Satellite Ocean Surface Winds: The Why and How and What Should We Do Next

Paul S. Chang and Zorana Jelenak

Ocean Winds Science Team

(Seubson Soisuvarn, Suleiman Alsweiss, Joe Sapp, Faozi Said, Casey Shoup,
Qi Zhu, Adama Sombie)

NOAA/NESDIS/Center for Satellite Applications and Research

Presentation to the

NOAA Systems Performance Assessment Team

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Wind is a Vector Quantity: Speed and Direction

- Satellite OSVW is important to many parts of NOAA’s mission (NWS, NMFS and NOS)
- Safe and efficient maritime transportation
  - Safety of Life at Sea (SOLAS) convention
- Management and protection of marine life
- Support predictive capabilities for HABs, SAR and HAZMAT situations

NOAA OSWV Requirements

NGSP GOAL	NOSIA II Mission Service Areas (MSAs)
Climate	Assessments of Climate changes and its impacts
Climate	Climate Science and Improved Understanding
Healthy Oceans	Ecosystem Monitoring, Assessment and Forecast
Healthy Oceans	Healthy Ocean Science, Services, and Stewardship Advances
Resilient Coastal Communities and Economies	Coastal Water Quality
Resilient Coastal Communities and Economies	Marine Transportation
Resilient Coastal Communities and Economies	Planning and Management
Resilient Coastal Communities and Economies	Resilient Coasts Science, Services, and Stewardship Advances
Weather-Ready Nation	Hurricane/ Tropical Storms
Weather-Ready Nation	Routine Weather
Weather-Ready Nation	Weather Ready Nation Science, Services, and Stewardship Advanced
Weather-Ready Nation	Tsunami
Weather-Ready Nation	Winter Weather

- There are 57 observational requirements for ocean surface wind speed, wind direction and wind stress from the five (5) NOAA Line Offices: NESDIS, NMFS, NOS, NWS, and OAR.
- Of these 57, 44 are Priority 1 (mission Critical) requirements
    - Priority-1: Mission Critical – Cannot meet operational mission objectives without this data
    - 24 are Line Office validated, 20 are in the process of being validated

Requirements:

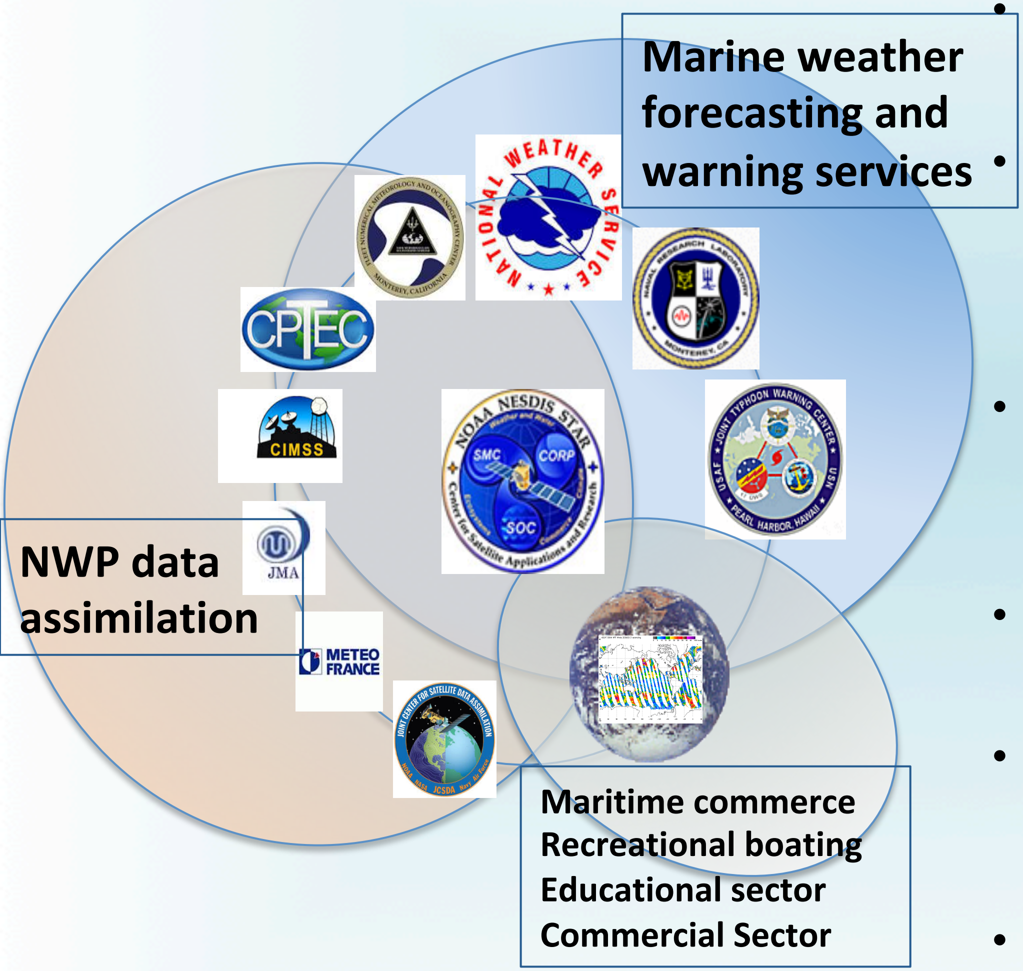
5min, 1km, Global ocean Hurricane/Tropical Storms

12hr, 100km, Global Ocean Climate studies

As documented in TPIO's Consolidated Observation Requirements List (CORL)

Why are OSVW Important to NOAA?

Satellite OSVW provides actionable environmental intelligence over the global oceans



Marine weather forecasting and warning services

NWP data assimilation

Maritime commerce
Recreational boating
Educational sector
Commercial Sector

- **NWS forecasters utilize these data every day in their decision making process**
- **NWS is required to warn and forecast on the ocean surface wind field**
  - Satellite OSVW provides forecasters the ability to see the detailed wind field over vast data-sparse ocean areas of the Atlantic and Pacific
  - Major impact on shipping routes
- **OSVW are input into NWP models during the data assimilation process**
  - Satellite OSVW are routinely assimilated in global NWP models across the world. Forecast error reduction between 2-8%
- **Continuity…These data have been supporting NWS operations for over 20 years now**
- The air-sea interface is an important Earth ecosystem boundary condition and plays a pivotal role in balancing the system’s energy budget.
- User requirement: critical data set
- Main U.S. users receiving NESDIS data: NWS, NAVY and Air Force

Winds are the destructive force!

OSVW is a Priority 1 Observational Requirement NOAA Marine Weather and Tropical Cyclone Mission Service Areas

“The National Oceanic and Atmospheric Administration (NOAA) Marine Weather Program (MWX) issues operational marine weather warnings and forecasts to ensure the safety of marine transportation operations, a critical link in world commerce. The MWX program serves a broad marine user community, including commercial shipping, offshore operations, commercial and recreational fishing, and recreational boating. The program also provides on-demand forecasts and information services for USCG search and rescue and response to hazard materials (HAZMAT) spills on the high seas internationally and in the offshore regions adjacent to the U.S. The MWX program services are a critical element of NOAA and National Weather Service (NWS) operational responsibilities to protect life and property, enhance the Nation's economic benefits and protect the environment. Operational services provided by the MWX program fulfill U.S. responsibilities in the interests of commerce, transportation, and homeland security under Executive Order 12234 (Enforcement of the Convention for the Safety of Life at Sea).” (MWX Observational User Requirements Document, June 23, 2021)

“The NOAA NWS Tropical Cyclone Services Program has the responsibility among Federal agencies to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts, and analyses of hazardous tropical weather and by increasing understanding of these hazards.” (TC Observational User Requirements Document, June 23, 2021)

Knowledge of the ocean winds and currents is important from the open ocean to the coastal zone

- The coastal wind profile near shore (within ~ 20 km) is really important to the structure of upwelling
- Many ecosystem processes (e.g., primary production, vertical distribution of organisms) are dependent on vertical movements in the water column that add variability to an otherwise sharp, but stagnant gradient in inorganic nutrients and dissolved oxygen.
- Improved spatial resolution of the gradients in the surface processes that force the Ekman layer, particularly along coastlines, where the cross-shore gradient in winds is difficult to resolve over large scales if data are coarse or inaccurate near landmasses, will offer insight to the location, intensity, and variability in the upwelling process.
- Coastal upwelling processes have implications for critical fisheries on a global scale
    - Resolution of the coastal winds at about 3 km or less has been identified as important for forcing upwelling dynamics (but rarely have higher-resolution wind data been explored at the ecosystem scale).

The How

- Active Microwave
- Passive Microwave
- Signals of opportunity (i.e. GNSSR)

Active Microwave (Radar)

- Scatterometry (“gold standard”)
  - Primary mission: ocean surface wind vector (speed and direction)
- Altimetry
  - Primary mission: sea surface height
- Synthetic Aperture Radar
  - Primary mission: fine resolution NRCS imagery (all weather)

Passive Microwave

- Multi-channel
  - Primary mission: multiple EDRs including ocean surface wind speed
- Polarimetric
  - Primary mission: multiple EDRs including ocean surface wind speed and direction
- L-band
  - Primary mission: soil moisture and ocean salinity

Signals of Opportunity

- GPS (GNSSR)
  - Primary mission: precise location and navigation

Some Pros and Cons

- Active
  - You know the signal you are looking for
  - Finer spatial resolution for a given antenna size
  - Retrievals in the coast zone
  - Generally higher power requirements
- Passive (multi-channel)
  - Multiple EDRs possible dependent upon frequencies and polarizations
  - No transmitter required
  - Land contamination and RFI a larger issue

Active Microwave (Radar)

- Scatterometry
  - Mature and proven methodology with broad community acceptance
  - In use today operationally supporting NOAA’s weather mission
  - Depending upon frequency rain can impact measurements
- Altimetry
  - Specular scattering (only works for low wind speeds), speed only, single line of measurements
- Synthetic Aperture Radar
  - Speed only, limited availability and coverage, cross swath absolute calibration challenges
  - Very fine spatial resolution

Passive Microwave

- Multi-channel
  - Wind speed only, lower frequency channels needed for retrievals in conditions with significant water in the atmosphere, coarser spatial resolution and more susceptible to land contamination and RFI
- Polarimetric
  - Wind speed and direction, in addition to the above the consistency and performance of OSVW has not validated in the context of able to support NOAA’s operational mission
- L-band
  - Wind speed only, coarse spatial resolution, while tuned to infer the peak winds in tropical cyclones the coarse spatial resolution means the peak winds are being inferred versus retrieved

Signals of Opportunity

- GPS (GNSSR)
  - Wind speed only, sensitive to low winds but poor sensitivity to higher wind speeds, unknowns in GPS constellation make consistent and calibrated measurements even more challenging

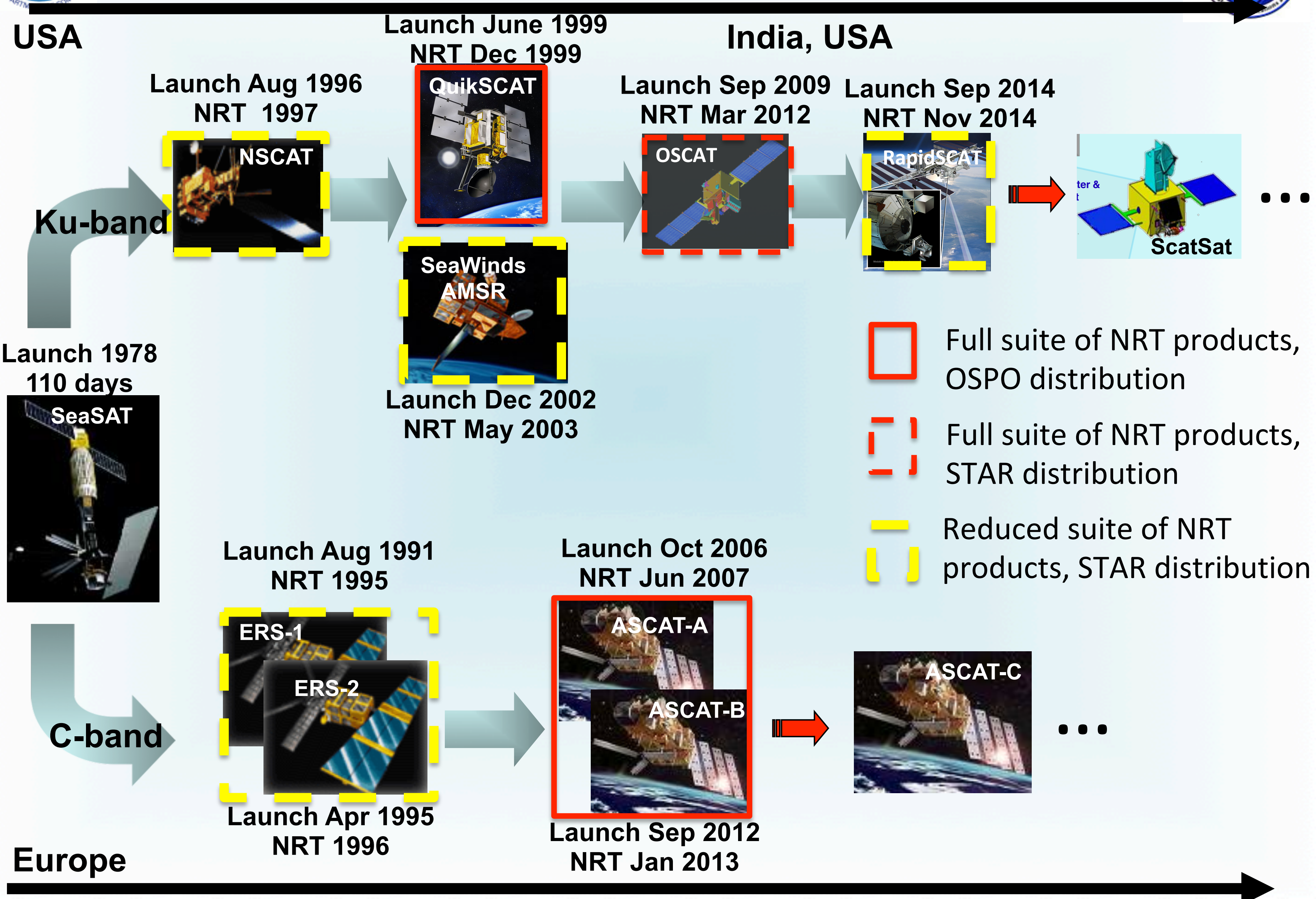
What Should NOAA Do?

- Satellite OSVW is a critical observable for NOAA (real-time and climate time scales)
  - We now totally depend upon EUMETSAT and ISRO to partially meet requirements
- NOAA should **contribute** to the virtual OSVW constellation
  - Target under sampled orbit crossing times to achieve 6 hourly revisit times
  - Pursue proven and mature methodologies to support operational requirements (i.e. scatterometry)

Be wary of shiny objects!

