORTUS features (II)

3. Seamless importation and integration of all surface currents and waves data into third party IT systems

Formats:
Codar, ASCII, GRIB, netCDF, Data Layers, Kml, Kmz

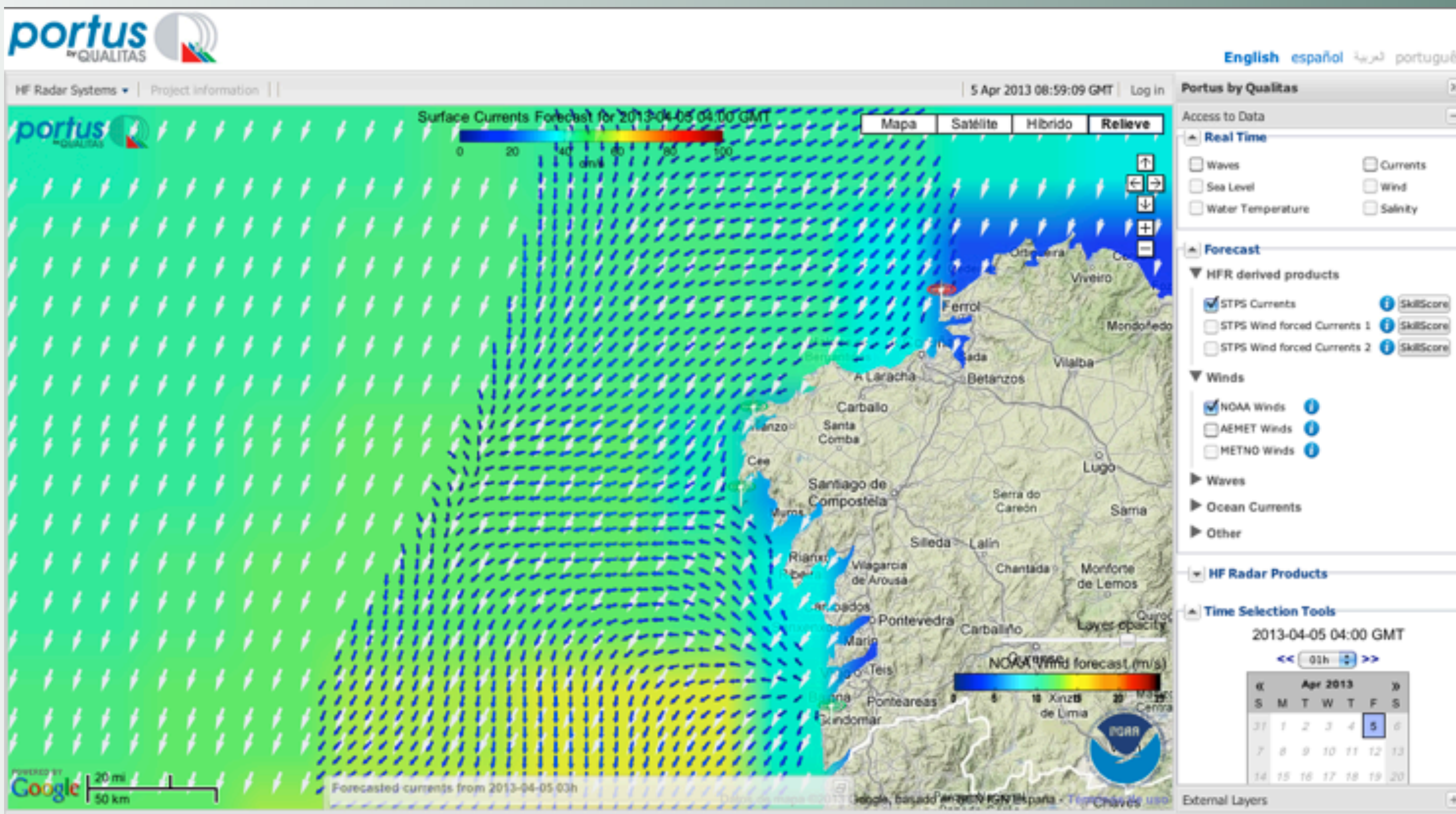
Protocols:
OPEnDAP
FTP
WMS

4. Extra monitoring and reporting tools to track systems status and the physical medium status

General PORTUS features (III)

5. Value added data products based on SeaSonde: STPS

- Surface Currents Short Term Prediction System
- Data fusion with third party observations and models



STPS based on NOAA modeled winds and SeaSonde measured currents

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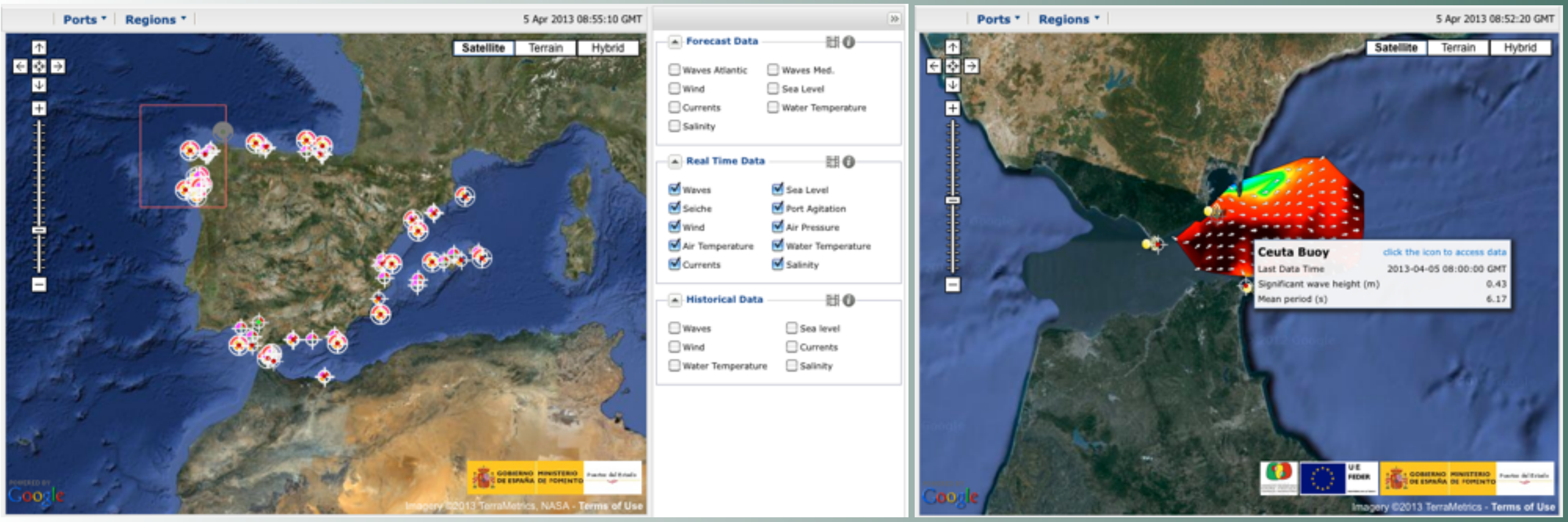
General PORTUS features (IV)

6. Value added data products based on SeaSonde: OPEN
   - 25h average, divergence, convergence maps
   - Comparison with models (currents, waves, SST, etc.)

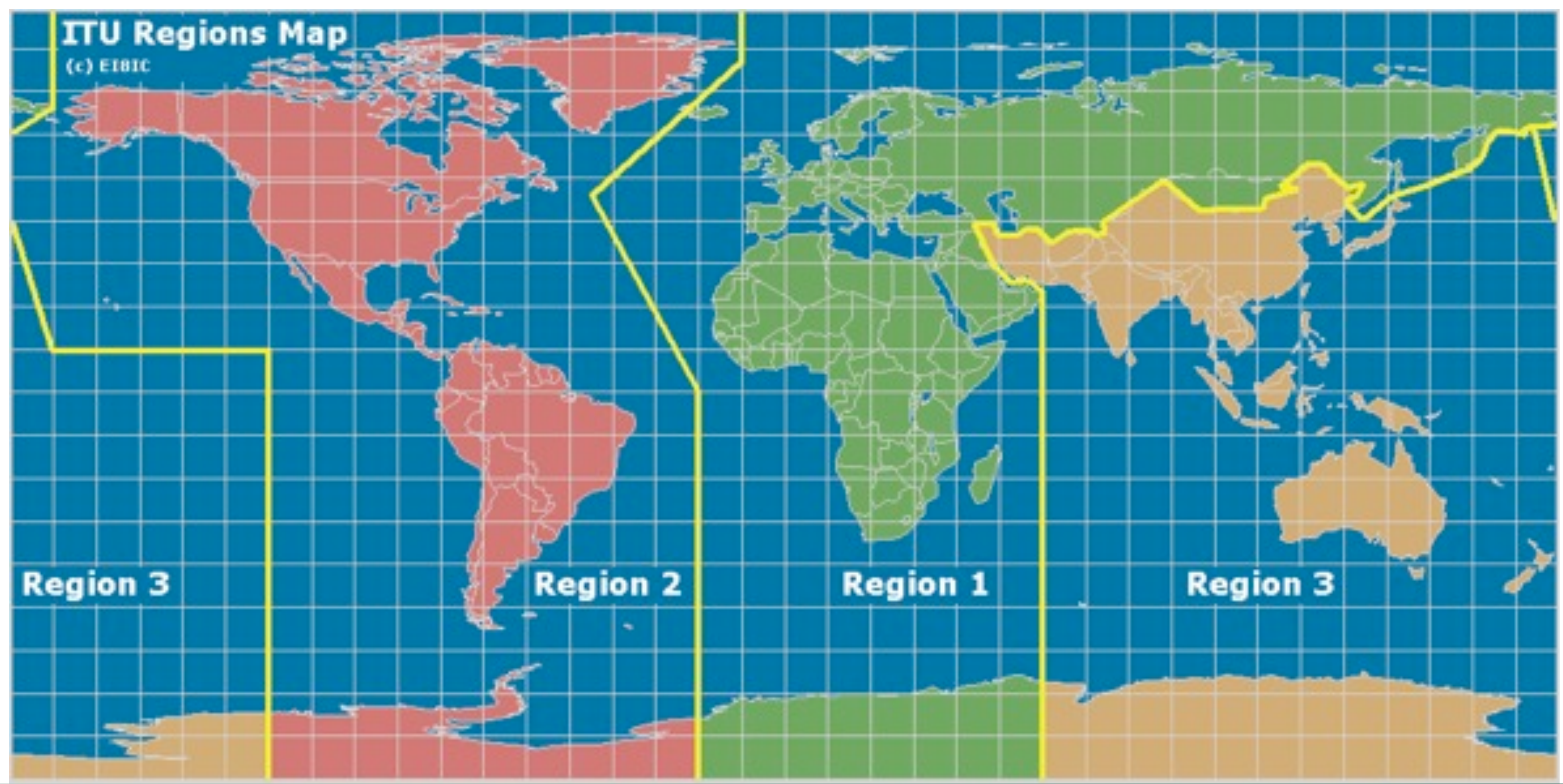


Spanish National Ports and Harbours Authority (PdE) buoy network (left) and Gibraltar Strait HF Radar System in its Portus Marine Information System

SHARE® & Multi-Static

ITU Ocean Radar Frequency Allocations (kHz)

Region 1	Region 2	Region 3
4 438 - 4 488	4 438 - 4 488	4 438 - 4 488
5 250 - 5 275	5 250 - 5 275	5 250 - 5 275
9 305 - 9 355	No allocation	9 305 - 9 355
13 450 - 13 550	13 450 - 13 550	13 450 - 13 550
16 100 - 16 200	16 100 - 16 200	16 100 - 16 200
24 450 - 24 600	24 450 - 24 650	24 450 - 24 600
26 200 - 26 350	26 200 - 26 420	26 200 - 26 350
39 000 - 39 500	No allocation	39 500–40 000
42 000 - 42 500	No allocation	No allocation