A statement in a glossy brochure does not directly translate to a validated and verified product that has the accuracy and consistency to support operational decision making

History of OSVW in NOAA Operations



□ Full suite of NRT products, OSPO distribution

⬚ Full suite of NRT products, STAR distribution

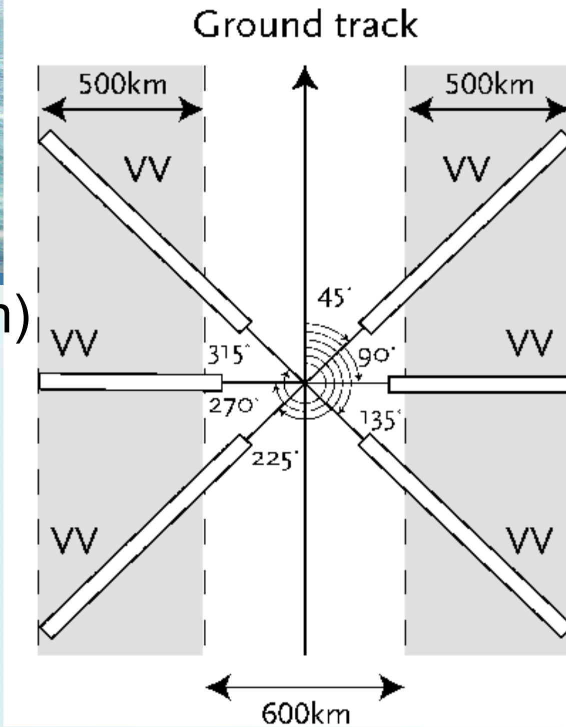
⬚ Reduced suite of NRT products, STAR distribution

How Do Scatterometers Work

Scatterometer instruments

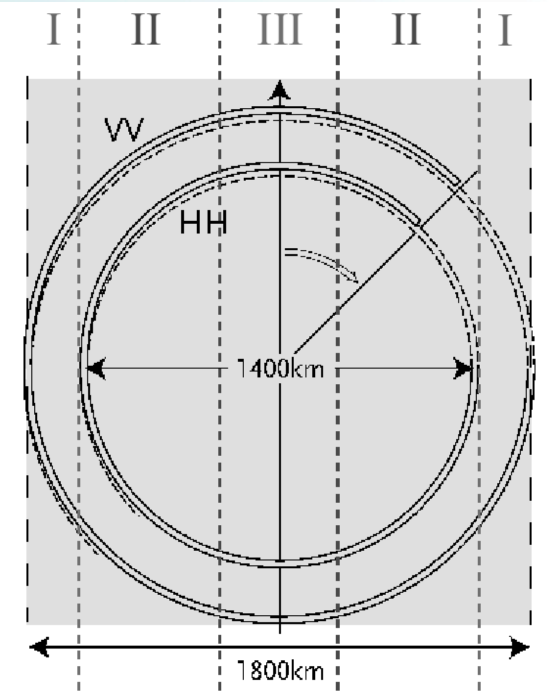
Fixed fan beam

- C-band (5 cm), Ku-band (2 cm)
- VV-pol & Dual-pol
- Resolution: 25-50 km
- Fixed geometry
- Seasat, ERS-1/2, NSCAT, ASCAT

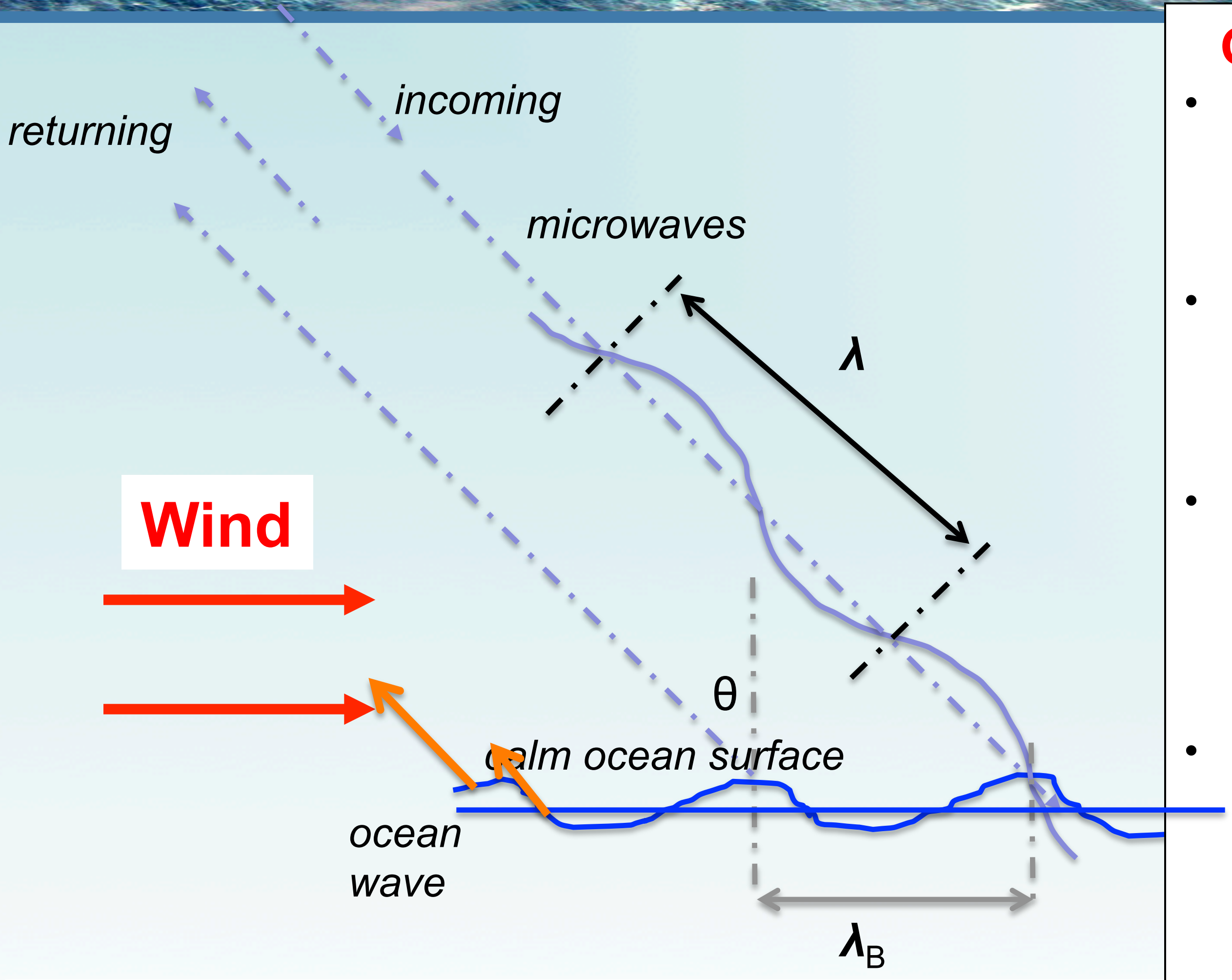


Rotating pencil beam

- Ku-band (2cm)
- Dual polarization
- Resolution: 25 km
- Varying geometry
- SeaWinds-1/2, OSCAT



Theoretical Basis

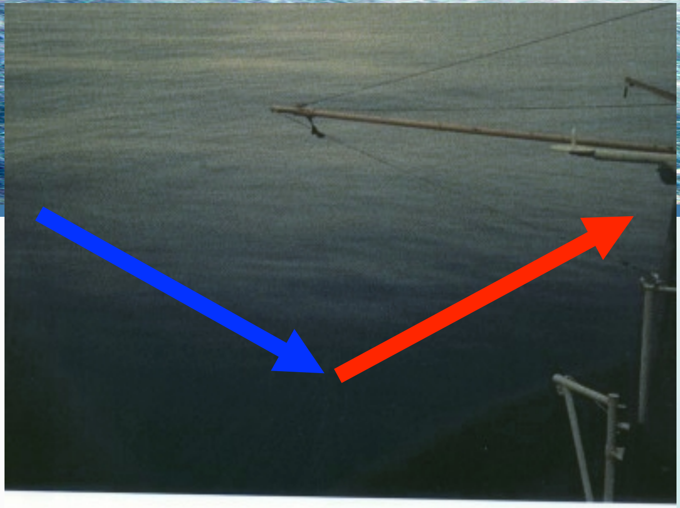


$\lambda_B = 2\lambda/\cos(\theta)$

$\lambda=2cm,\ \theta = 60deg\ \ \lambda_B = 8cm$

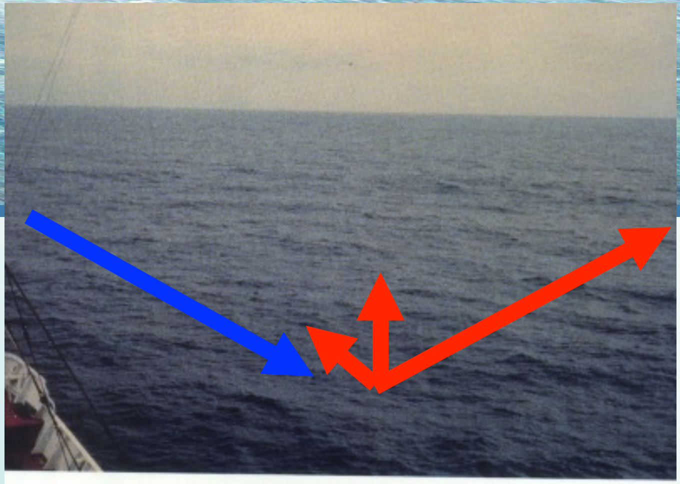
Gravity-capillary waves

- **Respond almost instantaneously to strength of local wind**
- **Caps of waves tend to align perpendicular to local wind direction**
- **Sharp shape of leeward side of the capillary wave results more ocean radar return upwind than in the downwind direction**
- **Microwave (Bragg) Scattering**
  •Incoming microwave radiation is in resonance with small scale ocean waves of comparable wavelength
- **Accuracy of theoretical models ~1 dB and not adequate**



BEAUFORT FORCE 0
WIND SPEED: LESS THAN 1 KNOT

SEA: SEA LIKE A MIRROR

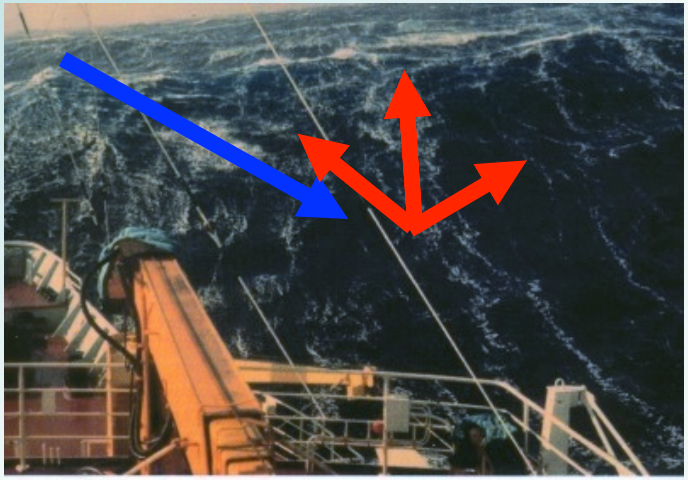


BEAUFORT FORCE 3
WIND SPEED: 7-10 KNOTS

SEA: WAVE HEIGHT .6-1M (2-3FT), LARGE WAVELETS, CRESTS BEGIN TO BREAK, ANY FOAM HAS GLASSY APPEARANCE, SCATTERED WHITECAPS

BEAUFORT FORCE 6
WIND SPEED: 22-27 KNOTS

SEA: WAVE HEIGHT 3-4M (9.5-13 FT), LARGER WAVES BEGIN TO FORM, SPRAY IS PRESENT, WHITE FOAM CRESTS ARE EVERYWHERE

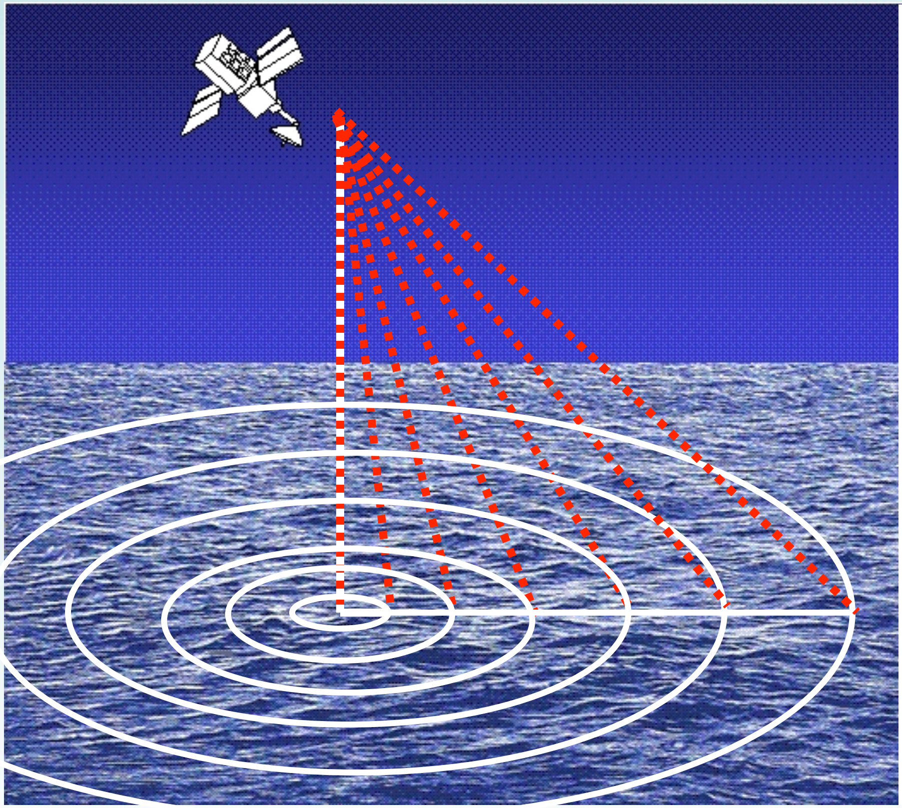


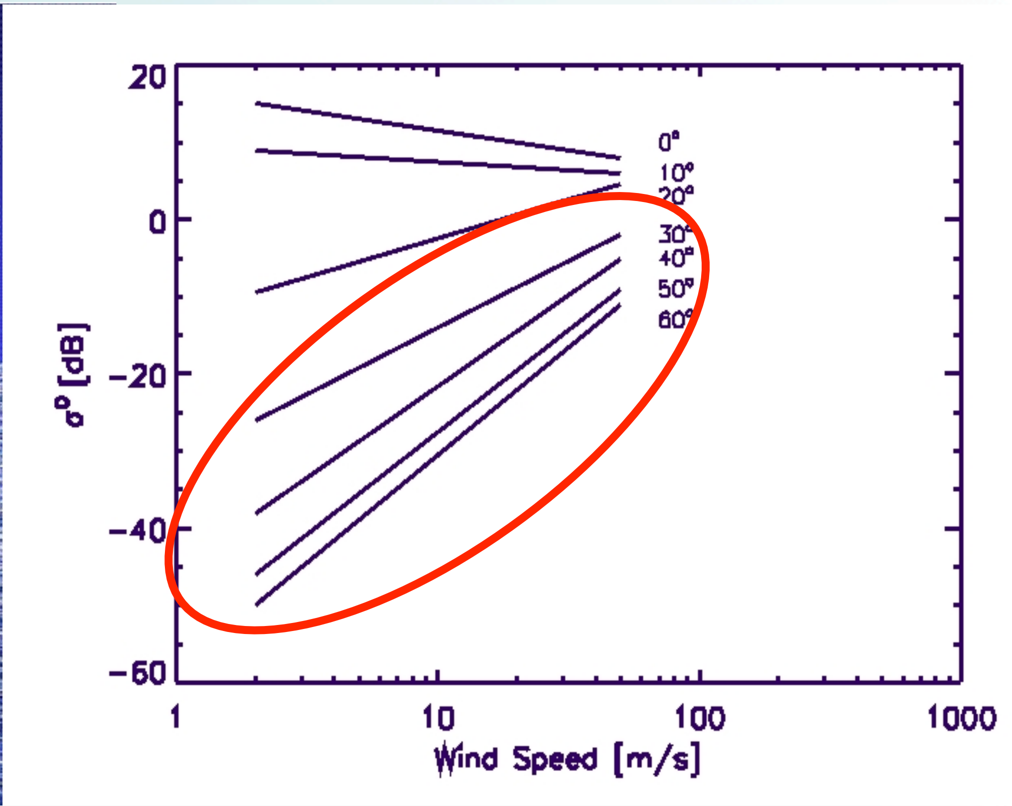
BEAUFORT FORCE 9
WIND SPEED: 41-47 KNOTS

SEA: WAVE HEIGHT 7-10M (23-32FT), HIGH WAVES, DENSE STREAKS OF FOAM ALONG DIRECTION OF THE WIND, WAVE CRESTS BEGIN TO TOPPLE, TUMBLE, AND ROLL OVER. SPRAY MAY AFFECT VISIBILITY.

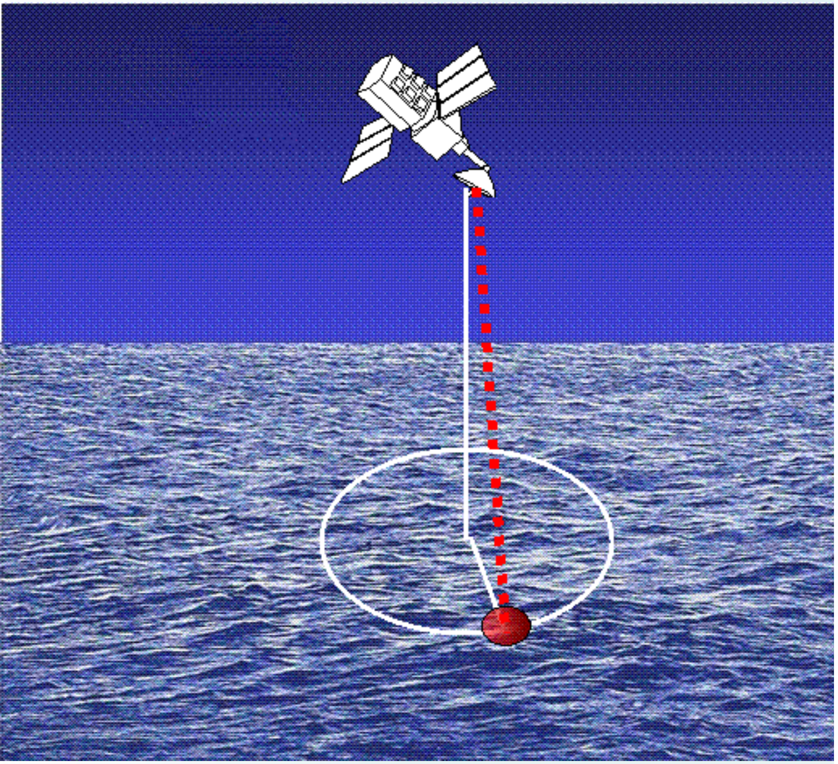
Backscatter as a Function of Wind Speed and Incidence Angle

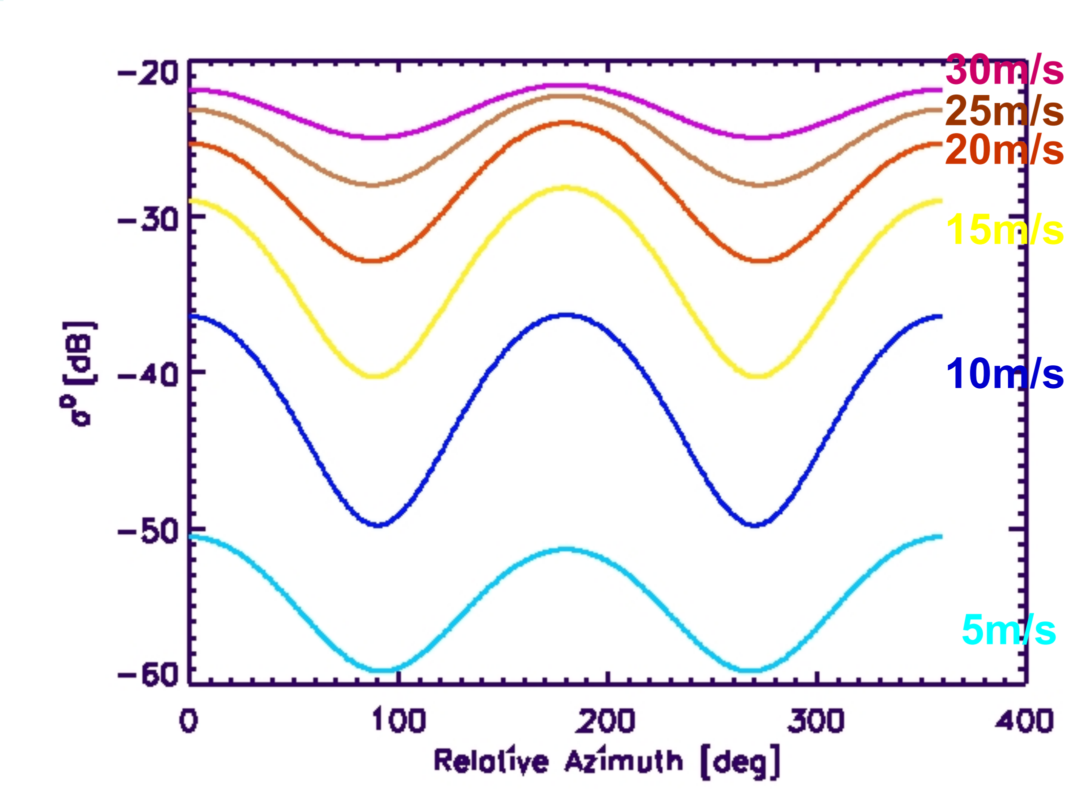
Most sensitivity to wind at moderate incidence angles 30°-60°





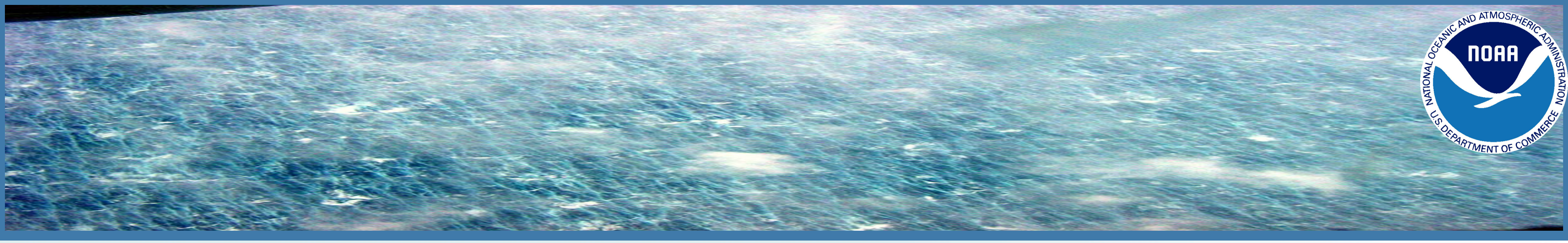
Backscatter Sensitivity to Wind Direction





Why is azimuth angle important?

- **Defines instruments ability to derive wind direction**



From Measurements to Winds

Geophysical Model Function

- An empirical geophysical model function (GMF) relates ocean surface wind speed and direction to the backscatter cross section measurements.

$$\sigma_o^{\text{model}} = GMF(U_{10N}, \phi, \theta, p, \lambda)$$

U_{10N}: equivalent neutral wind speed
ϕ : wind direction w.r.t. beam pointing
θ : incidence angle
p : radar beam polarization
λ : microwave wavelength

A Little More History

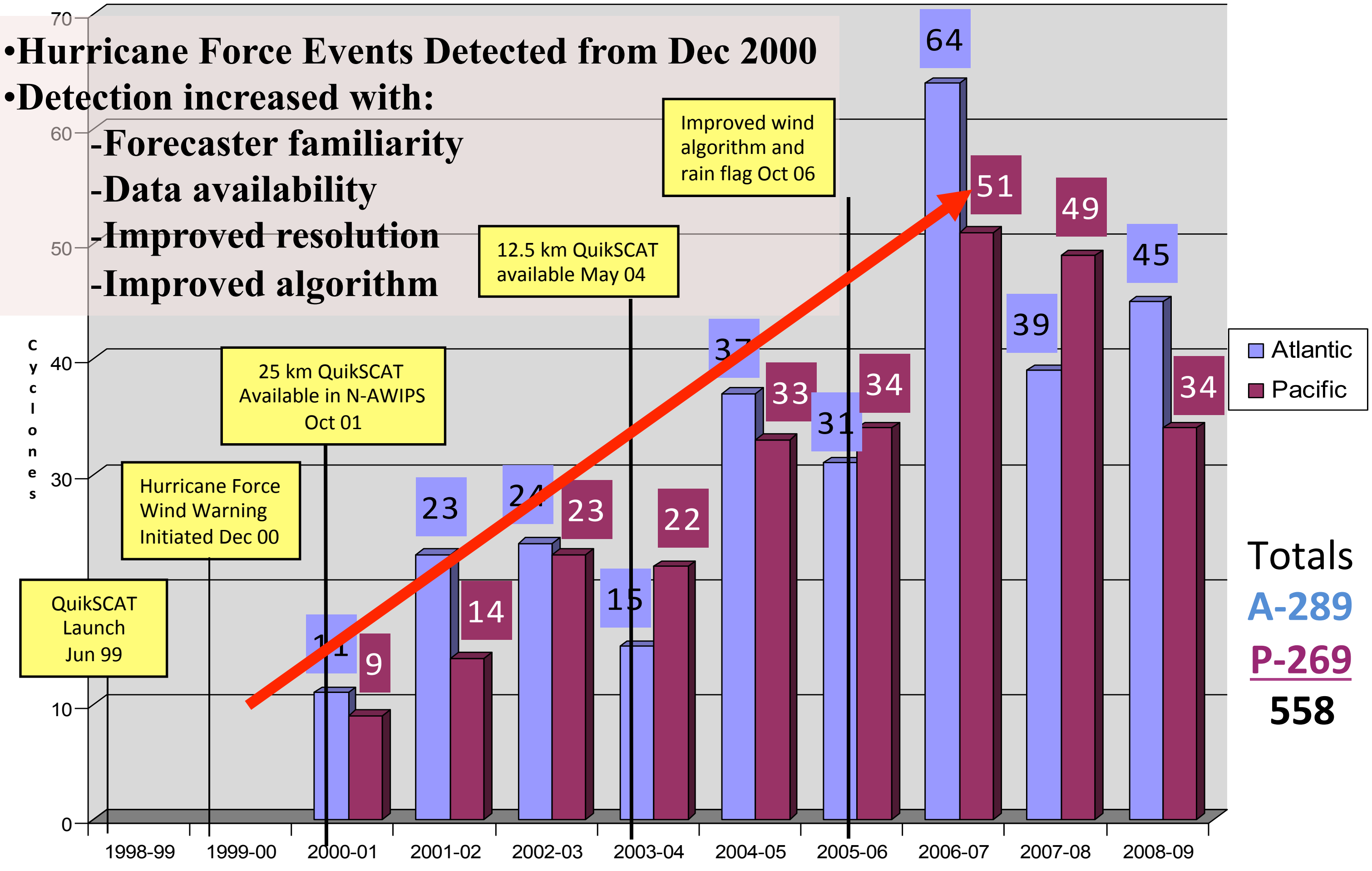
The Use of Scatterometer Data in OPC Operations

The quality, consistency and coverage of QuikSCAT OSVW data significantly impacted the marine weather warning and forecasting

WARNING CATEGORIES

Pre- QSCAT
1. GALE 34-47 kt
2. STORM ≥48

QSCAT ERA
1. GALE 34-47 kt
2. STORM 48 -63 kt
3. HURCN FORCE ≥ 64 kt



- **Hurricane Force Events Detected from Dec 2000**
- **Detection increased with:**
  - **-Forecaster familiarity**
  - **-Data availability**
  - **-Improved resolution**
  - **-Improved algorithm**

QuikSCAT Launch Jun 99

Hurricane Force Wind Warning Initiated Dec 00

25 km QuikSCAT Available in N-AWIPS Oct 01

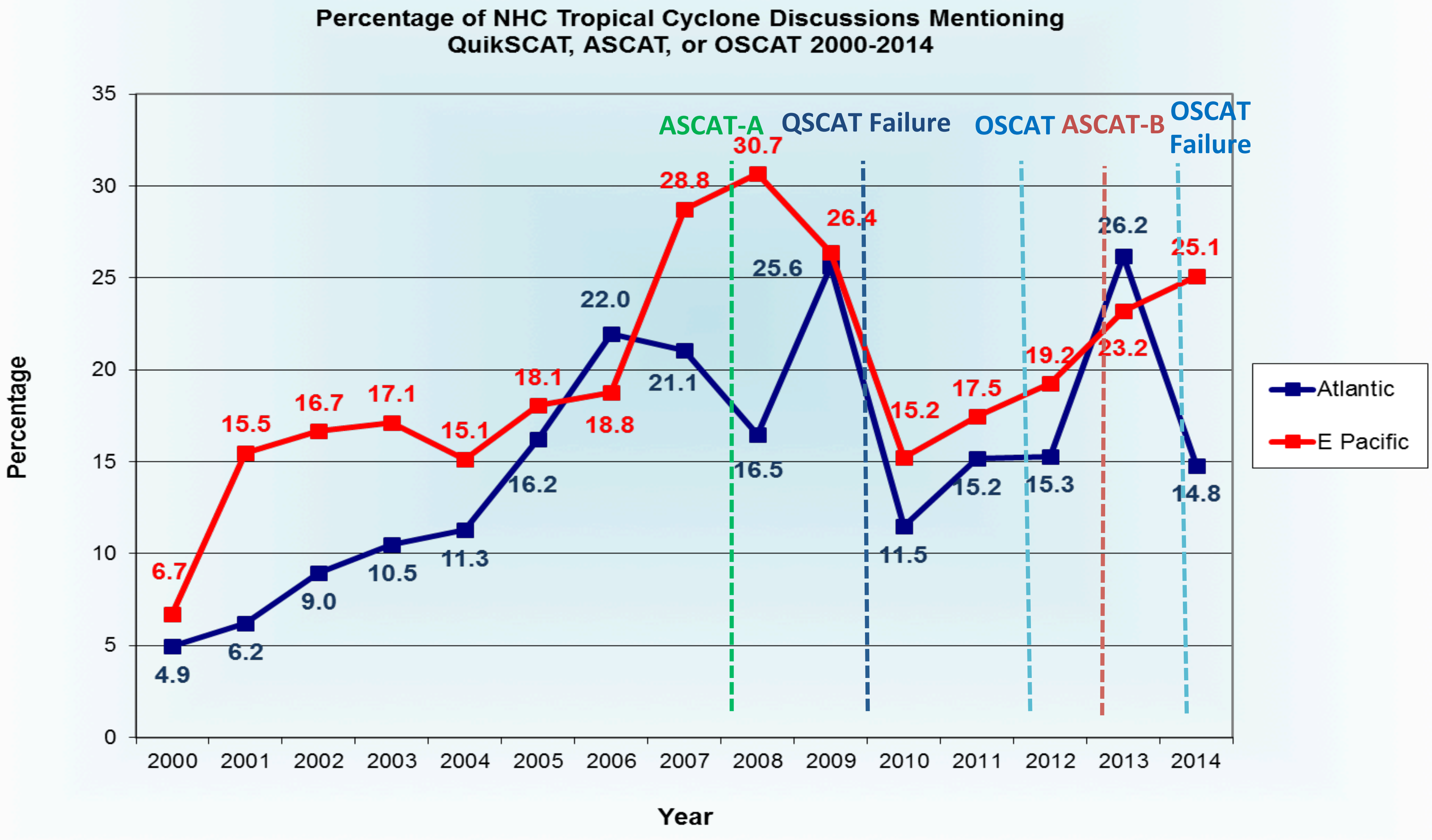
12.5 km QuikSCAT available May 04

Improved wind algorithm and rain flag Oct 06

Totals
A-289
P-269
558

Increasing trend in number of Hurricane Force wind events in `ETC's can be attributed to increased familiarity and consistency of QuikSCAT data strengthened by aircraft data validation

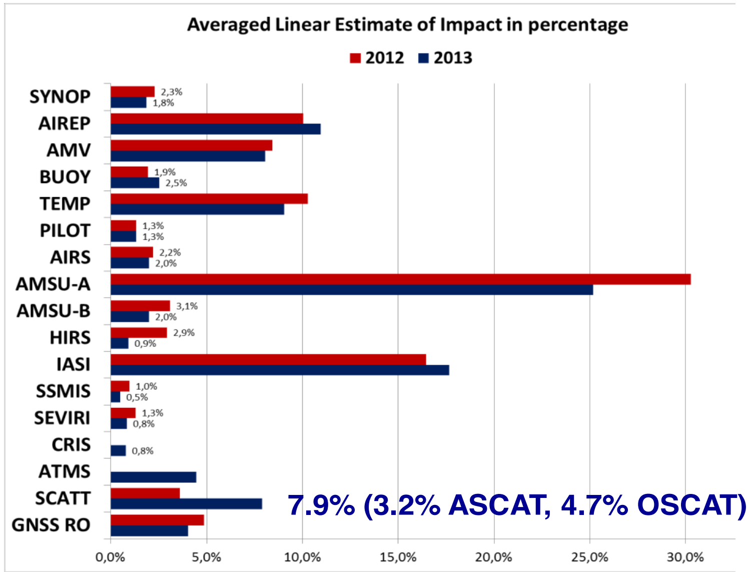
Use of Scatterometer Data in NHC Operations



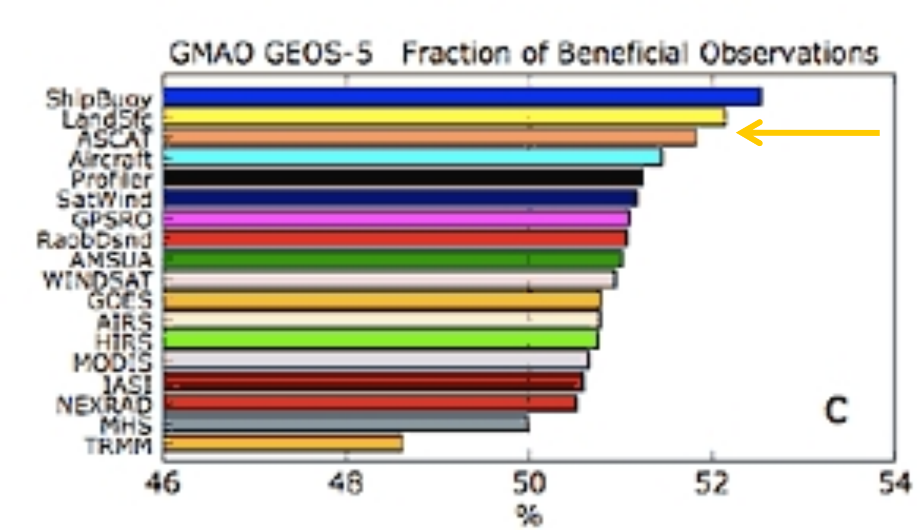
Satellite OSVW Impact on NWP Models

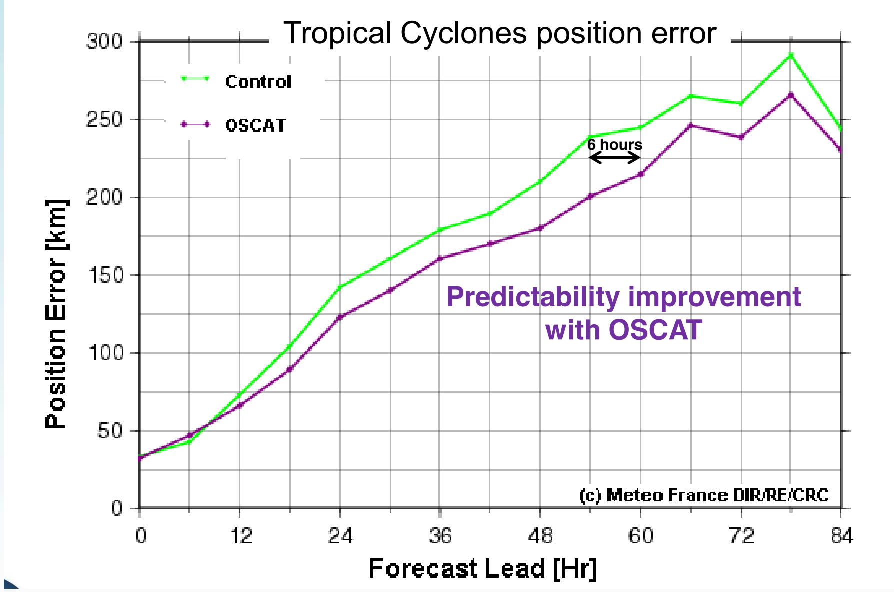
Forecast Error Contribution (reduction) in %