Modulation Multiplexing

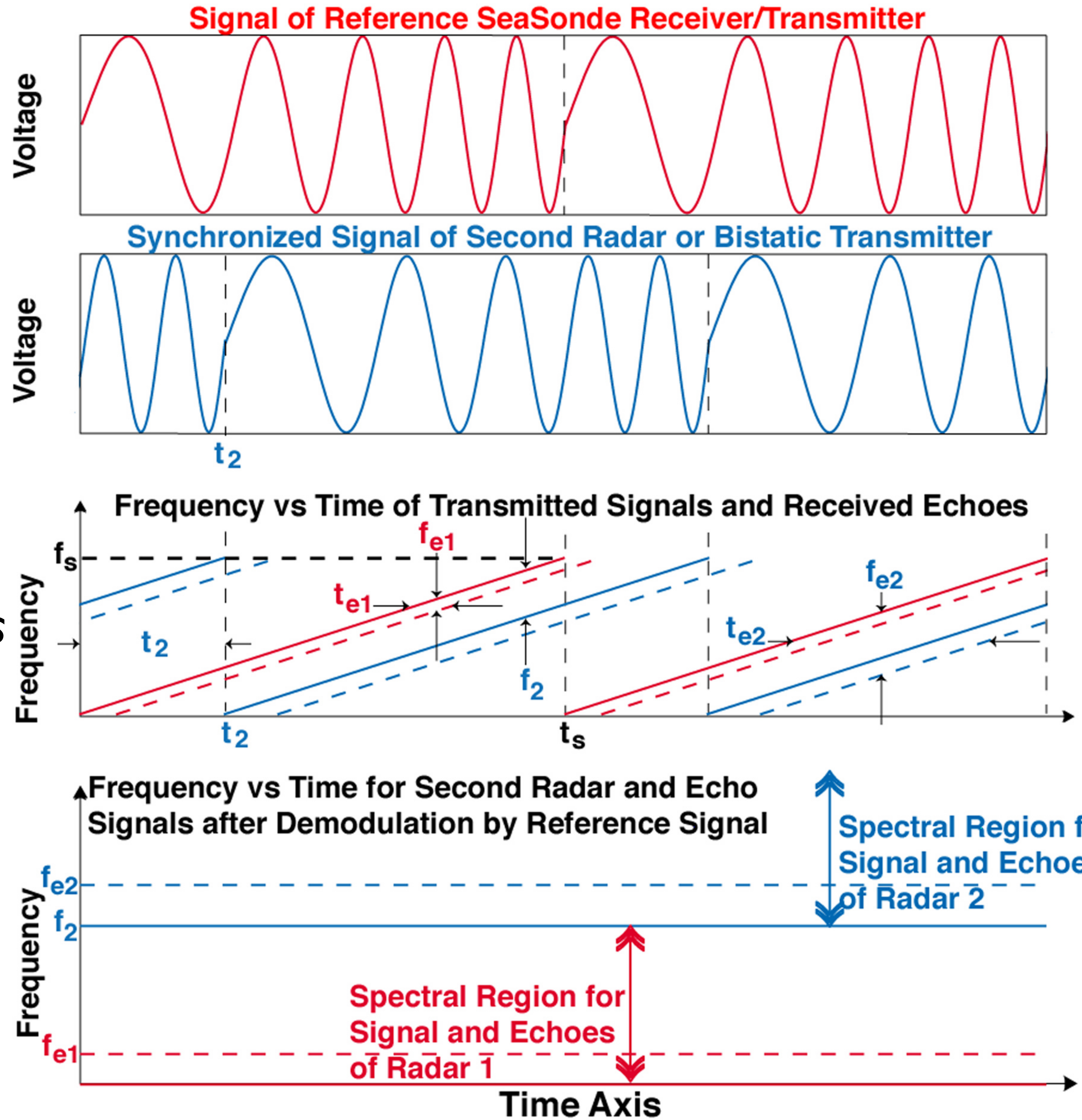
Share Bandwidth

Multiple Systems can sweep through same band without interfering

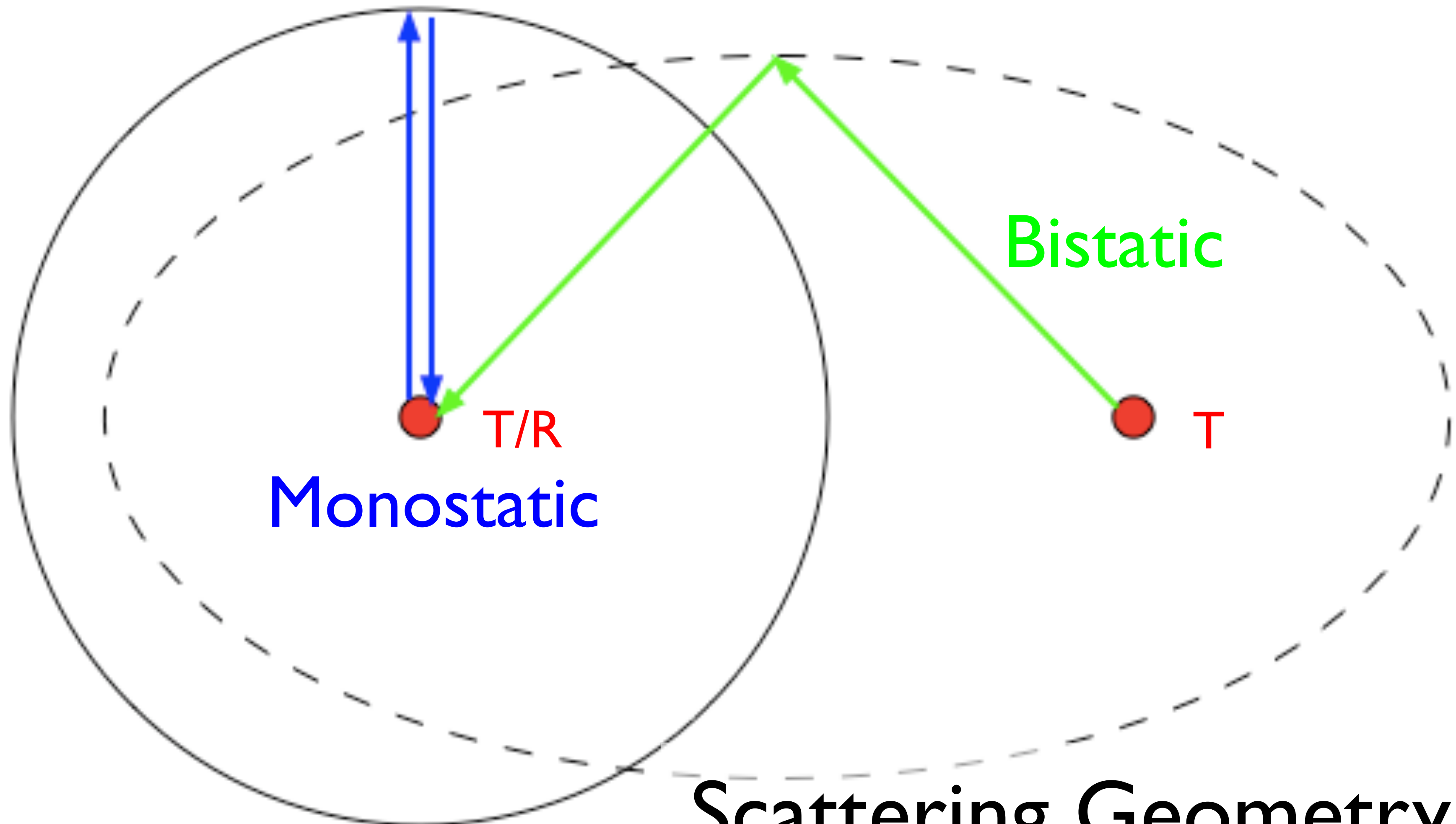
Multistatic Operation

Use Sea echo from another's site's transmission (requires 10^{-11} precision oscillator)*