September 2012: ASCAT-A
September 2013: ASCAT-A&B, OSCAT



7.9% (3.2% ASCAT, 4.7% OSCAT)



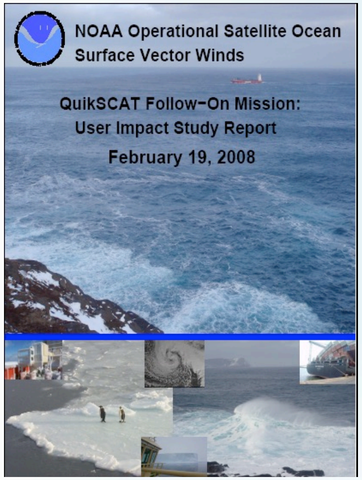


- Observed forecast error reduction due to OSVW data assimilation spans between 2-8% (GEOS-5, ECMWF,UK-Met, ARPEGE)
- The average influence of individual observations can be expressed in terms of the average reduction in the error measure per observation.
  - With roughly 52% of these data improving the 24-h forecast on average ASCAT winds provide one of the largest positive impacts per observation in GEOS-5 system
- 6h tropical cyclone position improvement at 60h forecast observed in South Indian Ocean due to OSCAT assimilation in ALADIN regional model

NOAA Operational OSVW Requirements


NOAA Operational Ocean Surface Vector Winds Requirements Workshop

National Hurricane Center
Miami, FL
June 5–7, 2006


NOAA Operational Satellite Ocean Surface Vector Winds

QuikSCAT Follow-On Mission:
User Impact Study Report
February 19, 2008

- Through the QuikSCAT experience NESDIS and NWS realized that satellite **OSVW was a vital observational capability**
- A **satellite OSVW requirements workshop was held** to define and document what is needed to support operational marine weather forecasting and warning. Subsequently, the **NRC Decadal Survey recommended satellite OSVW** should pursued by NOAA as an operational capability.
- **NESDIS funded JPL to study QuikSCAT follow-on options**. The decision was made to pursue a partnership with JAXA (scatterometer on GCOM-W2&3) and NESDIS&NASA funded JPL to study accommodation/integration of a scatterometer with AMSR-3.
- After several attempts to establish an OSVW budget initiative NESDIS acknowledged to NASA that it was not going to be able to realize a QuikSCAT follow-on mission. **NESDIS and NWS agreed to continue pursuing/leveraging OSVW missions of partner agencies to address the OSVW requirement.** Thus far NESDIS has been unable to secure designated funding to support OSVW and the OSVW effort has been supported in an ad-hoc manner. Enterprise funding will improve the support of leverage missions of opportunity.

NOAA Operational Ocean Surface Vector Winds Requirements Workshop Report (2006) Executive Summary

- Although satellite ocean surface vector wind (OSVW) data are revolutionizing operational marine weather warnings, analyses, and forecasts, critical but solvable gaps in OSVW capability remain leaving life and property at risk. This report from a workshop held June 5 to 7, 2006, at the Tropical Prediction Center/National Hurricane Center (TPC/NHC) in Miami, Florida, documents (1) the utilization and impact of presently available satellite OSVW data in the production and use of operational marine weather analyses, forecasts, and warnings at NOAA, (2) the OSVW operational requirements within NOAA based on actual experience and phenomena observed, and (3) a preliminary exploration of sensor/mission concepts that would be capable of meeting the requirements. Seven years after NOAA first began routinely utilizing satellite OSVW data, the nation still has no plans for an operational OSVW data stream that addresses the present and future satellite OSVW requirements of the National Oceanic and Atmospheric Administration (NOAA).

NOAA Operational Ocean Surface Vector Winds Requirements Workshop, June 5-7 2006, National Hurricane Center, Miami, FL. https://manati.star.nesdis.noaa.gov/SVW_nextgen/SVW_workshop_report_final.pdf

In Their Own Words…

- **Rick Knabb,** Senior Hurricane Specialist, Tropical Prediction Center/National Hurricane Center, NOAA/NWS/NCEP, Miami, Florida:
  "QuikSCAT has been a tremendous benefit to the Tropical Prediction Center."
  "When QuikSCAT is gone, it will be like going back seven years in tropical cyclone analysis."
  "Losing QuikSCAT would be like losing a limb, especially for Tropical Analysis and Forecasting Branch."

Hugh Cobb, Tropical Prediction Center/National Hurricane Center, NOAA/NWS/NCEP, Miami, Florida:
"QuikSCAT is our bread and butter."

Capt. Caroline Bower, Science Officer, Naval Pacific Meteorology and Oceanography Center (NPMOC)/Joint Typhoon Warning Center (JTWC), Pearl Harbor, HI:
"QuikSCAT plays a critical role in our tropical cyclone analysis and forecasting operations."

Roger Edson, Science and Operations Officer, NOAA/National Service Forecast Office in Guam:
"QuikSCAT has been absolutely vital for understanding the structure of tropical cyclones."

Joe Sienkiewicz, Chief (Acting), Ocean Application Branch W/NP42, Science Officer, NOAA/NWS/NCEP/OPC, Camp Springs, Maryland:
"Because of QuikSCAT, our ability to assess current conditions has never been better and our warnings never more accurate."

John Lovegrove, Meteorologist-in-Charge (MIC), NOAA/National Service Forecast Office, in Medford, Oregon:
"QuikSCAT has been instrumental in forecasting coastal jets. We didn't know they were out there before QuikSCAT."

Mark Freeberg, President of OCENS Inc., Seattle, Washington:
"We have thousands of users and QuikSCAT accounts for 15 percent of download of all wind products downloaded by these users."

NOAA Operational Ocean Surface Vector Winds Requirements Workshop, June 5-7 2006, National Hurricane Center, Miami, FL. https://manati.star.nesdis.noaa.gov/SVW_nextgen/SVW_workshop_report_final.pdf

OSVW Requirements from 2006 OSVW Requirements Workshop at NHC

Parameter	**NOAA Requirements**	**Next-Generation Performance**
All-weather capabilities	Accurate retrievals in cloudy or rainy conditions	Retrievals under cloudy and rainy conditions
Wind Speed Range	2m/s - 82.5 m/s	2 m/s - 55m/s (or greater?)
Wind Speed Accuracy (10 m/ 1 minute)	1m/s (2σ)	**Wind speed <7m/s:** <1m/s (2σ) at 2km resolution; <0.3 m/s (2s) at 12.5 km resolution. **Wind speed <15m/s:** <1.6m/s (2σ) at 2km resolution; <0.4 m/s (2σ) at 12.5 km resolution. **Wind Speed ~50 m/s:** ~10 m/s (2σ) at 12.5 km resolution (C-band)
Wind Direction Accuracy (2m/s - 5m/s)	20° (2σ)	74° (2σ) at 2km resolution. 28° (2σ) at 12.5 km resolution
Wind Direction Accuracy (5m/s - 83m/s)	10° (2σ)	<24° (2σ) at 2km resolution. <6° (2σ) at 12.5 km resolution
Grid Horizontal Resolution	2.5 km (1 km goal)	1 km - 5km horizontal resolution. Grid spacing 2km
Coastal Coverage	2.5 km (1 km goal)	1 km - 5km horizontal resolution. Grid spacing 2km
Revisit Time	6 hours (1-3 hour goal)	**1 Platform:** ~18 hours. **2Platforms:** ~9 hours
Data Latency	45-60 minutes from measurement product availability (15 minute goal)	**1 Polar Ground Station:** ~90 minutes for data download, 15 minute latency. **2 Polar Nort/South Ground Stations:** ~45 minutes for data download, 15 minutes latency.

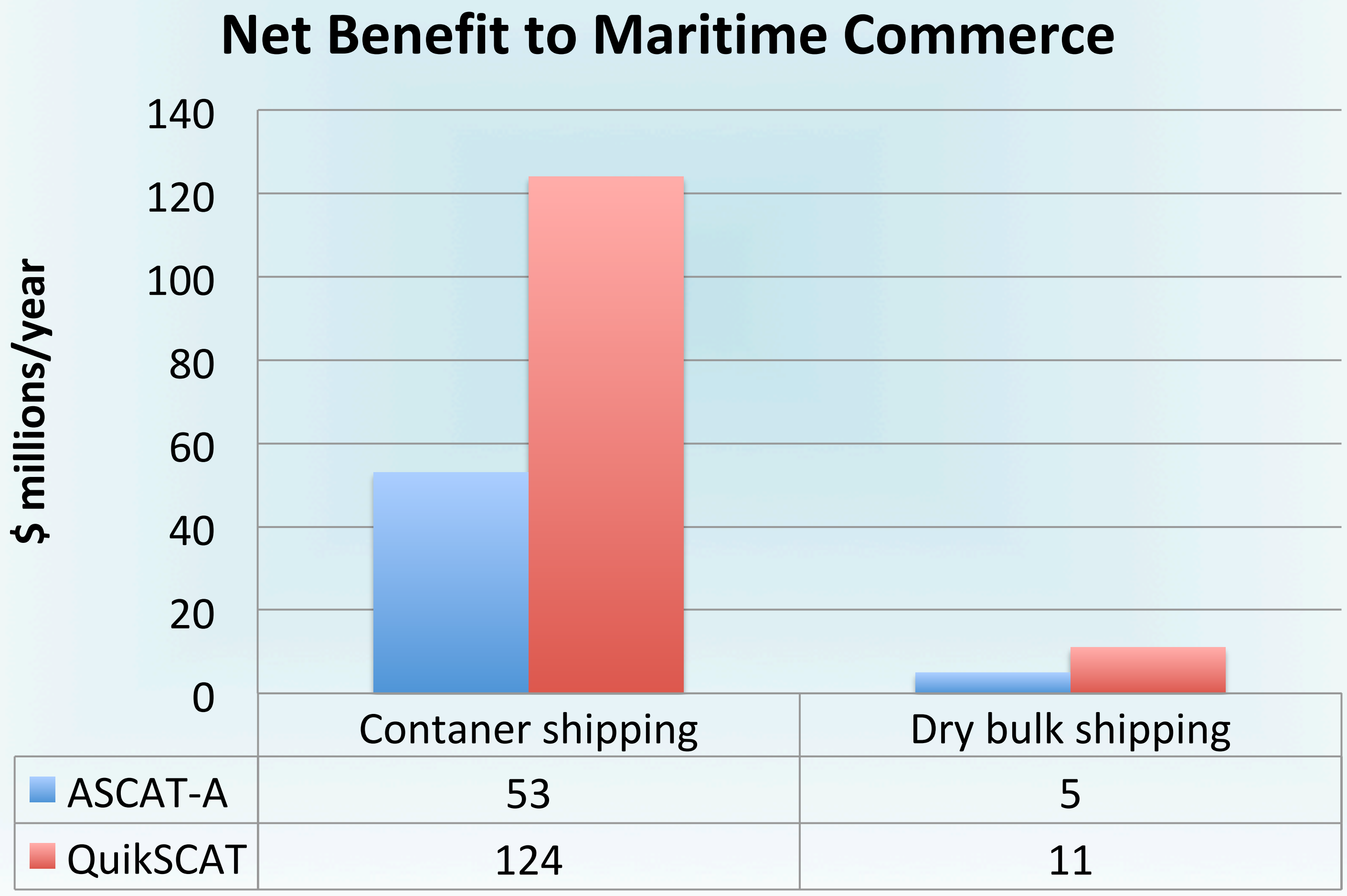
Table 6.1.1. NOAA OSVW measurement requirements and expected JPL-proposed (*Rodrigez at al, 2006*) next-generation ocean vector wind mission performance.

https://manati.star.nesdis.noaa.gov/SVW_nextgen/SVW_workshop_report_final.pdf

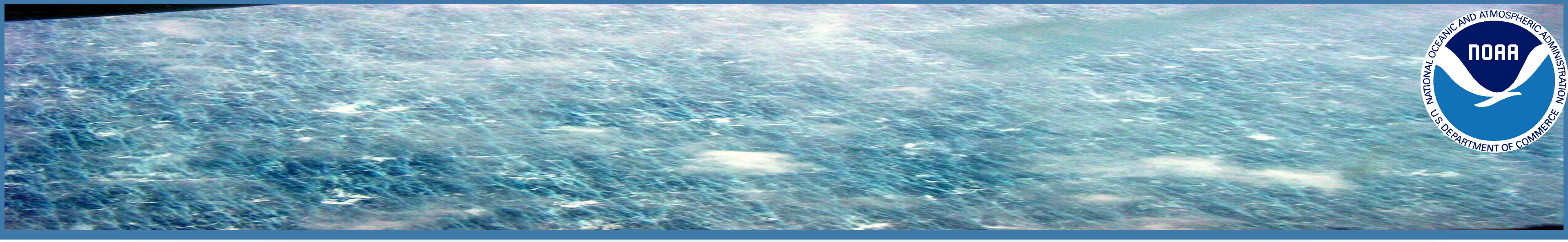
Economic Impact

Annual Saving to Maritime Transportation due to Reduced Exposure to Damaging Winds in Extratropical Storms

Kite-Powell, Hauke, 2008: Benefits to Maritime Commerce from Ocean Surface Vector Wind Observations and Forecasts, Maritime Economics and Logistics, pp. 15. Available online at: http://manati.orbit.nesdis.noaa.gov/SVW_nextgen/ QuikSCAT_maritime_report_final.pdf

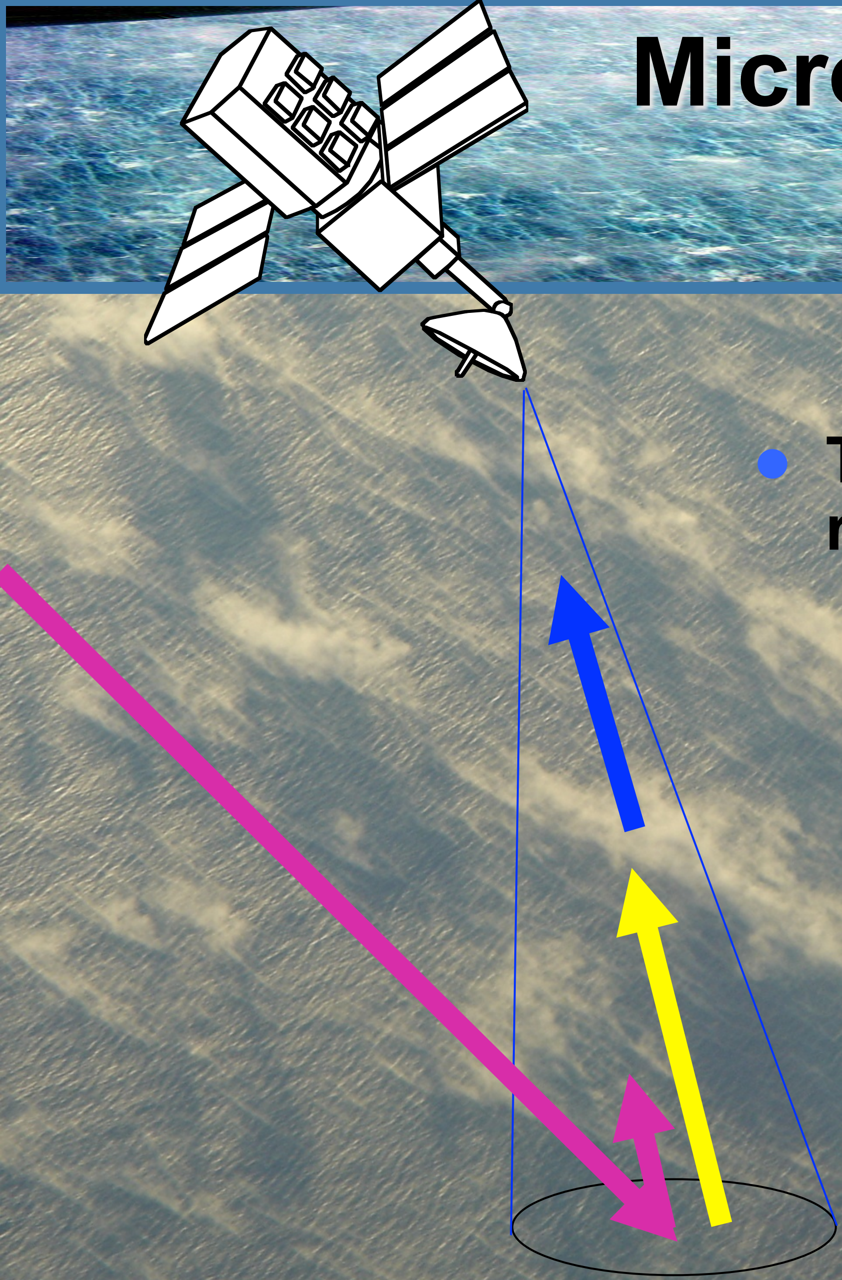


	Contaner shipping	Dry bulk shipping
🟦 ASCAT-A	53	5
🟥 QuikSCAT	124	11

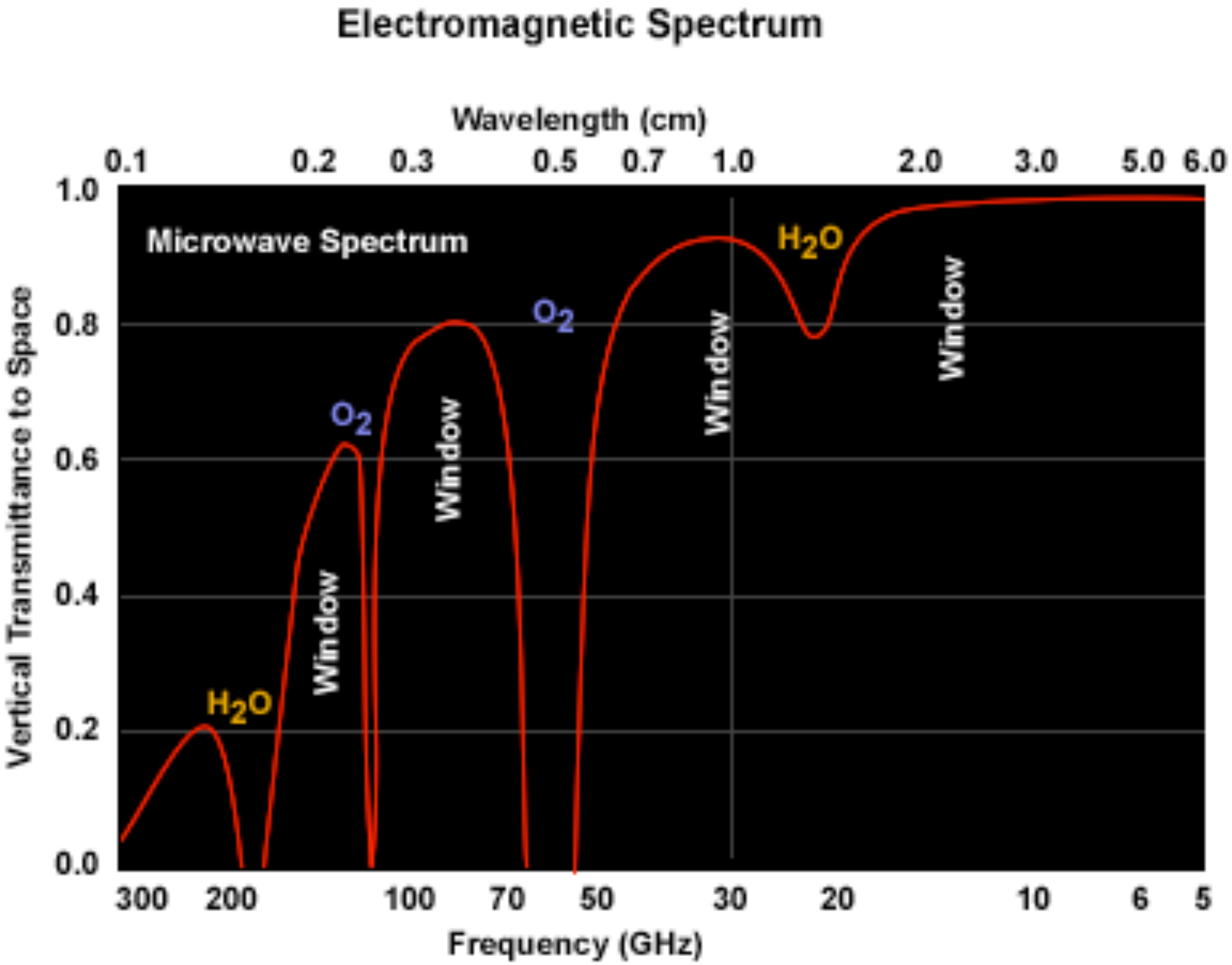


Passive Microwave

Microwave Radiometry



- Tb's measured by satellite radiometer consists of:
  - Signal that is emitted from the ocean surface and travels upwards
  - Upward traveling atmospheric radiation
  - Downward traveling atmospheric and cold space radiation that is scattered back from the ocean surface



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Multi Channel Passive Microwave

Long history with varying capabilities for ocean surface wind speeds

- SSM/I (DMSP 1987, 1990, 1991, 1995, 1997, 1999)
- SSMIS (DMSP 2003, 2006, 2009, 2014)
- TMI (TRMM 1997)
- AMSR (ADEOS-II 2002)
- AMSR-E (Aqua 2004)
- AMSR2 (GCOM-W1 2012)
- GMI (GPM 2014)
- AMSR3 (GOSAT-GW 2023)

The lowest frequency channel for SSM/I and SSMIS was 19 GHz
TMI and GMI have 10 GHz as their lowest frequency
All the AMSR sensors have frequencies as low as 6 GHz, which is necessary for ocean surface wind retrievals when there is significant levels of liquid water in the atmosphere.

Multi Channel Polarimetric Passive Microwave

- WindSat
    - NRL proof of concept mission for passive polarimetric retrieval of the ocean surface wind vector
    - Used by the IPO as risk reduction for CMIS planned for NPOESS
    - NESDIS part of the WindSat core science team and developed the first wind vector retrieval algorithm used by the WindSat mission
    - Initial feedback from NWS was that they say cloud signatures in the wind direction (i.e. water in the atmosphere was influencing the retrievals)
    - IPO/NPOESS funding disappeared to continue so while WindSat lasted forever, the OSVW was never fully validated and verified for suitability in NOAA's operations.
- COWVR
    - Technology demonstration to measure the polarimetric response by taking the cross correlation of the I&Q channels for V&H versus having separate feed horns for V/H,+-45 and RHC/LHC at each frequency as WindSat did.
        - Allows for larger swath and physically smaller package

Note: Current JV funded effort to investigate WindSat and COWVR in the context of NOAA's mission

L-band Passive Microwave

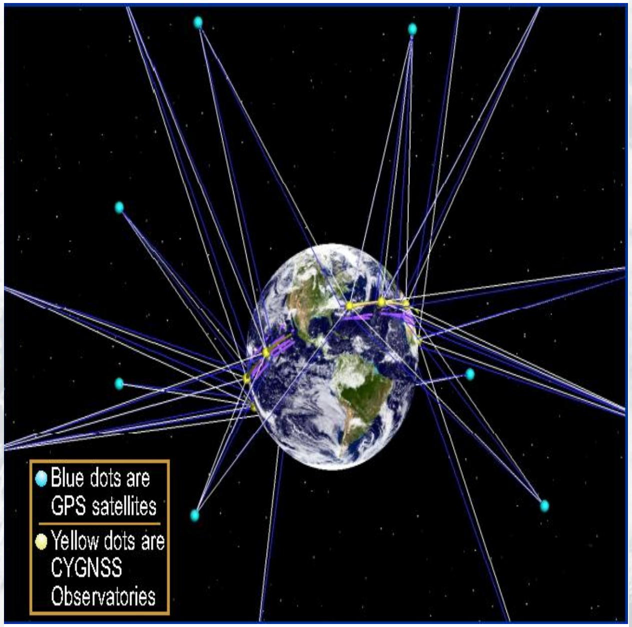
- Single frequency (L-band) microwave radiometer developed for soil moisture and salinity retrievals
- Relatively insensitive to water in the atmosphere
- Measured brightness temperature exhibits increasing trend with higher wind speeds in tropical cyclones (TCs)
- Relatively large antenna footprint
    - The footprint is larger than the areal extent of maximum winds found in TCs.
        - The measured brightness temperature comes from regions of high winds and low winds. (i.e. eye and eye wall region)
        - The L-band “retrieved” peak winds in a TC are not because the instrument viewed a area of peak winds over the ocean surface commensurate in size to the antenna footprint.
        - This artificial linking of the brightness temperature measurements to a peak TC wind tends to skew the wind distribution at the lower winds.

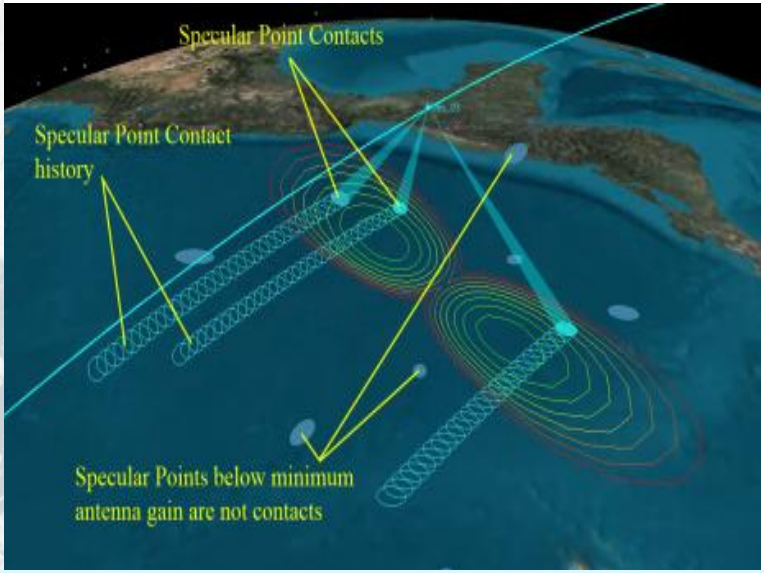
Note: Co-I’s on a NASA SMAP proposal working with JPL to evaluate and update their SMAP retrievals in the context of supporting NOAA’s marine weather mission

GNSSR-CYGNSS

CYGNSS Mission

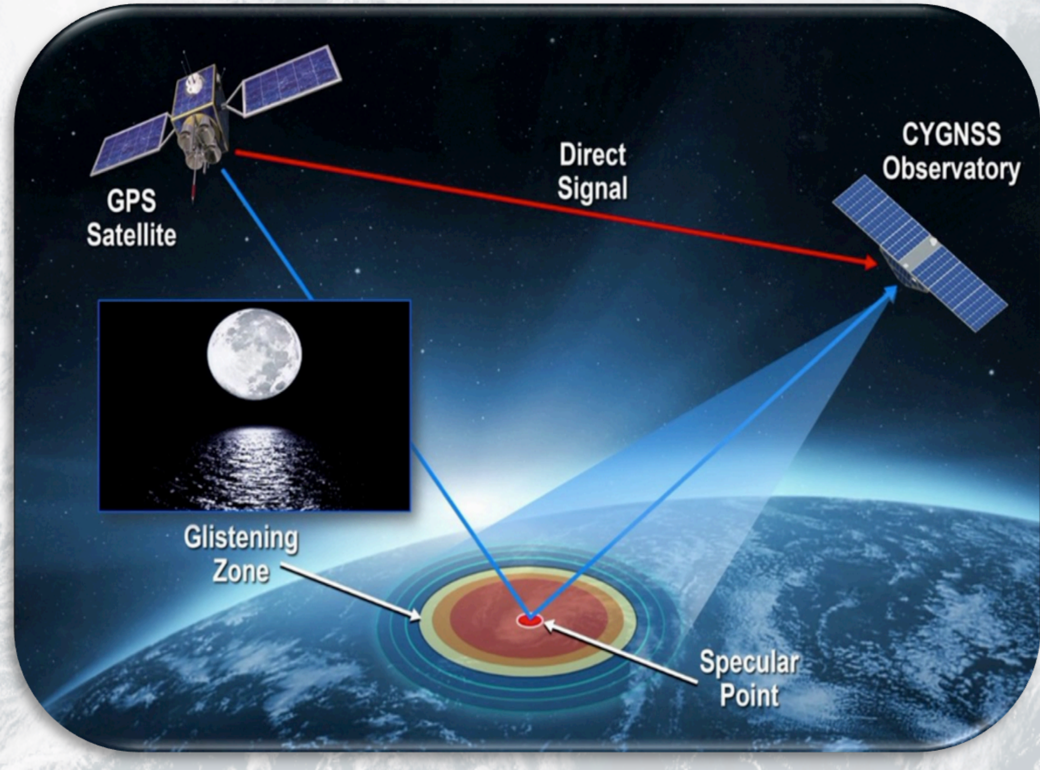
- Cyclone Global Navigation Satellite System (CyGNSS) is NASA Earth Venture Mission
  - PI lead Mission
  - Surrey GPS Recievers
- Launched 15th, Dec 2016
- Constellation
  - 8 spacecrafts
  - 2 receiving antennas
  - Transmitted signal generated from 32 GPS satellites
  - Each antenna can follow up to 4 reflections at the same time



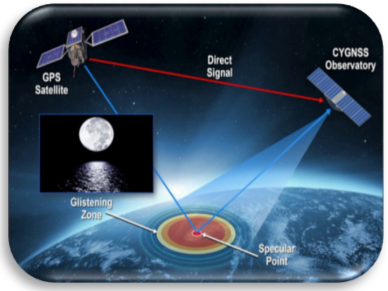


CYGNSS Observation Concept

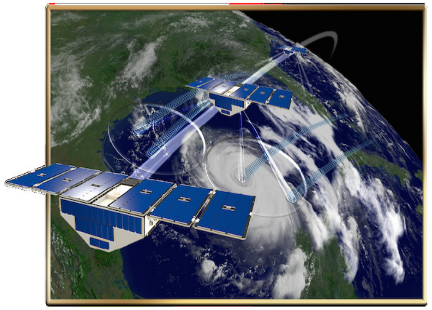
- The measurement concept relies on bi-statically reflected signals transmitted from global navigation satellites
- The unique range coded modulation of the GPS signals, allows for the mapping of received power as a function of both time- delay and Doppler frequency across the ocean surface.



Brief Background on CyGNSS

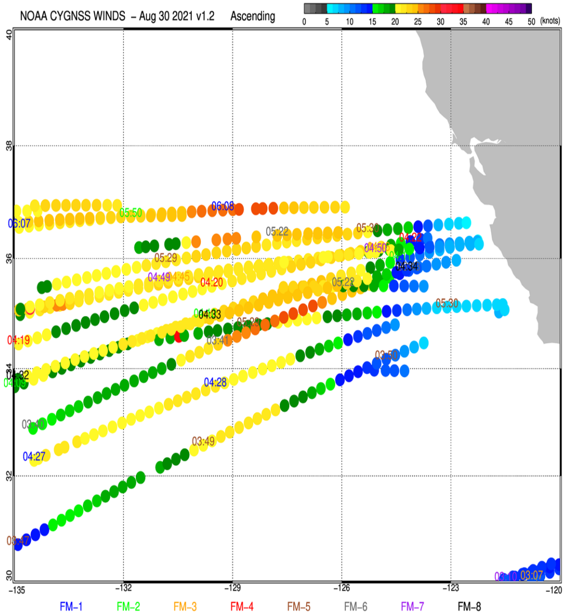


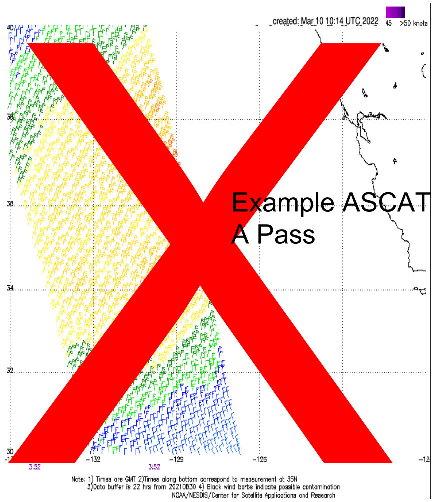
Source: University of Michigan



Source: PODAAC

- Constellation of 8 (low cost) micro-satellites launched on December 15 2016, processing specular reflections from Global Positioning System (GPS) satellites (1.57 GHz L1-band radio frequency) **resulting in a set of tracks (up to 4 per sensor) instead of the usual 'swath based coverage'**
- Wind speed is inferred from the normalized bi-static radar cross section (NBRCS)
- Some of the major challenges with this mission:
  - intersatellite NBRCS calibration
  - Signal sensitivity decreases as the wind speed increases
  - No exact knowledge of GPS transmit power
- v1.2 is the latest NOAA CyGNSS 25km wind data product (based on v2.1 NBRCS) soon to be available on the PO.DAAC
- Global wind images already available on the NOAA Manati site (https://manati.star.nesdis.noaa.gov/datasets/CYGNSSData.php)





Example ASCAT-A Pass

Publication providing details on the NOAA Track-wise algorithm:

F. Said, Z. Jelenak, J. Park, P. S. Chang, "The NOAA track-wise wind retrieval algorithm and product assessment for CyGNSS", Geoscience and Remote Sensing, IEEE Transaction on, July 2021, DOI: 10.1109/TGRS.2021.3087426

Why We Were in Interested to be Part of the CYGNSS Mission Proposal?