**CODAR-patented GPS-disciplined oscillator waveform works worldwide*

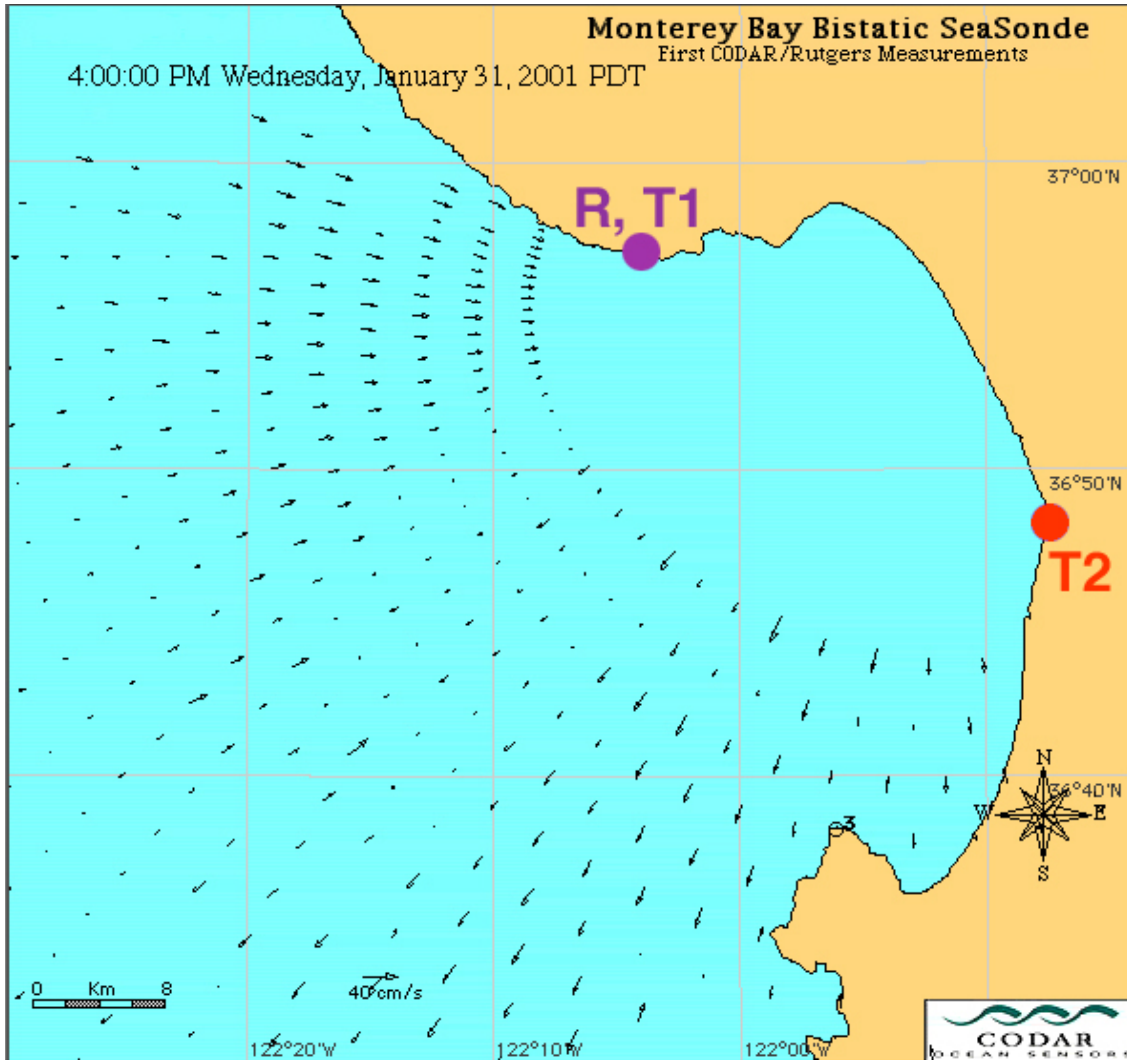


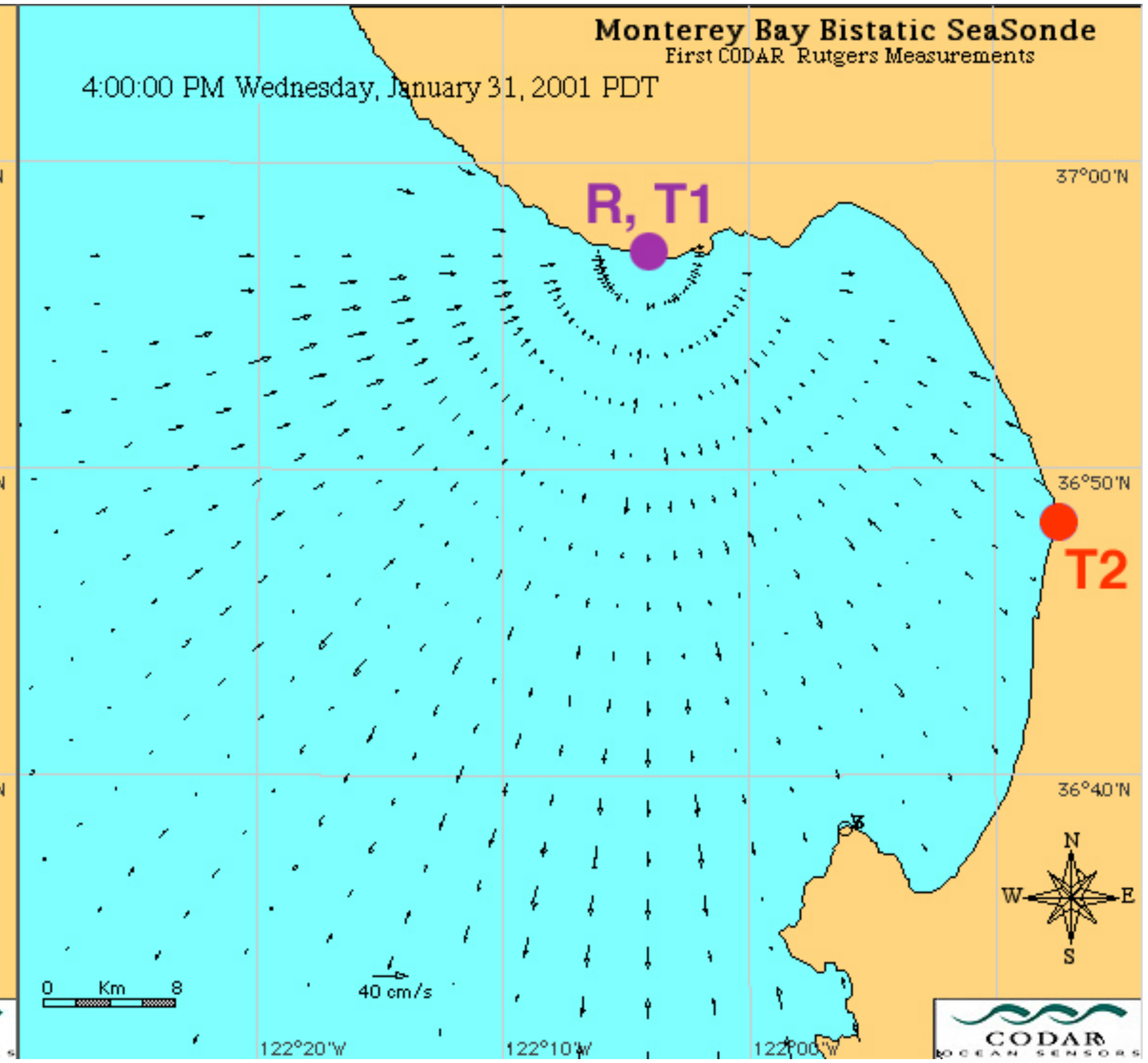
Multi-Static



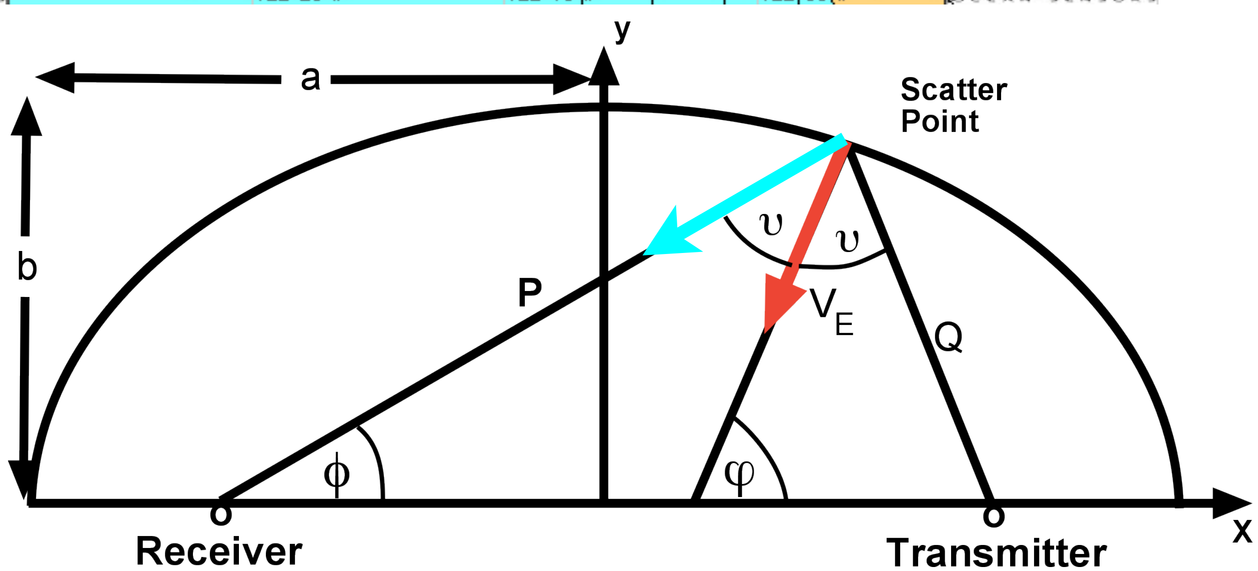
Scattering Geometry

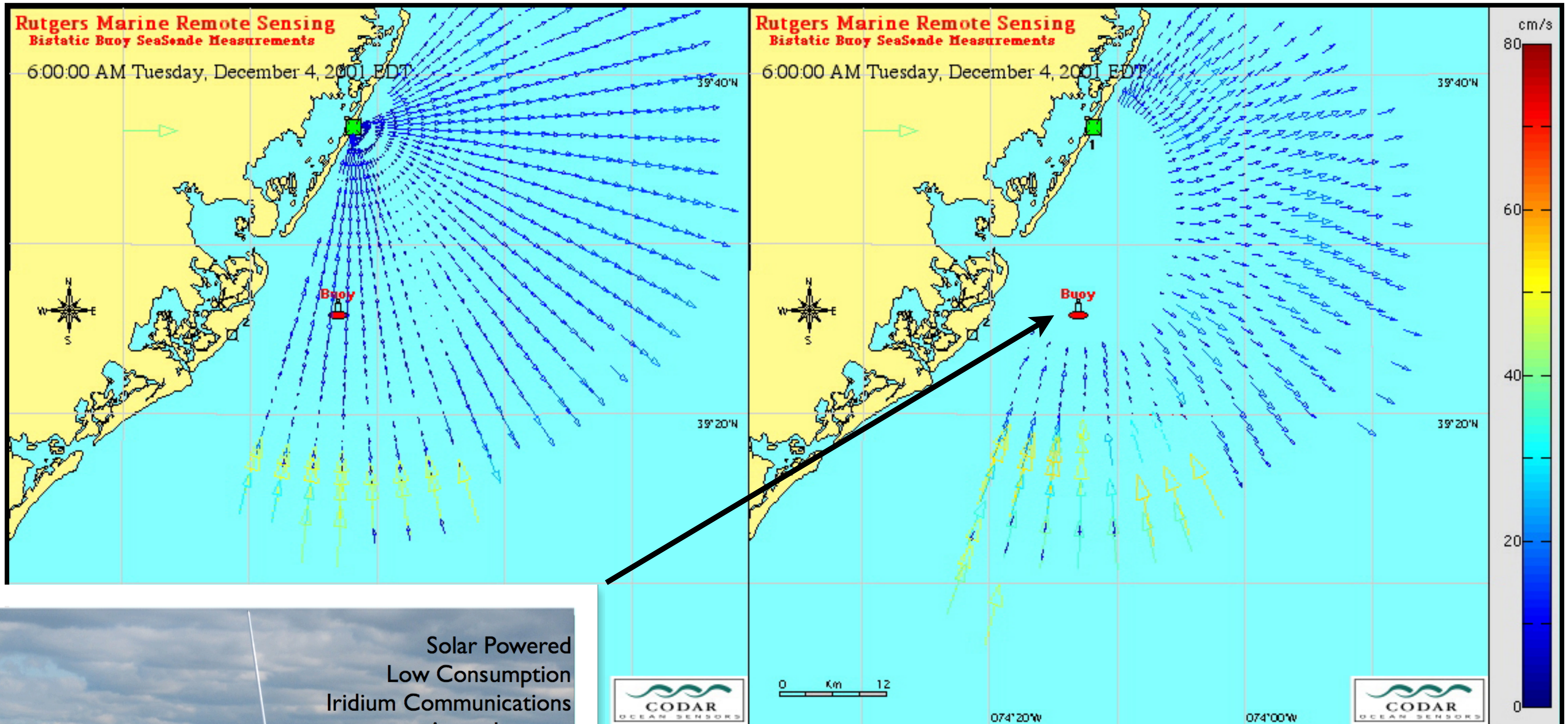
Receive signals and sea echo coherently from multiple other SeaSondes





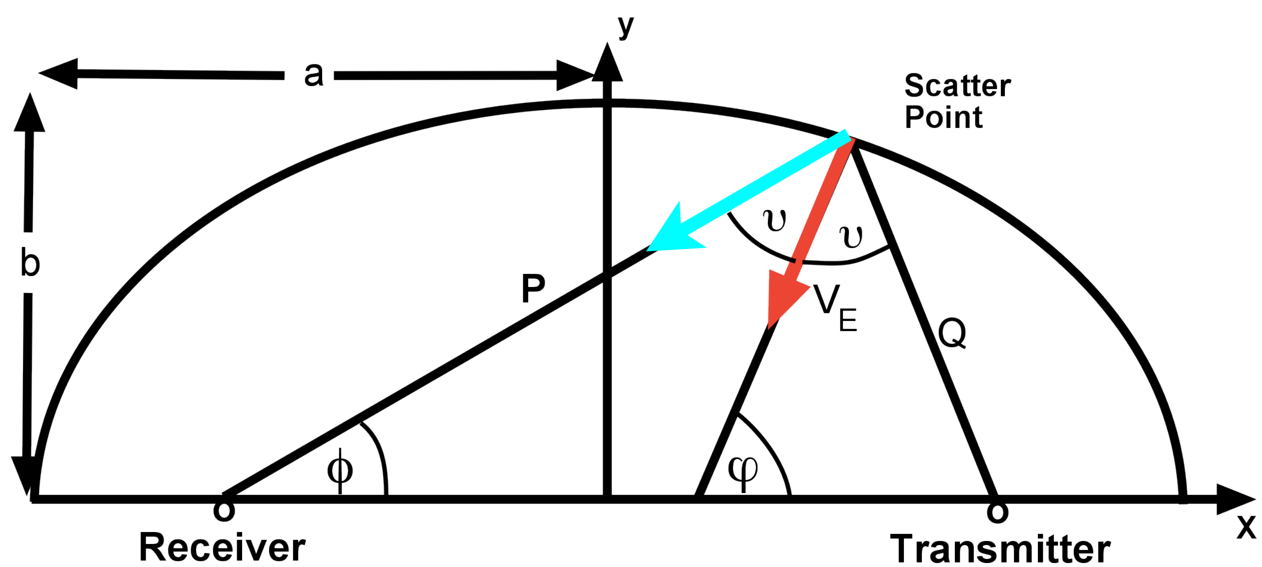
Collect Multi-static data simultaneously with monostatic data



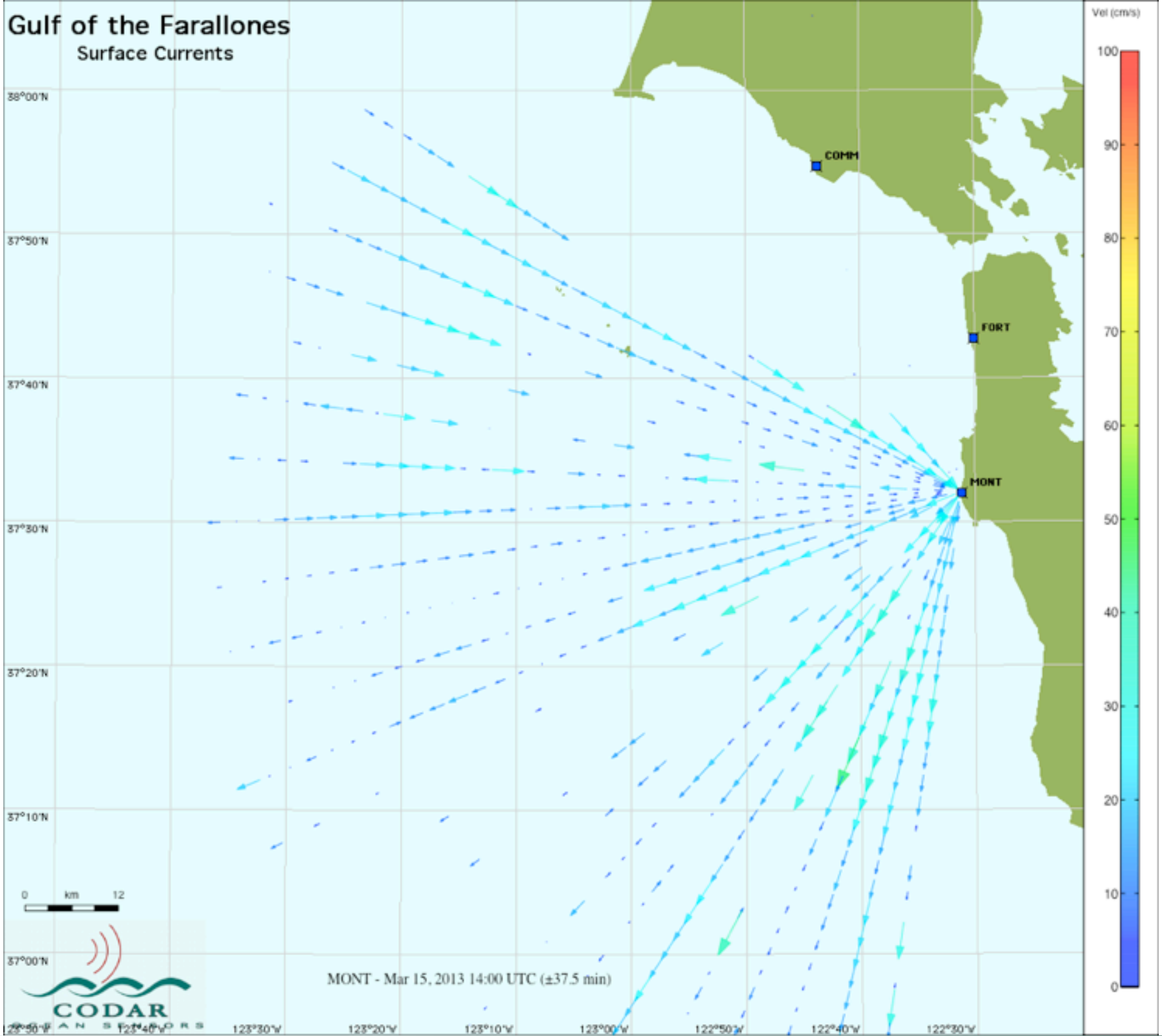


Rutgers Marine Remote Sensing
Bistatic Buoy SeaSonde Measurements
6:00:00 AM Tuesday, December 4, 2001 EDT
39°40'N
39°20'N
Buoy
Rutgers Marine Remote Sensing
Bistatic Buoy SeaSonde Measurements
6:00:00 AM Tuesday, December 4, 2001 EDT
39°40'N
39°20'N
Buoy
0 Km 12
074°20'W
074°00'W
CODAR
cm/s
80
60
40
20
0

Solar Powered
Low Consumption
Iridium Communications
Argos Locator



y
a
b
Scatter Point
υ
υ
P
V_E
Q
ϕ
φ
Receiver
Transmitter
x



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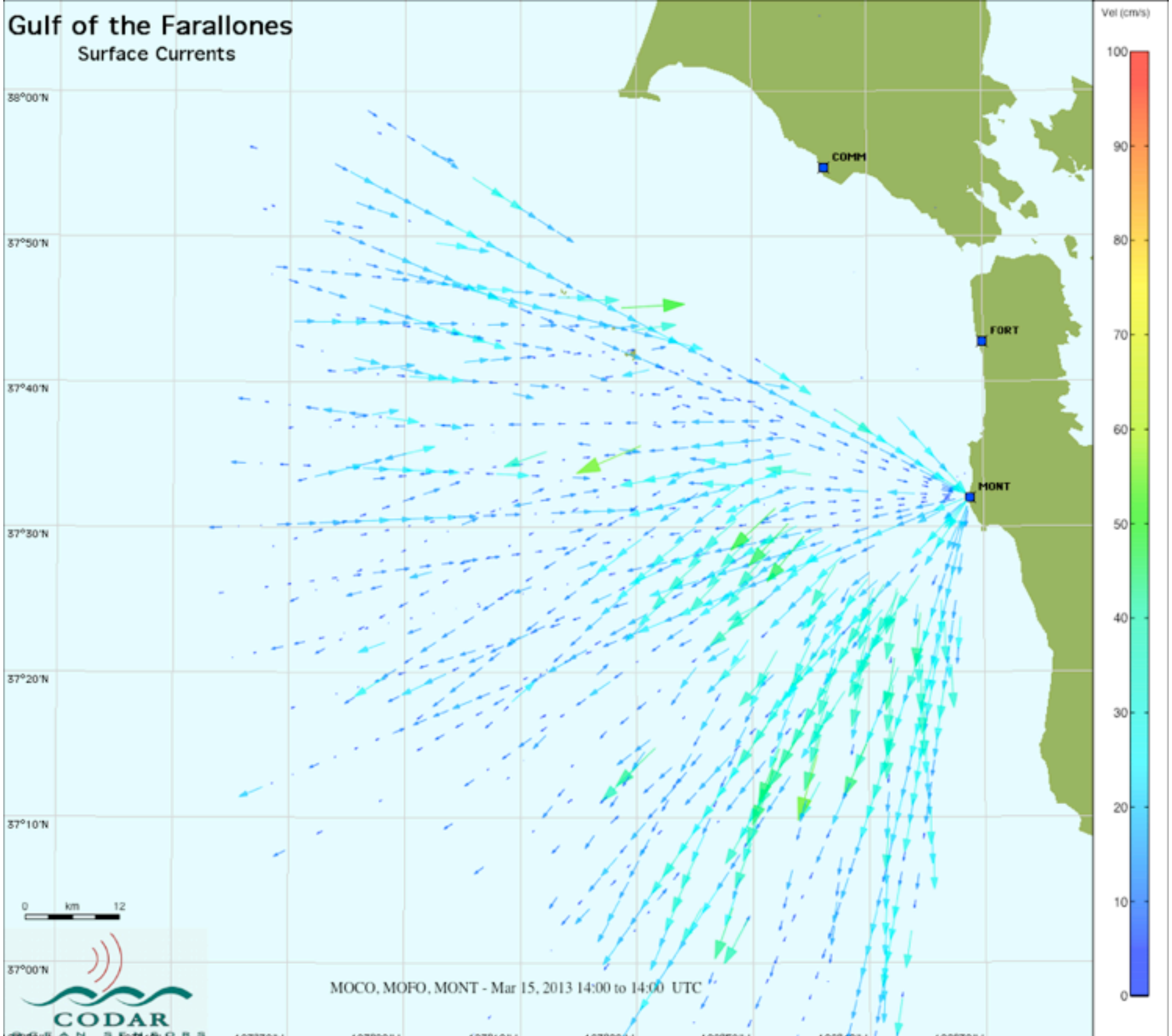
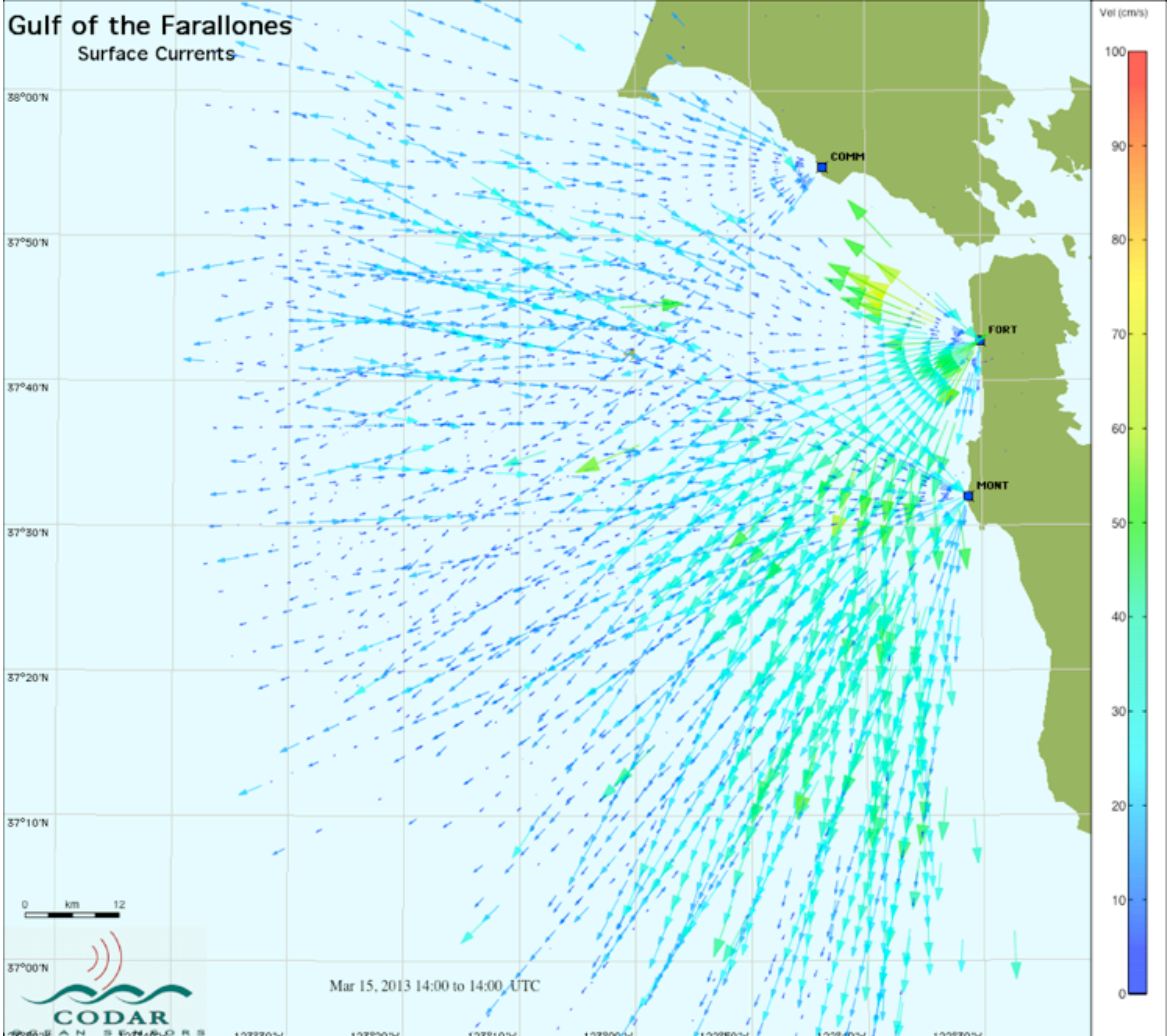