- Understand the capabilities and limitations of GNSS-R remote sensing for ocean surface wind speeds
  - How might GNSS-R complement the satellite observing system portfolio
  - Gain knowledge to guide NOAA when engaging commercial data providers
- Understand the value of a constellation sampling approach (frequent revisits over the course of about 100 minutes)
  - What benefits do increased temporal sampling provide
  - How frequently do we need to sample

Original Assumptions

Limiting funds for full antenna pattern characterization:

- All eight spacecraft supposedly identical in terms of hardware characteristics
  - Only one antenna gain pattern measured on the ground

No control over the transmitted signals but we assume:

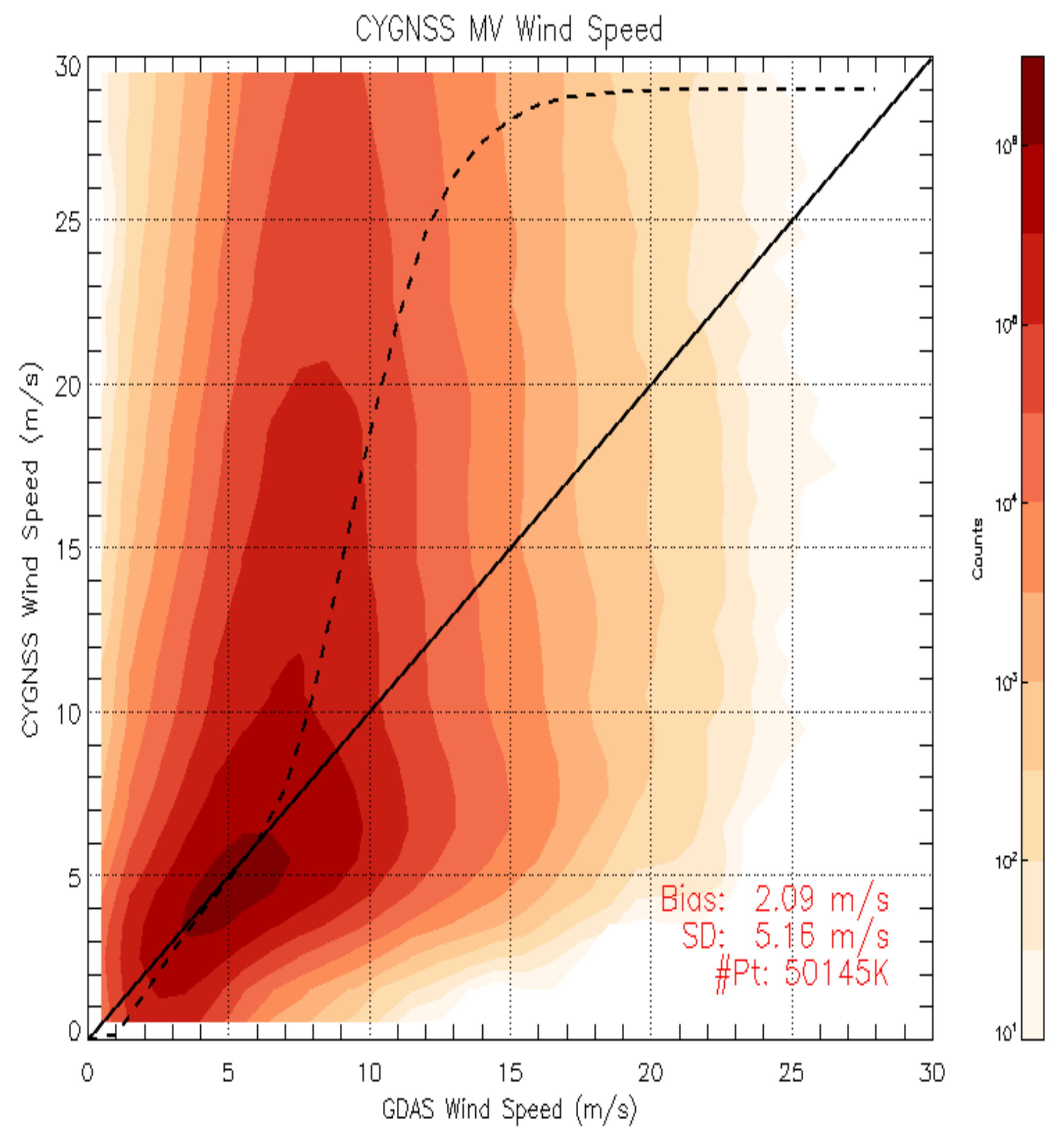
- All GPS satellites are consistent in its performance
  - May not have to worry about the exact transmitted power from the various GPS satellites

Published GPS Antenna Patterns are accurate:

- GPS Satellites separated into 3 blocks (IIR, IIR-M and IIF) by antenna designs

CYGNSS First Wind Data Release June 2017

All Quality Flags Applied

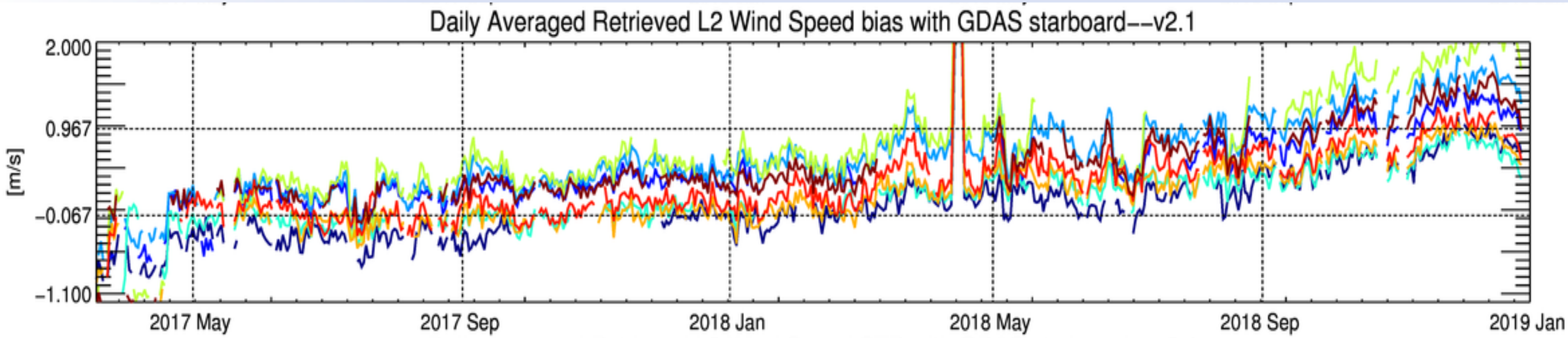


Wind Speed Bias Time Series

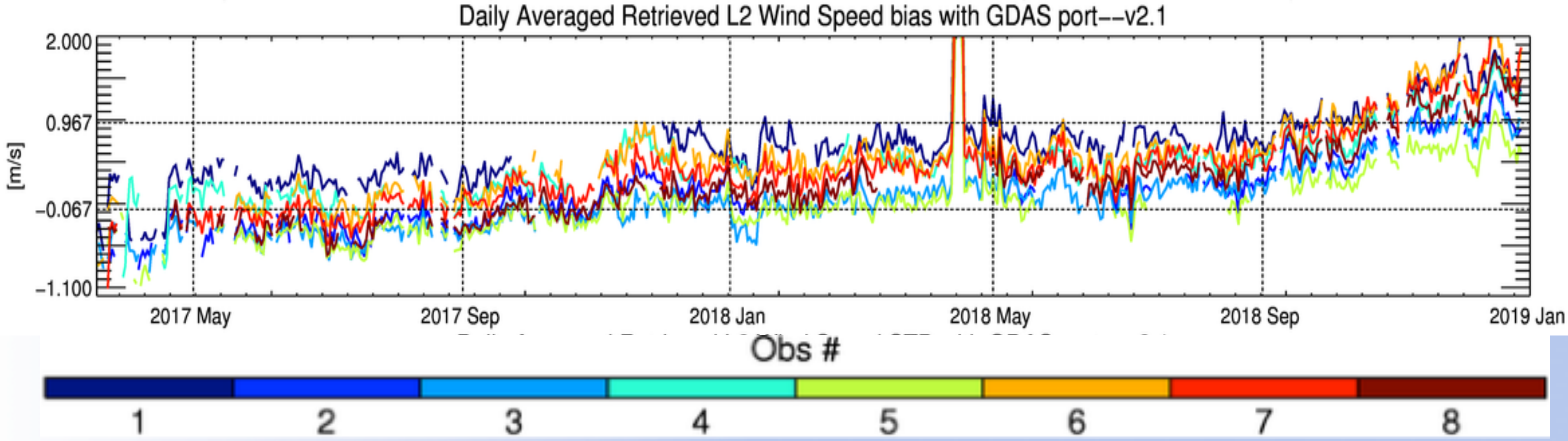
Starboard>Port 5,4,2,8,7

Port>Starboard 1,4,6

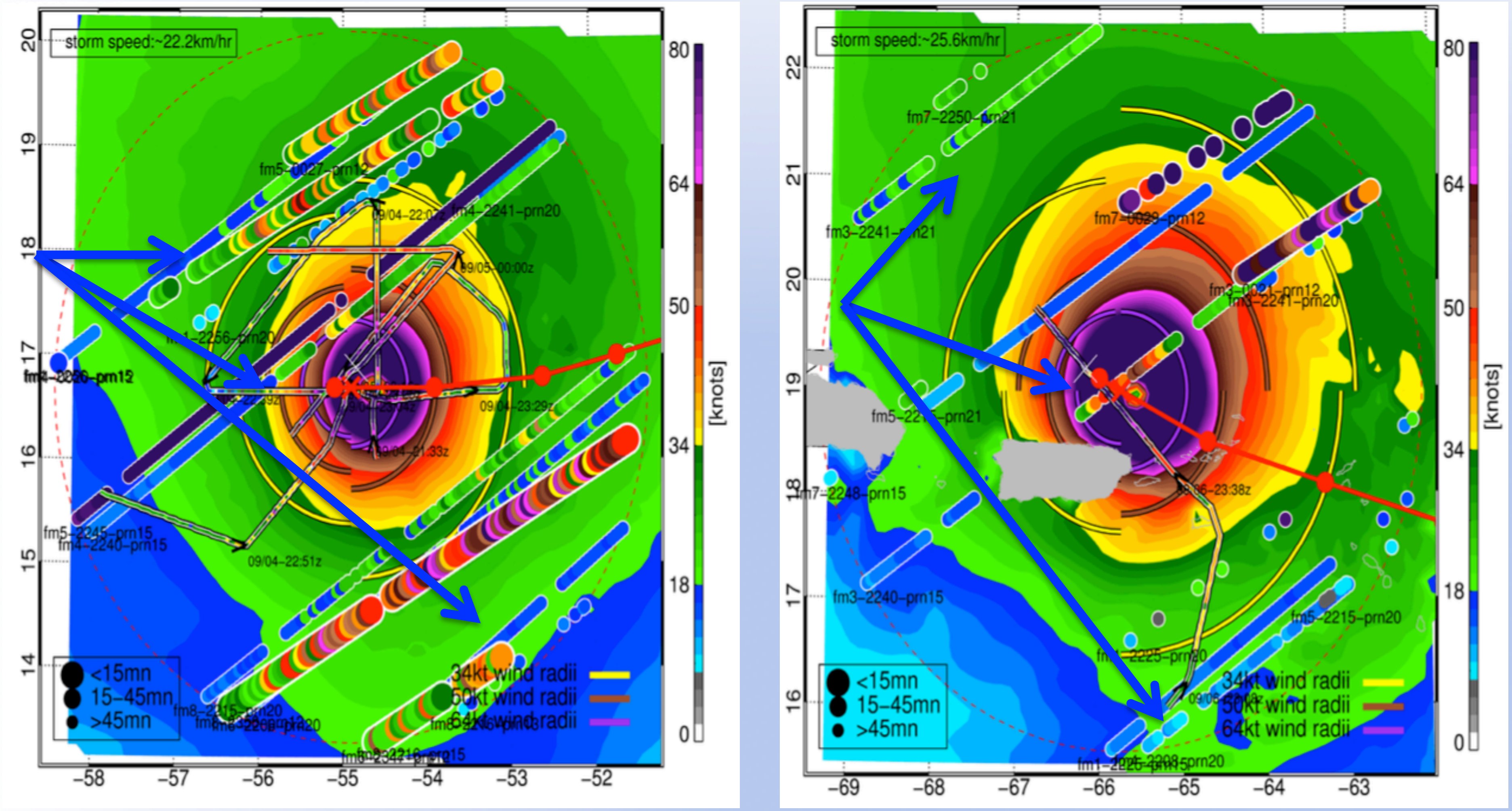
STARBOARD



PORT

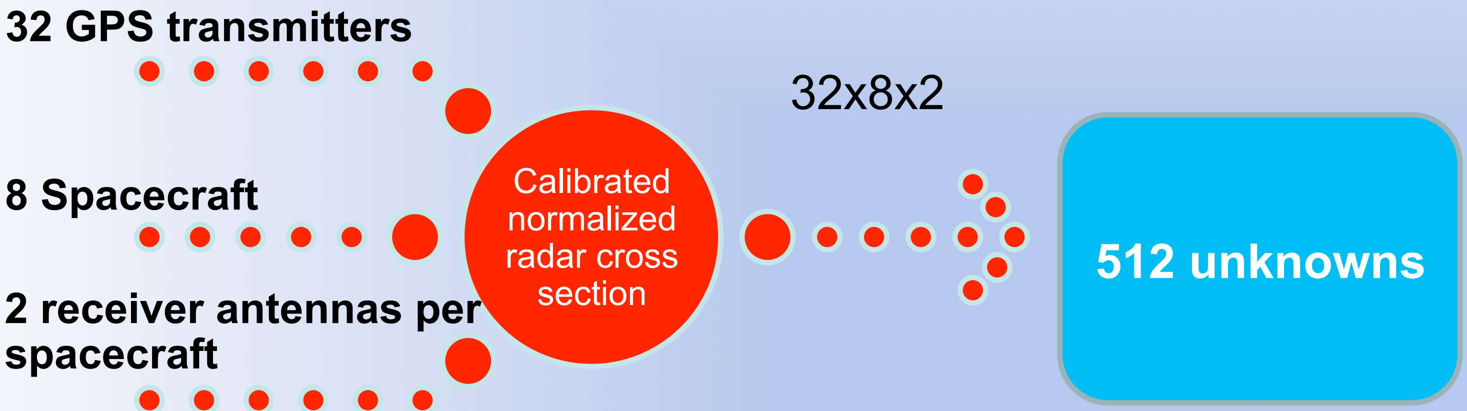


Cyclone Observations



Not a cherry picked example unfortunately….

CYGNSS Reality



32 GPS transmitters

8 Spacecraft

2 receiver antennas per spacecraft

Calibrated normalized radar cross section

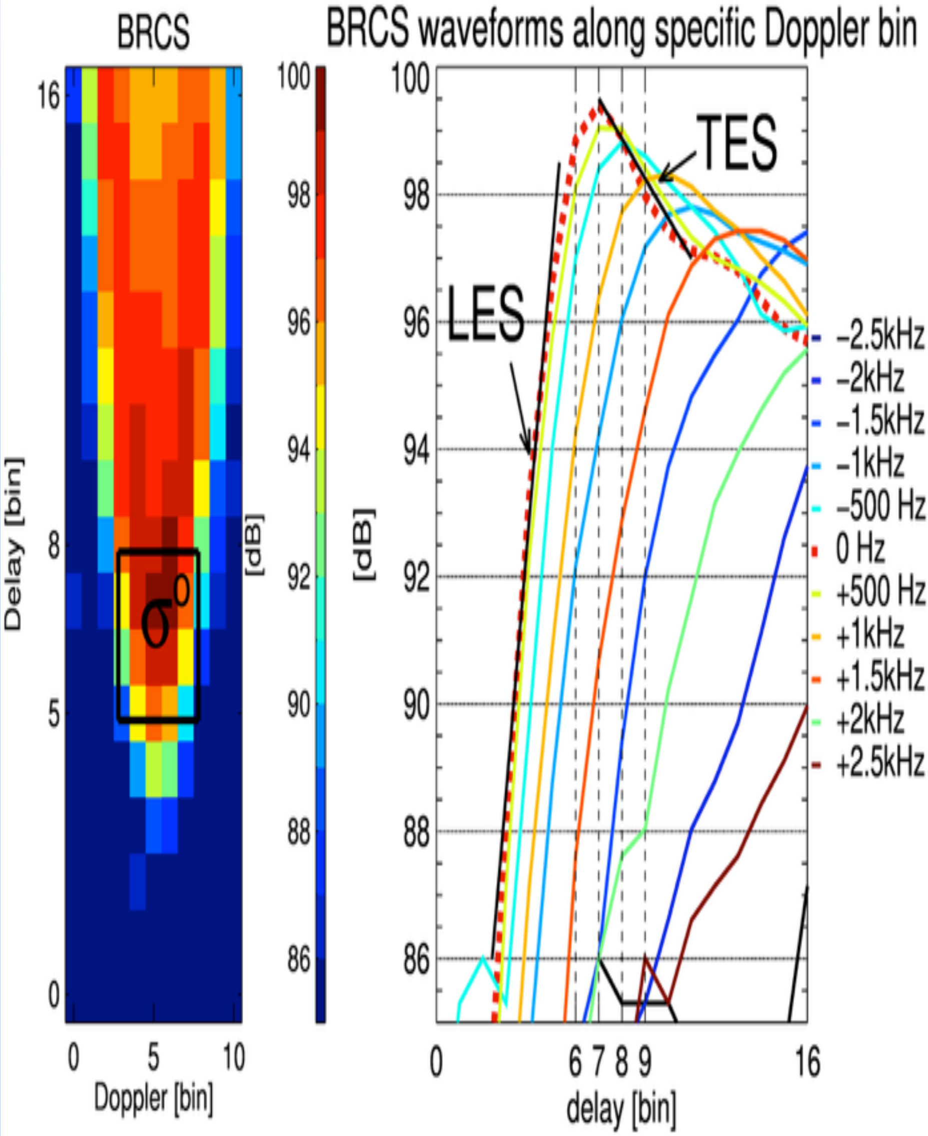
32x8x2

512 unknowns

UniversalImagesGroup via Getty Images
Boy scratching head (Photo by Universal Images Group via Getty Images)
Source: https://www.huffingtonpost.ca

CYGNSS Observables

- Wind estimates obtained from two observables: Leading Edge Slope (LES) and Normalized Bistatic Radar Cross Section (NBRCS)
- Observables reported every 6km along the track

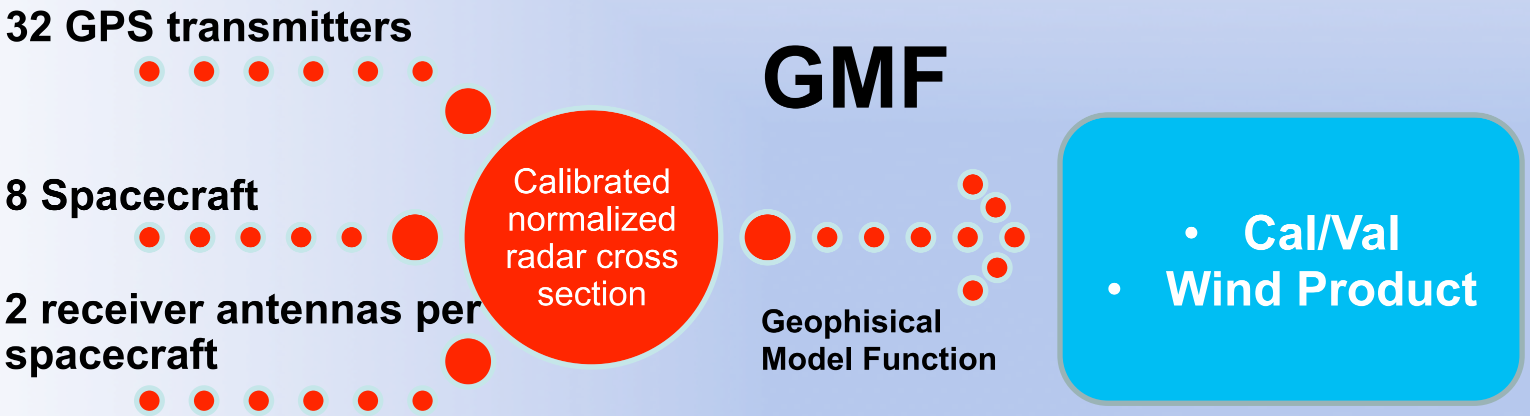


NOAA Wind Product Requirements for User Applications

- Stability
- Consistency
- Repeatability
- Error Characteristics - Bias, RMS

In order to assess CYGNSS viability for NOAA operations we decided we had to develop our own CYGNSS Wind Product

Starting Point



32 GPS transmitters

8 Spacecraft

2 receiver antennas per spacecraft

Calibrated normalized radar cross section

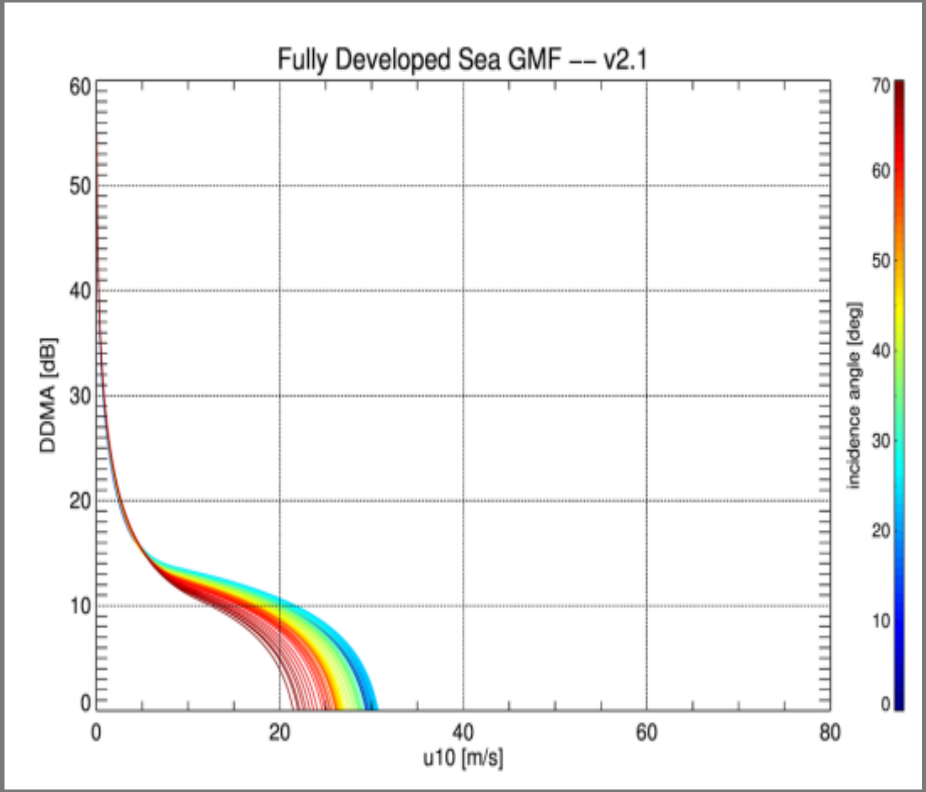
GMF

Geophisical Model Function

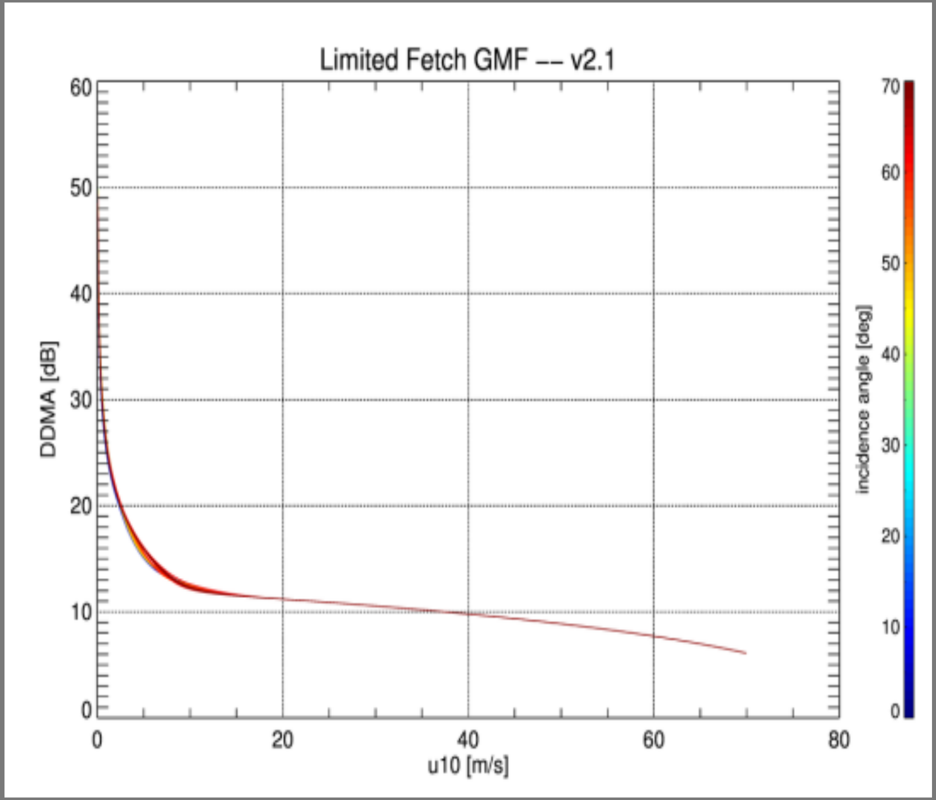
- **Cal/Val**
- **Wind Product**

UMICH GMFs – Official CYGNSS Project GMF

UMICH FDS v2.1



UMICH YSLF v2.1



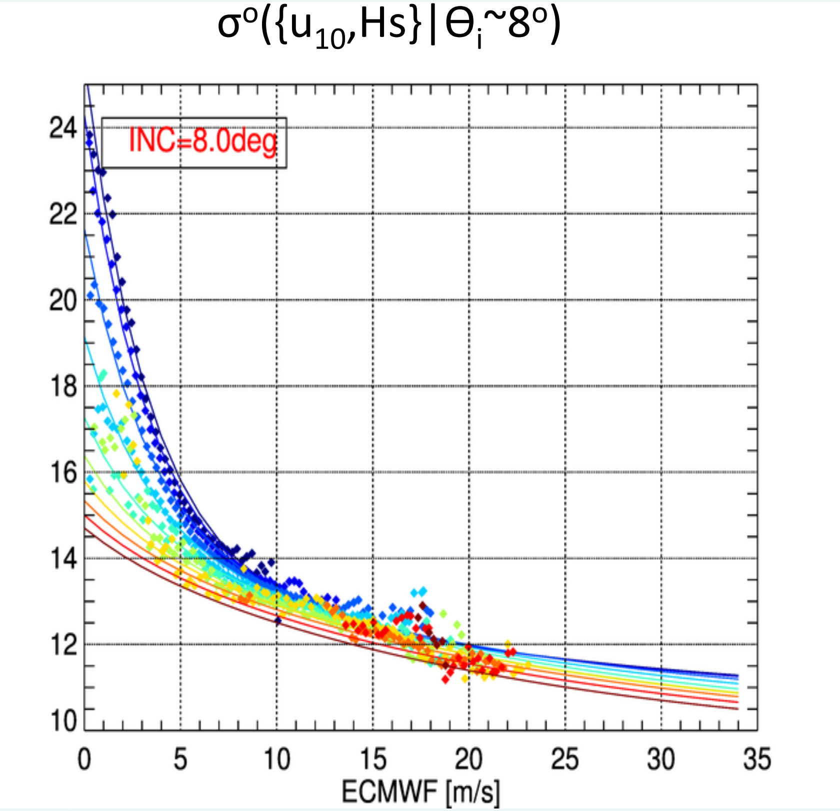
University of Michigan Developed CYGNSS GMF’s – UMICH GMF

***NOAA** Wind and Wave Dependent CYGNSS GMF*

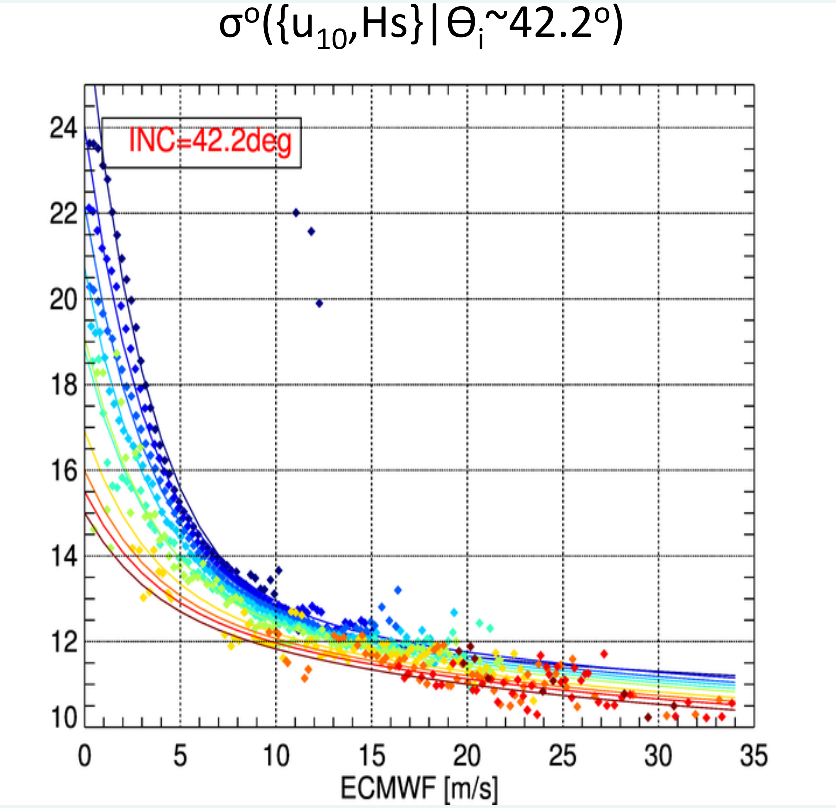
Utilizing CYGNSS Data Version 2.1

$$\sigma^o\underbrace{(u_{10},Hs,\Theta_i)}_{0\text{-}75m/s \mid 0\text{-}10m \mid 0\text{-}70^o}$$

$\sigma^o(\{u_{10},Hs\}|\Theta_i\sim8^o)$

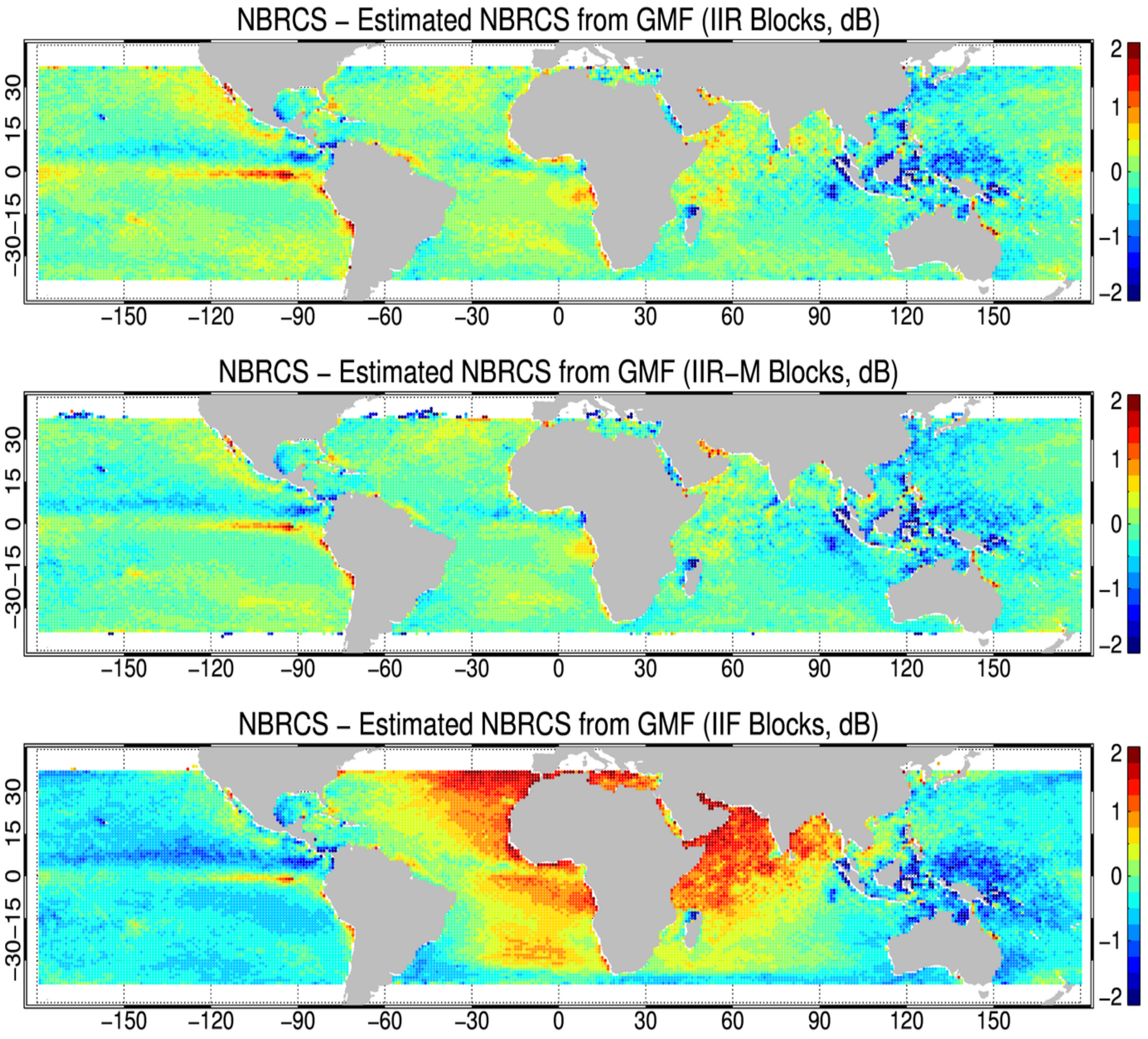


$\sigma^o(\{u_{10},Hs\}|\Theta_i\sim42.2^o)$



Understanding CYGNSS Measurements

GPS Blocks – NOAA GMF



NBRCS – Estimated NBRCS from GMF (IIR Blocks, dB)