Gulf of the Farallones
Surface Currents
COMM
FORT
MONT
38°00'N
37°50'N
37°40'N
37°30'N
37°20'N
37°10'N
37°00'N
123°30'W
123°20'W
123°10'W
123°00'W
122°50'W
122°40'W
122°30'W
0 km 12
MOCO, MOFO, MONT - Mar 15, 2013 14:00 to 14:00 UTC
CODAR
Vel (cm/s)
100
90
80
70
60
50
40
30
20
10
0


Gulf of the Farallones
Surface Currents
38°00'N
37°50'N
37°40'N
37°30'N
37°20'N
37°10'N
37°00'N
COMM
FORT
MONT
Vel (cm/s)
100
90
80
70
60
50
40
30
20
10
0
km
12
CODAR
Mar 15, 2013 14:00 to 14:00 UTC
123°30'W
123°20'W
123°10'W
123°00'W
122°50'W
122°40'W
122°30'W

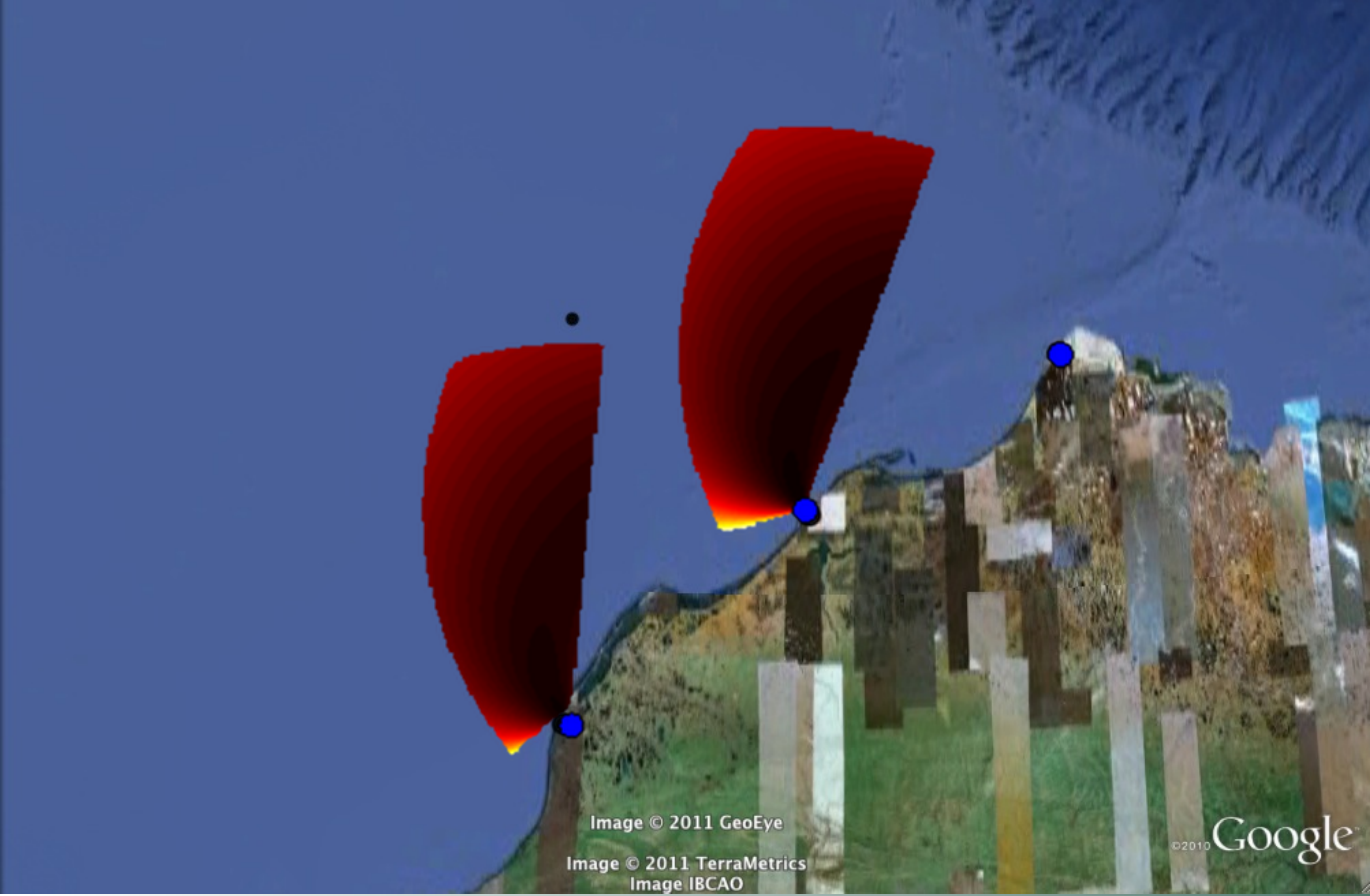


Image © 2011 GeoEye
Image © 2011 TerraMetrics
Image IBCAO
©2010 Google

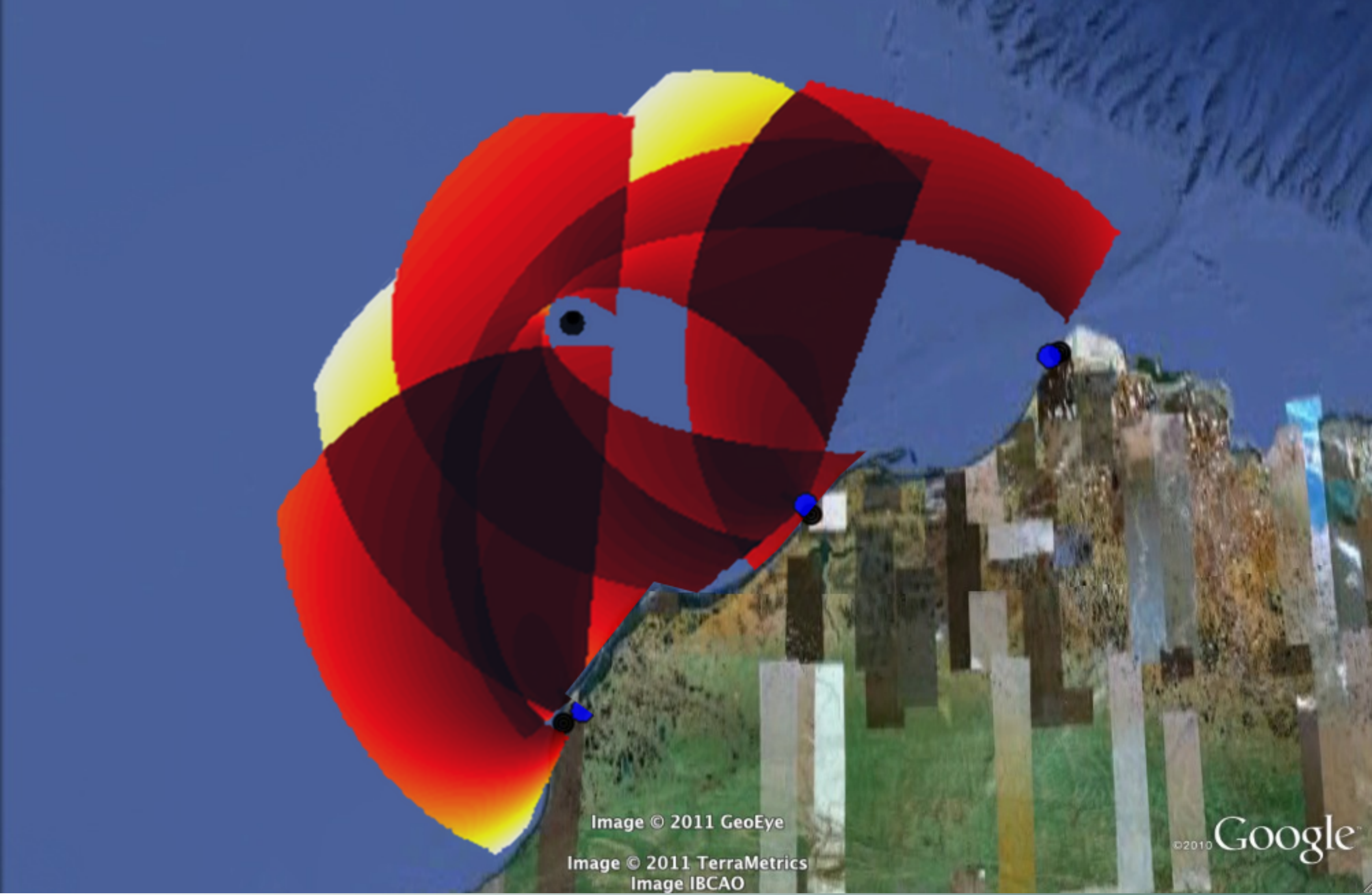


Image © 2011 GeoEye
Image © 2011 TerraMetrics
Image IBCAO
©2010 Google

Open Mode Analysis

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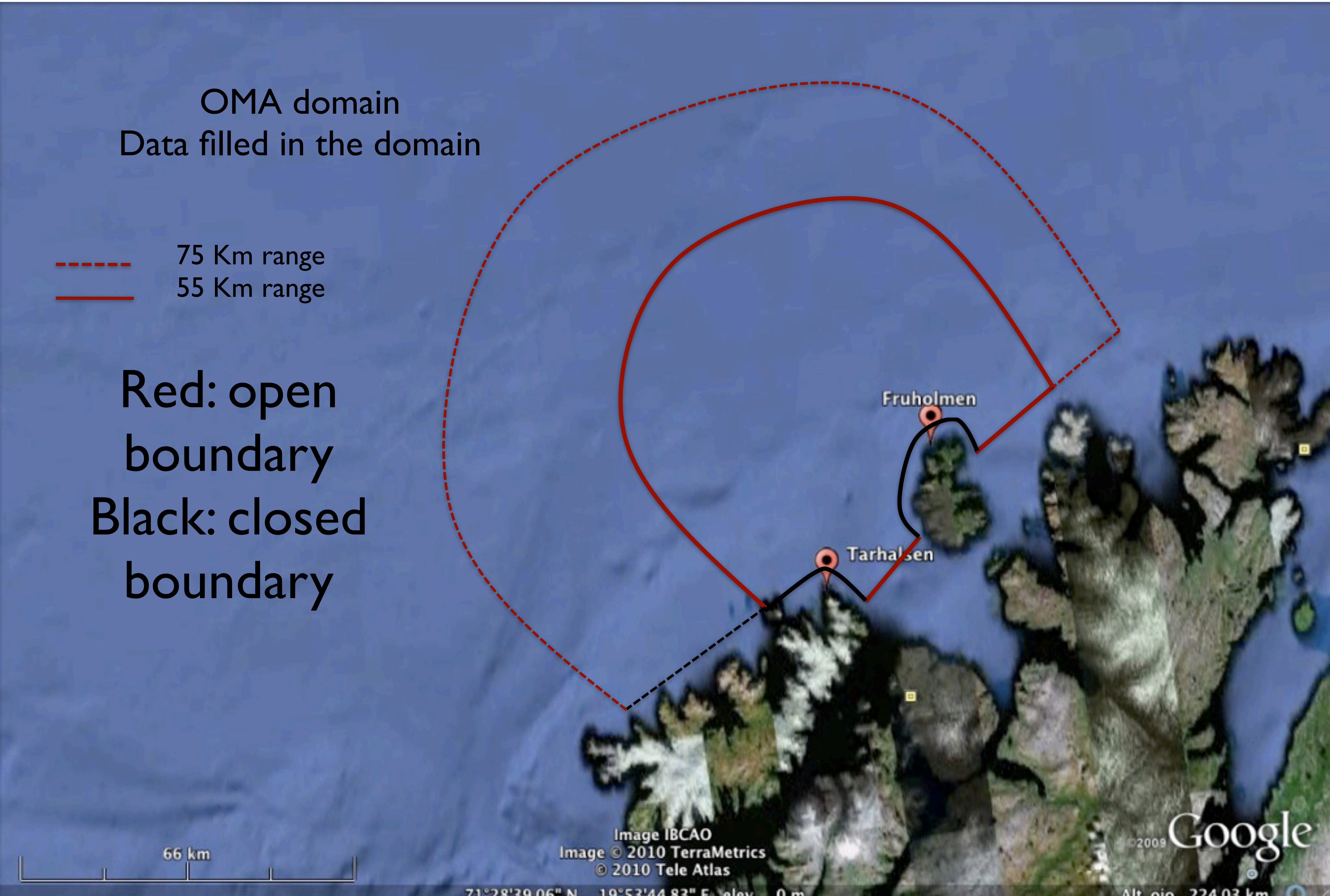
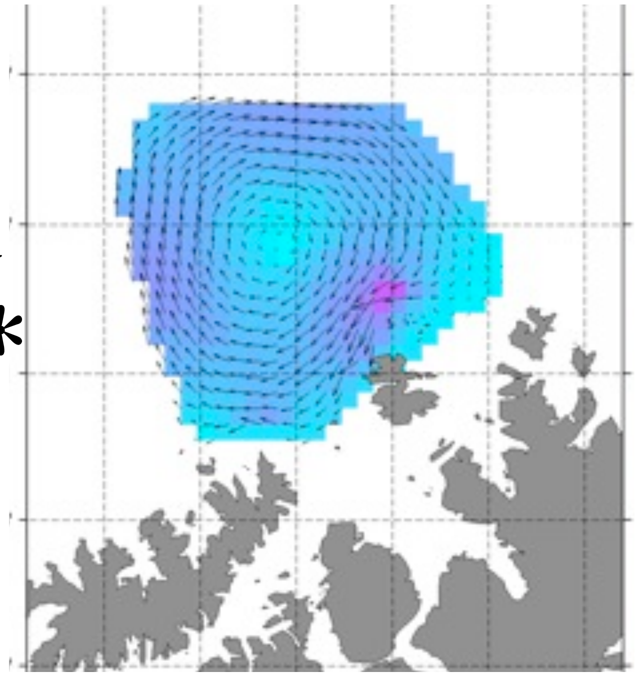
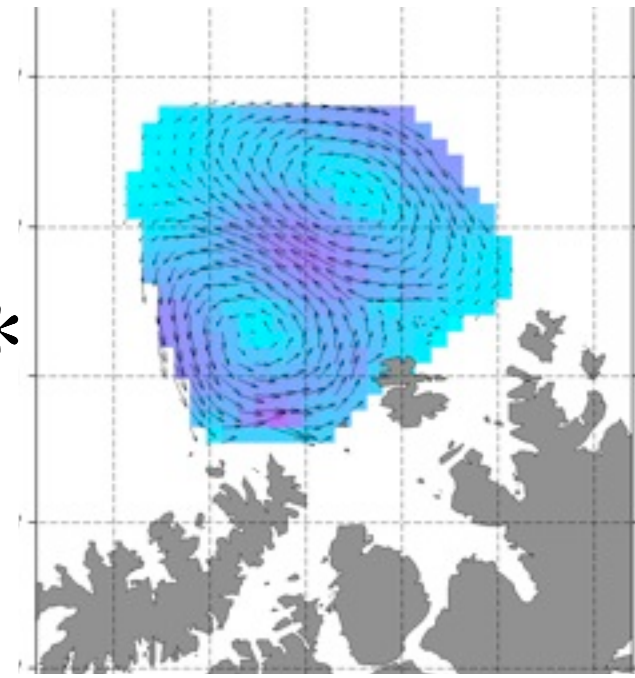
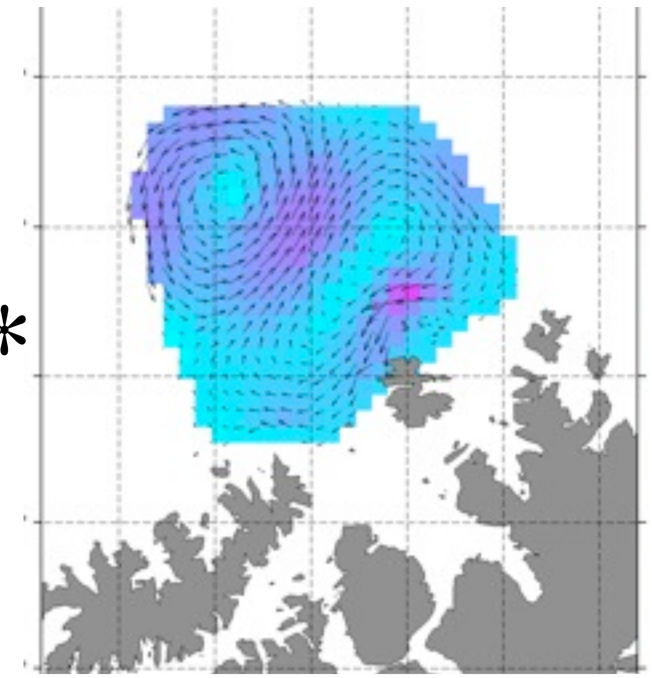
OMA domain
Data filled in the domain

75 Km range
55 Km range

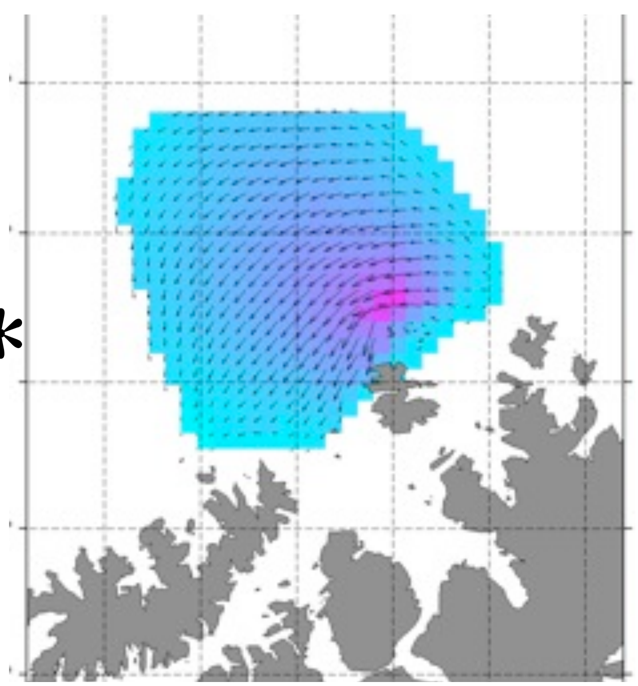
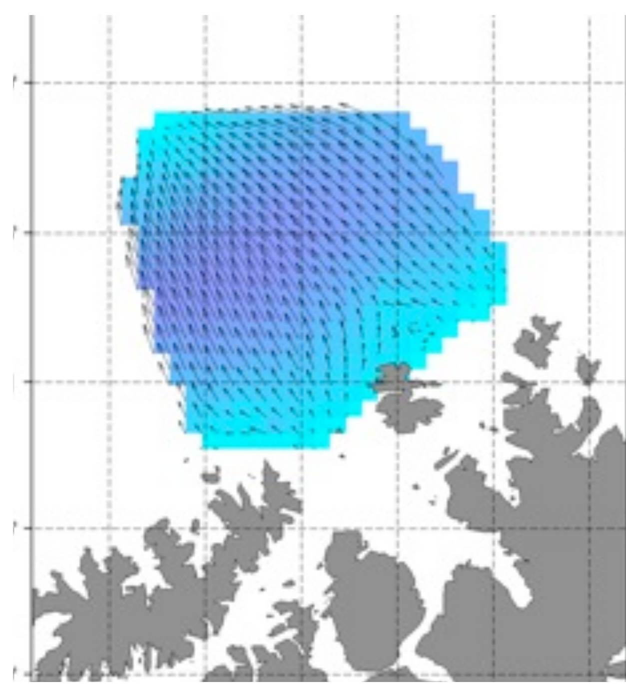
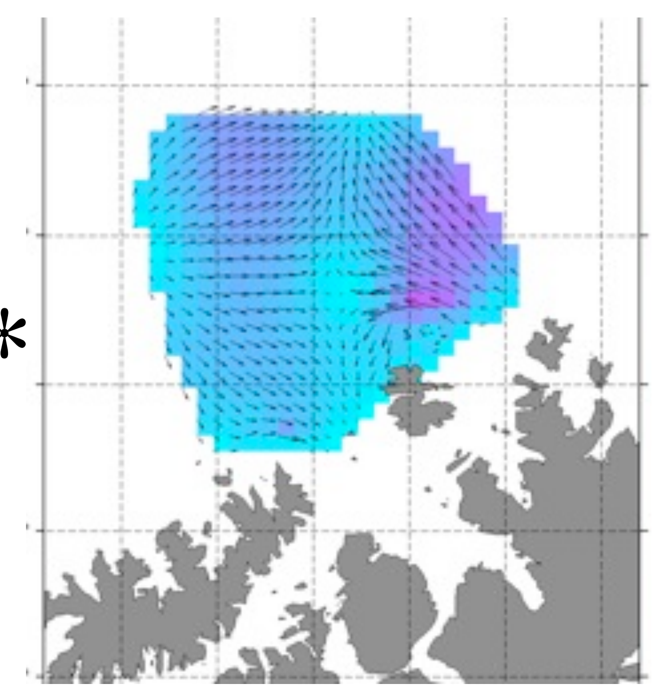
Red: open boundary
Black: closed boundary



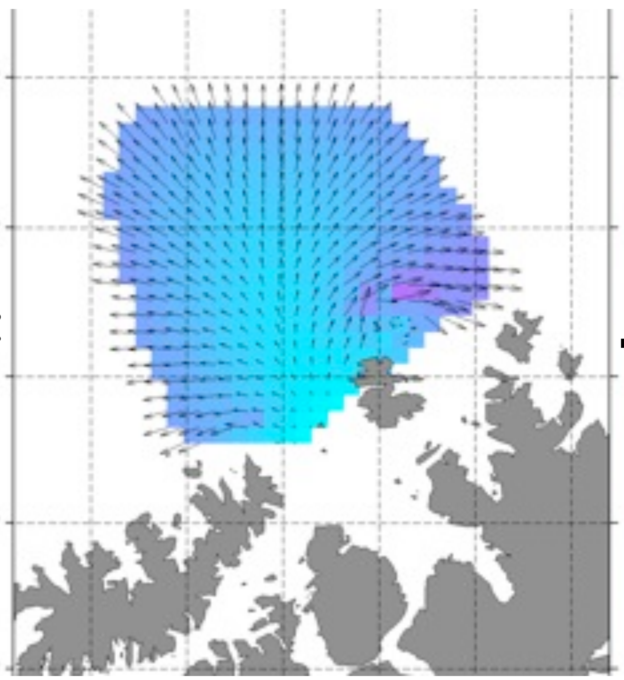
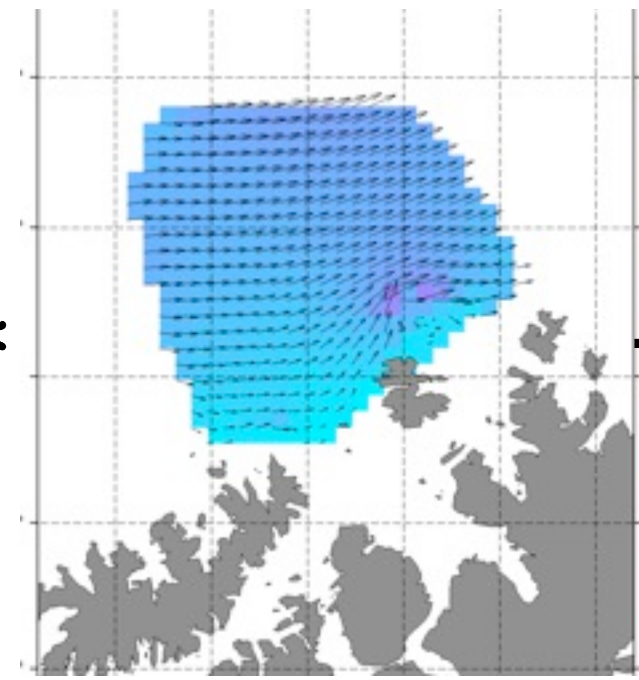
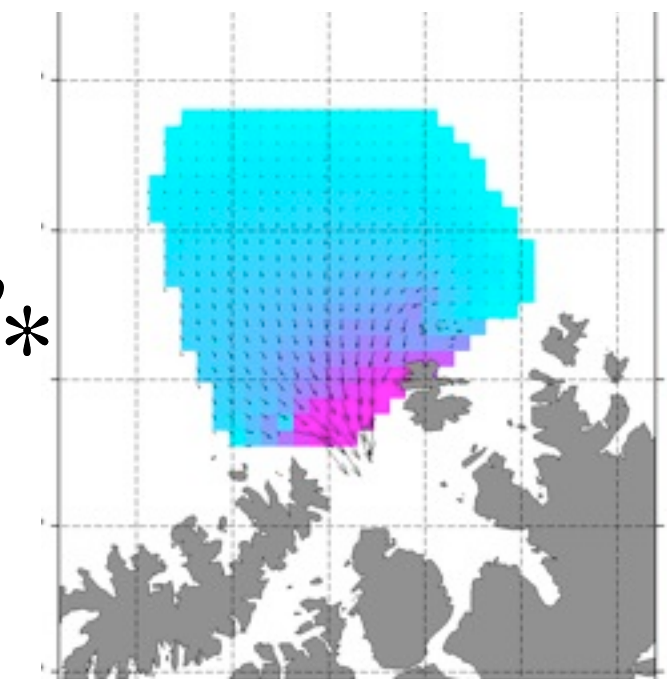
Non-divergent Modes ψ$_i$ (Dirichlet)

$\alpha_1^{\Psi} *$  $+\alpha_2^{\Psi} *$  $+\alpha_3^{\Psi} *$  ...

Non-rotational Modes φ $_i$ (Neumann)

$\alpha_1^{\varphi} *$  $+\alpha_2^{\varphi} *$  $+\alpha_3^{\varphi} *$  ...

Boundary Modes φ_i^b (Flow in and out the domain)

$\alpha_1^b *$  $+\alpha_2^b *$  $+\alpha_3^b *$  …

Any current field can be expanded in the interior and boundary modes:

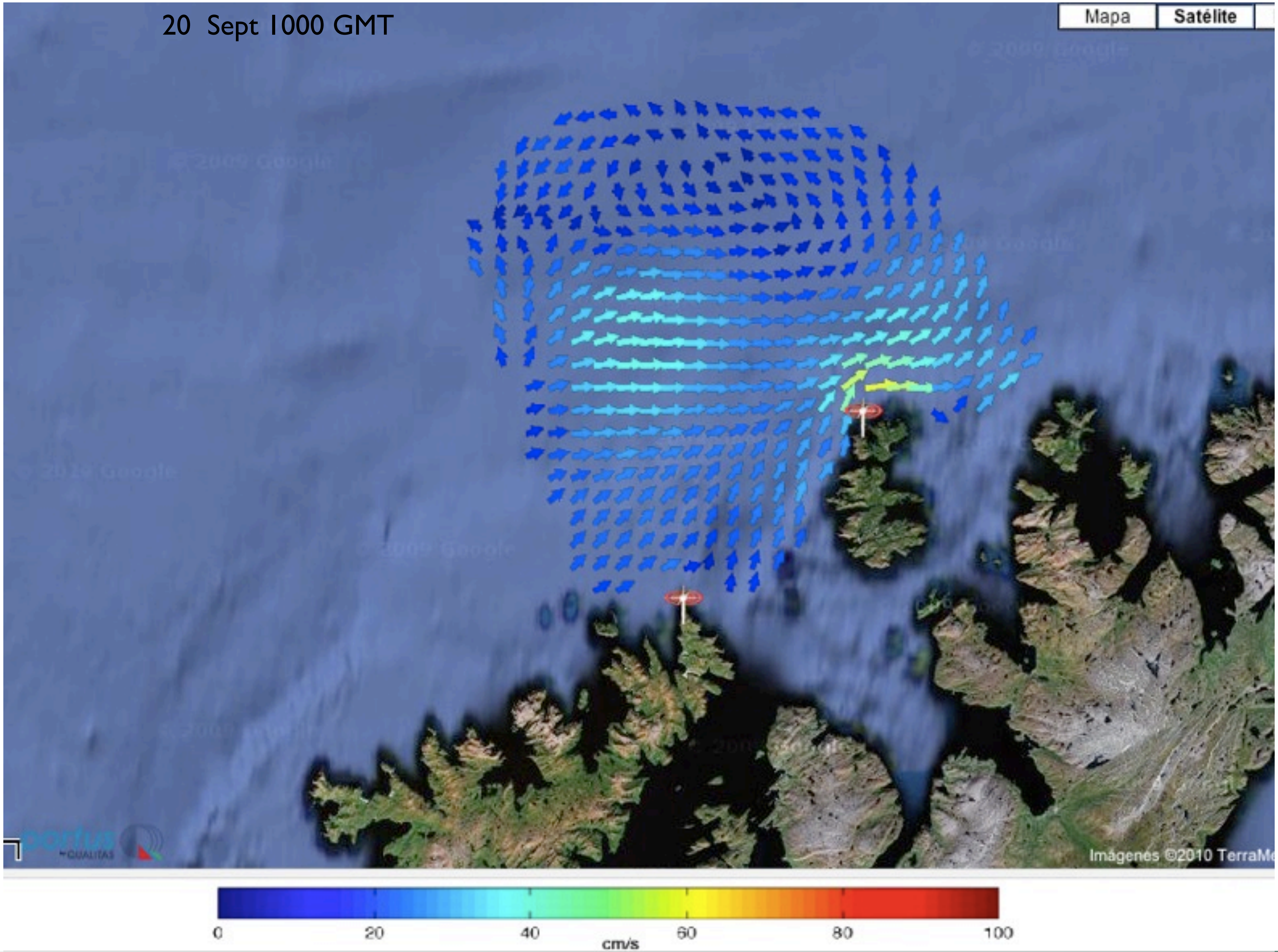
$$\vec{u} = \sum_{i=1}^{\infty} \alpha_i^{\Psi} \hat{k} \times \nabla \Psi_i + \sum_{i=1}^{\infty} \alpha_i^{\varphi} \nabla \varphi_i + \sum_{i=0}^{\infty} \alpha_i^{b} \nabla \varphi_i^{b}$$

<u>OMA Current field construction:</u>

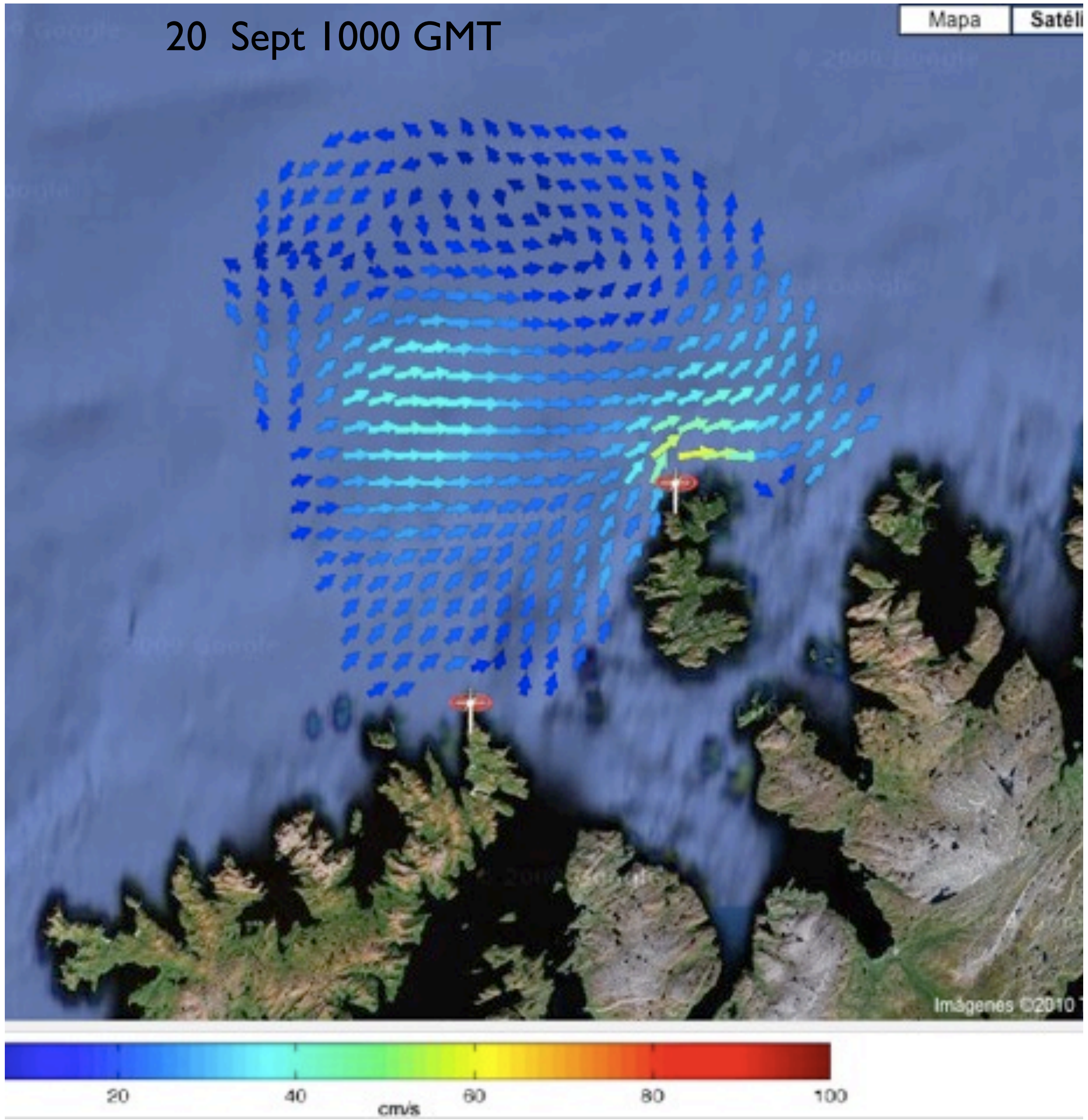
Minimizing a cost function to determine the ideal combination of modes which gives the **best fit to available measurement data (i.e radial vectors)**

Kaplan, D. M., and F. Lekien. "Spatial Interpolation and Filtering of Surface Current Data Based on Open-boundary Modal Analysis." Journal of Geophysical Research, Vol. 12, C12007, 1-20 (2007)

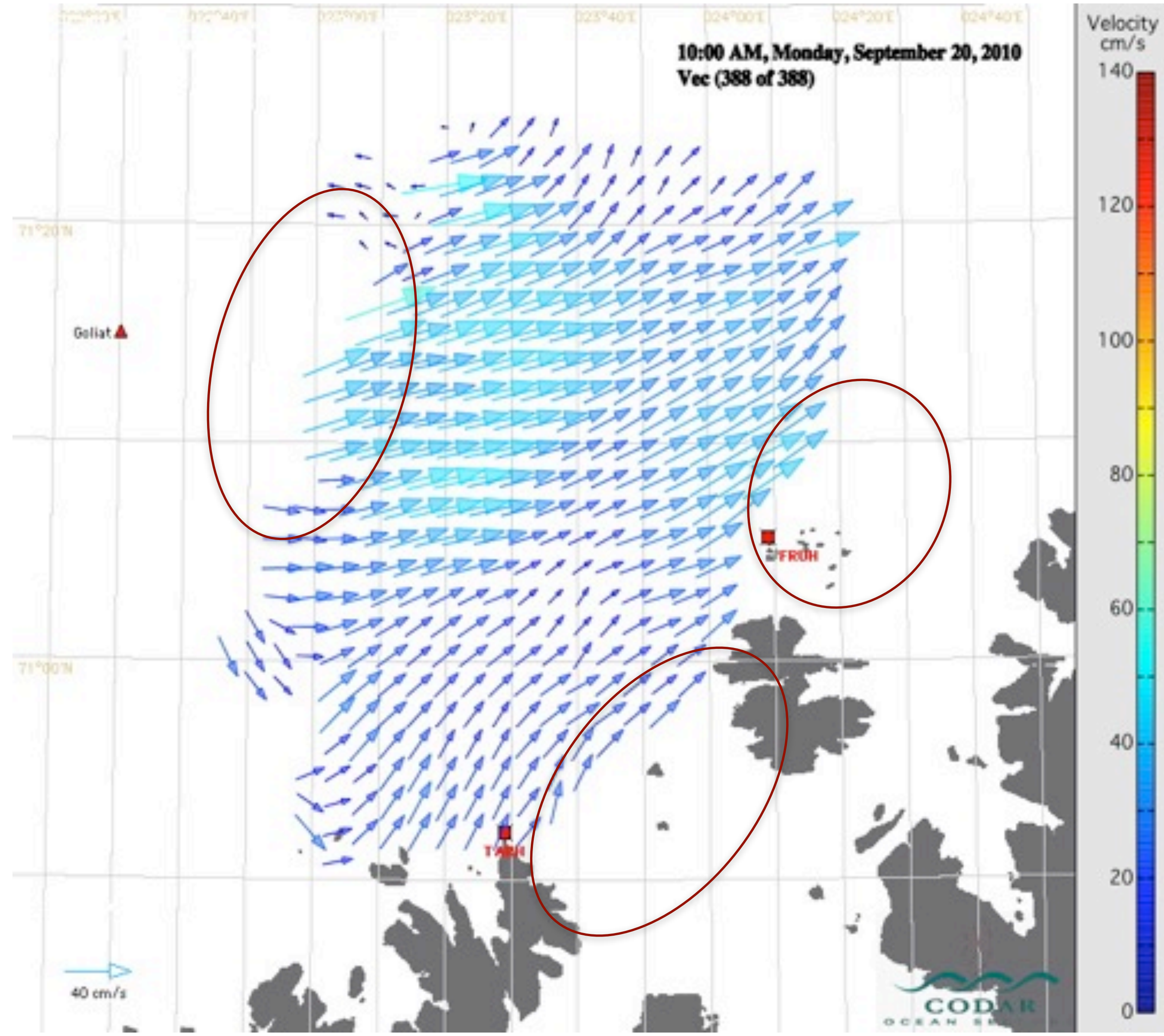
OMA reconstructed fields from radials



OMA reconstructed fields from radials



Standard LS LOCAL combining method



Short Term Predictions from Mode Coefficients

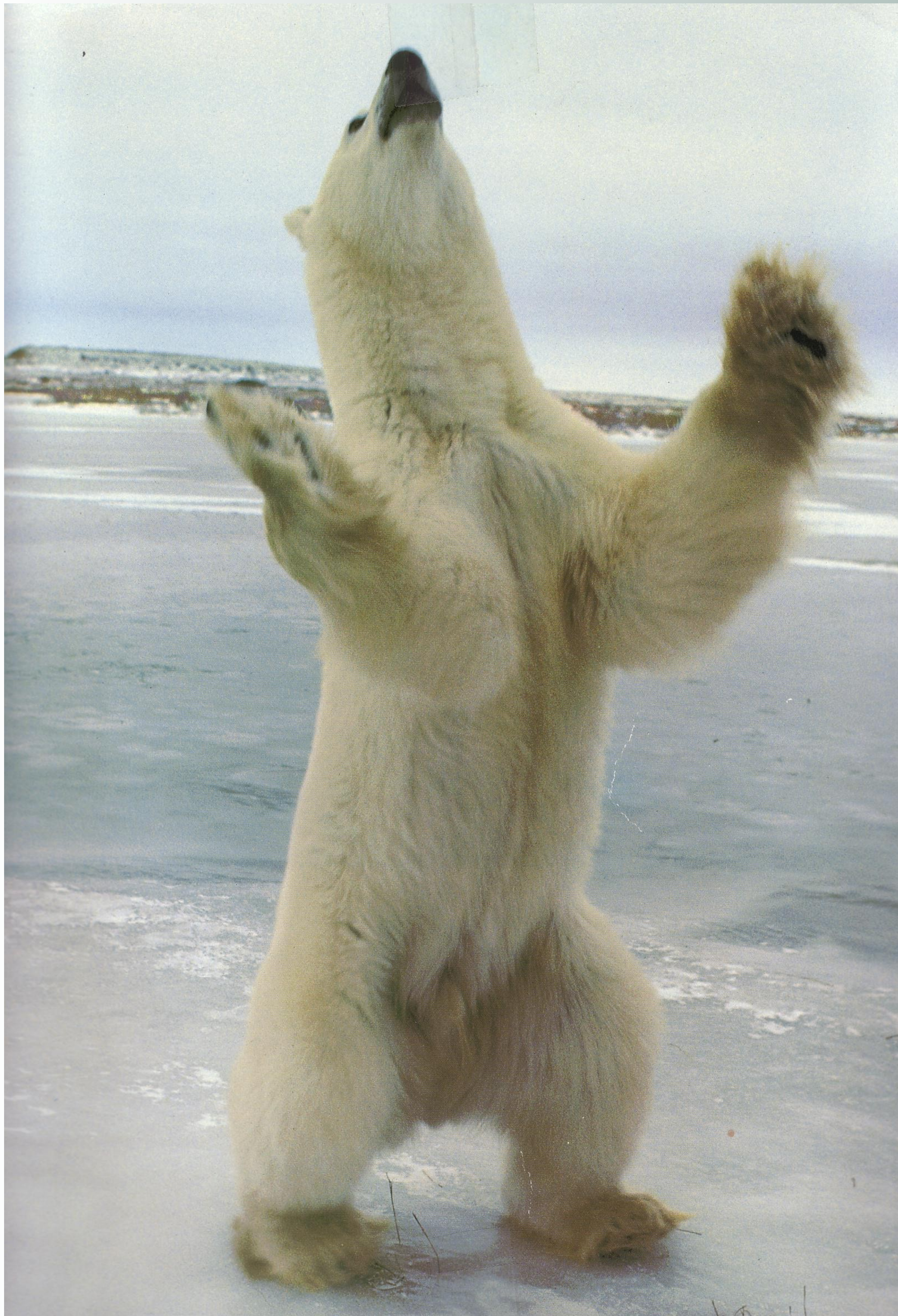
Trailing Time Series

$$
\begin{array}{ll}
\text{Dirichlet} & \left\{ \begin{array}{ccc} \alpha_1^{\Psi}(t_{-12}) & \cdots & \alpha_1^{\Psi}(t_0) \\ \vdots & & \vdots \\ \alpha_N^{\Psi}(t_{-12}) & \cdots & \alpha_N^{\Psi}(t_0) \end{array} \right. \\
\text{Neumann} & \left\{ \begin{array}{ccc} \alpha_1^{\varphi}(t_{-12}) & \cdots & \alpha_1^{\varphi}(t_0) \\ \vdots & & \vdots \\ \alpha_N^{\varphi}(t_{-12}) & \cdots & \alpha_N^{\varphi}(t_0) \end{array} \right. \\
\text{Boundary} & \left\{ \begin{array}{ccc} \alpha_1^{b}(t_{-12}) & \cdots & \alpha_1^{b}(t_0) \\ \vdots & & \vdots \\ \alpha_N^{b}(t_{-12}) & \cdots & \alpha_N^{b}(t_0) \end{array} \right.
\end{array}
$$

Fit trends to each trailing coefficient time series: diurnal, semi-diurnal, inertial, linear & constant

Short Term Predictions from Mode Coefficients

$$
\begin{array}{l}
\\
\text{Dirichlet}\left\{\begin{array}{l}\\ \\ \\ \end{array}\right. \\
\\
\text{Neumann}\left\{\begin{array}{l}\\ \\ \\ \end{array}\right. \\
\\
\text{Boundary}\left\{\begin{array}{l}\\ \\ \\ \end{array}\right.
\end{array}
\begin{array}{c}
\overbrace{\begin{array}{ccc} \phantom{\alpha_1^{\Psi}(t_{-12})} & & \phantom{\alpha_1^{\Psi}(t_{0})} \end{array}}^{\text{Trailing Time Series}} \\
\begin{array}{ccc}
\alpha_1^{\Psi}(t_{-12}) & \cdots & \alpha_1^{\Psi}(t_{0}) \\
\vdots & & \vdots \\
\alpha_N^{\Psi}(t_{-12}) & \cdots & \alpha_N^{\Psi}(t_{0}) \\
\alpha_1^{\varphi}(t_{-12}) & \cdots & \alpha_1^{\varphi}(t_{0}) \\
\vdots & & \vdots \\
\alpha_N^{\varphi}(t_{-12}) & \cdots & \alpha_N^{\varphi}(t_{0}) \\
\alpha_1^{b}(t_{-12}) & \cdots & \alpha_1^{b}(t_{0}) \\
\vdots & & \vdots \\
\alpha_N^{b}(t_{-12}) & \cdots & \alpha_N^{b}(t_{0})
\end{array}
\end{array}
\begin{array}{c}
\overbrace{\begin{array}{ccc} \phantom{\alpha_1^{\Psi}(t_{+1})} & & \phantom{\alpha_1^{\Psi}(t_{+12})} \end{array}}^{\text{Predicted Time Series}} \\
\begin{array}{ccc}
\alpha_1^{\Psi}(t_{+1}) & \cdots & \alpha_1^{\Psi}(t_{+12}) \\
\vdots & & \vdots \\
\alpha_N^{\Psi}(t_{+1}) & \cdots & \alpha_N^{\Psi}(t_{+12}) \\
\alpha_1^{\varphi}(t_{+1}) & \cdots & \alpha_1^{\varphi}(t_{+12}) \\
\vdots & & \vdots \\
\alpha_N^{\varphi}(t_{+1}) & \cdots & \alpha_N^{\varphi}(t_{+12}) \\
\alpha_1^{b}(t_{+1}) & \cdots & \alpha_1^{b}(t_{+12}) \\
\vdots & & \vdots \\
\alpha_N^{b}(t_{+1}) & & \alpha_N^{b}(t_{+12})
\end{array}
\end{array}
$$



Tusen Takk!

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