NBRCS – Estimated NBRCS from GMF (IIR–M Blocks, dB)

NBRCS – Estimated NBRCS from GMF (IIF Blocks, dB)

Sat. ASC/DES and ANT (IIF) - Anomaly

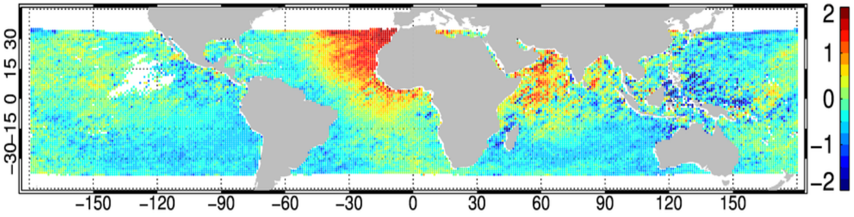
>300 points per grid

CYG ASC

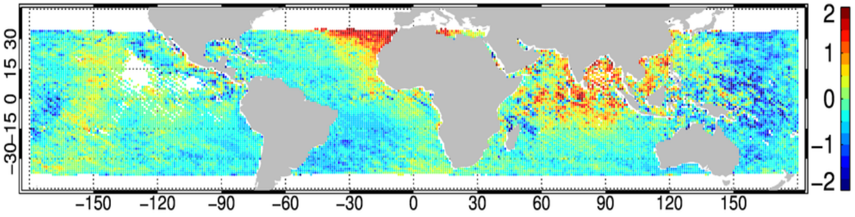
CYG DES

GPS ASC

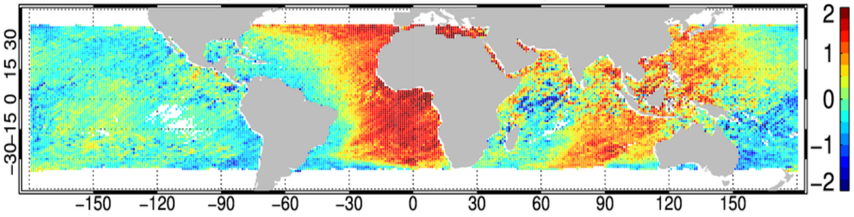
IIF, GPS ASC and CYG ASC, STARBOARD



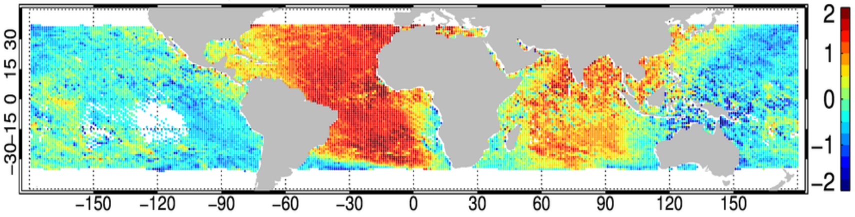
IIF, GPS ASC and CYG DES, STARBOARD



IIF, GPS ASC and CYG ASC, PORT

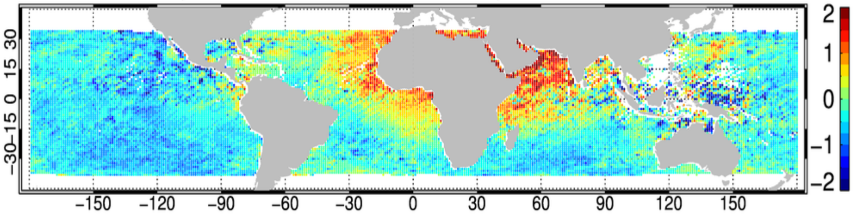


IIF, GPS ASC and CYG DES, PORT

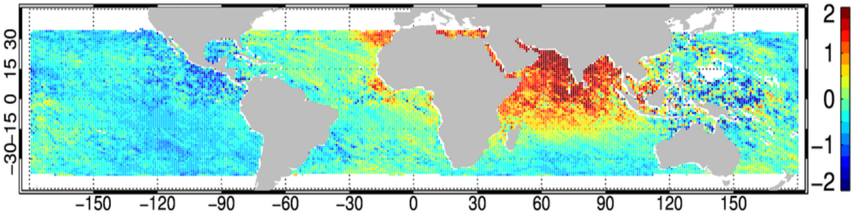


GPS DES

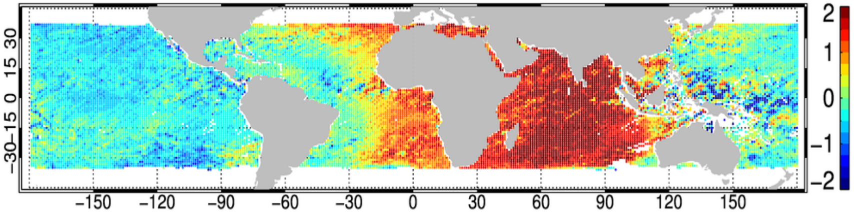
IIF, GPS DES and CYG ASC, STARBOARD



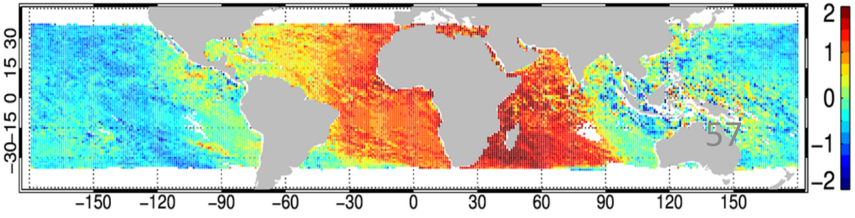
IIF, GPS DES and CYG DES, STARBOARD



IIF, GPS DES and CYG ASC, PORT

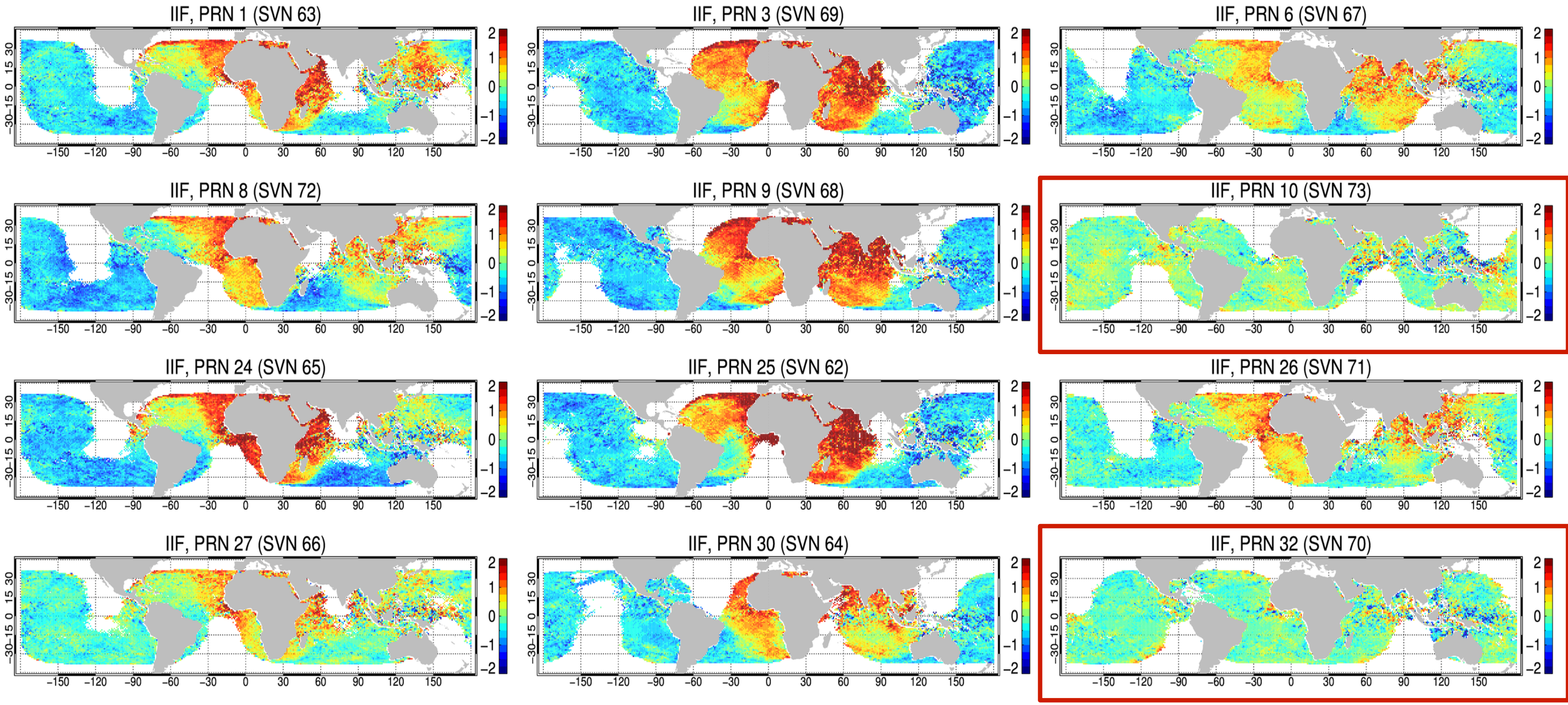


IIF, GPS DES and CYG DES, PORT



Each PRN Code (IIF) - Anomaly

>300 points per grid



IIF, PRN 1 (SVN 63)

IIF, PRN 3 (SVN 69)

IIF, PRN 6 (SVN 67)

IIF, PRN 8 (SVN 72)

IIF, PRN 9 (SVN 68)

IIF, PRN 10 (SVN 73)

IIF, PRN 24 (SVN 65)

IIF, PRN 25 (SVN 62)

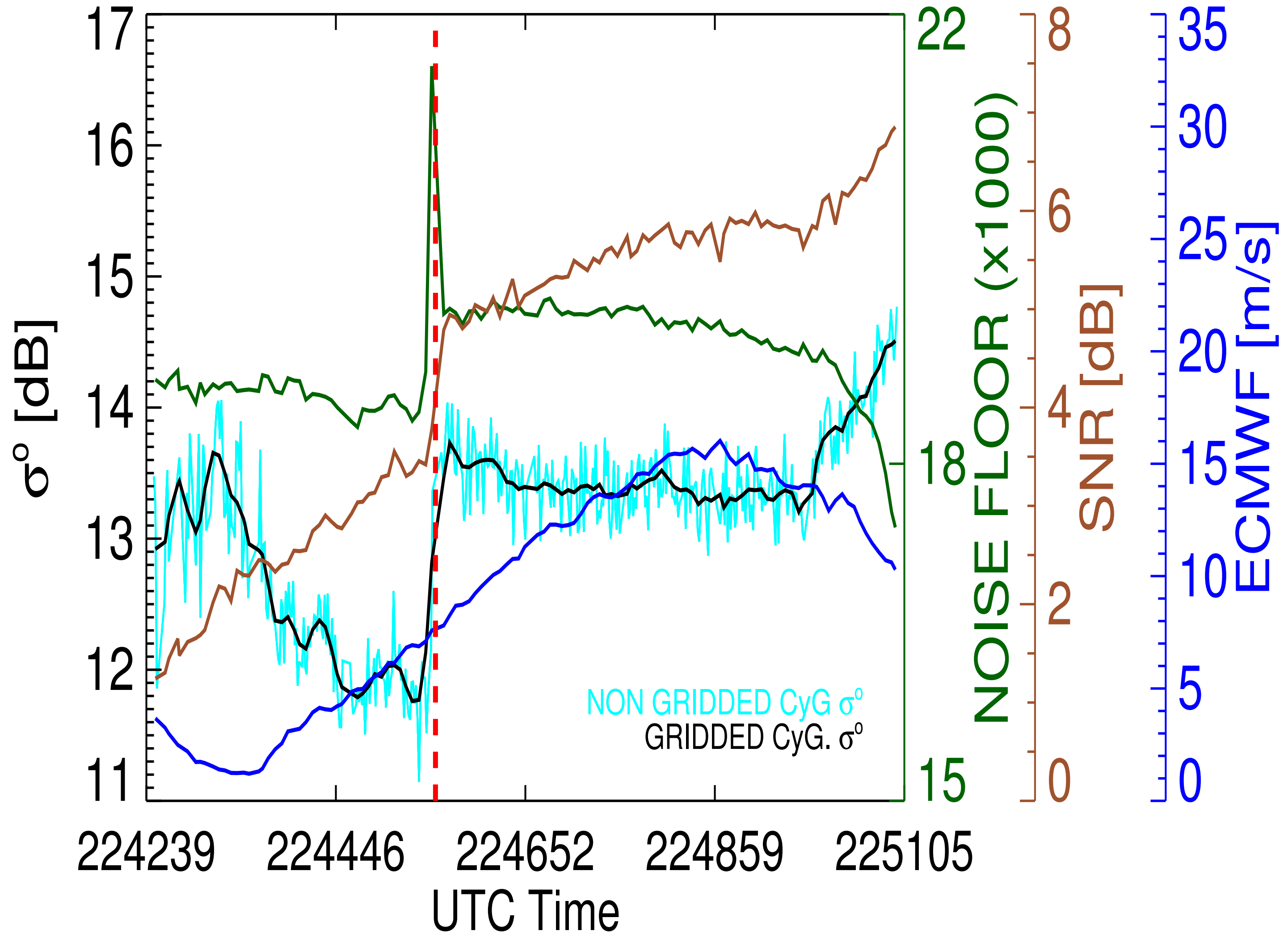
IIF, PRN 26 (SVN 71)

IIF, PRN 27 (SVN 66)

IIF, PRN 30 (SVN 64)

IIF, PRN 32 (SVN 70)

Power Flex Event Detected Along the Track

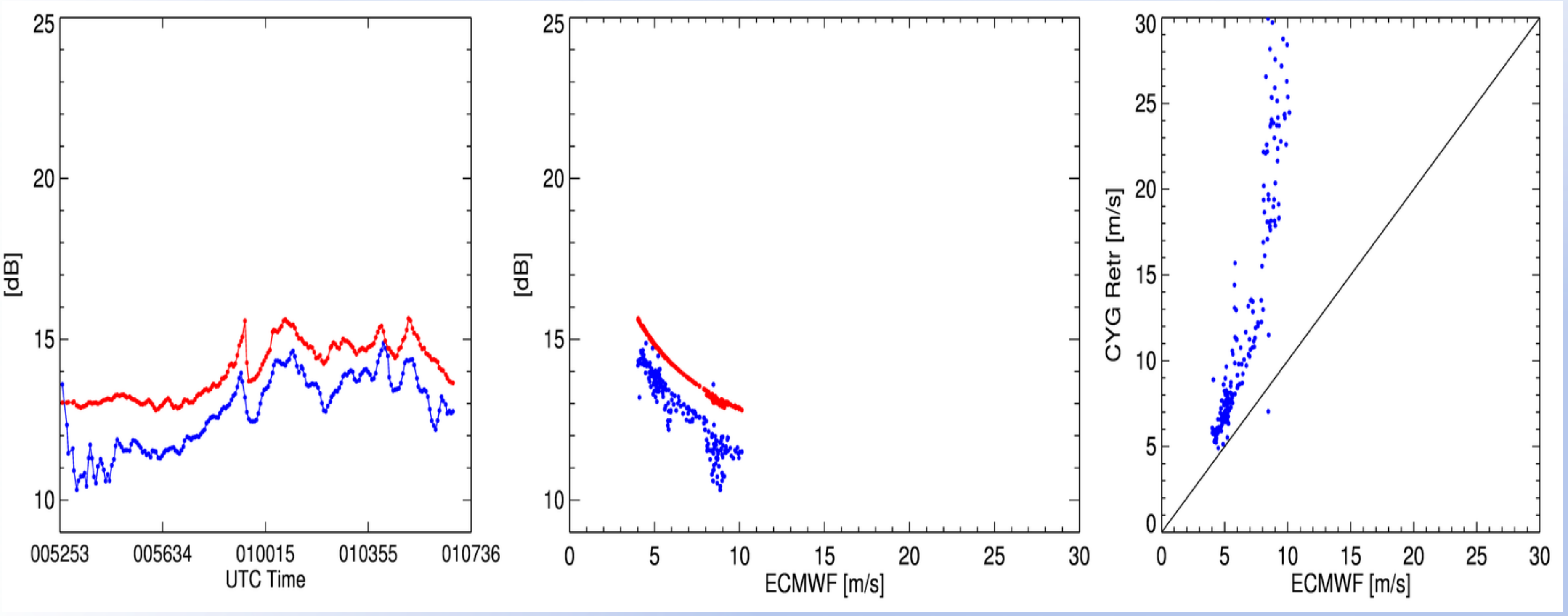


NOAA Solutions for CYGNSS

- To reduce measurement noise – create coarser resolution NBRCS product (0.25^0x0.25^0)

- Developed and Implemented Along Track Retrieval Algorithm (ATRA) with track debiasing procedure
  - For a given track (i.e. where consecutive specular points are ‘locked’ to a particular GPS transmitter), generate σ^o time series
  - Generate corresponding σ^o time series using the GMF
  - Compute overall σ^o bias between the two excluding ‘poor quality’ σ^o (e.g. Rx gain < 5dB and poor attitude)
  - Apply this fixed bias correction to all measured σ^o along the track

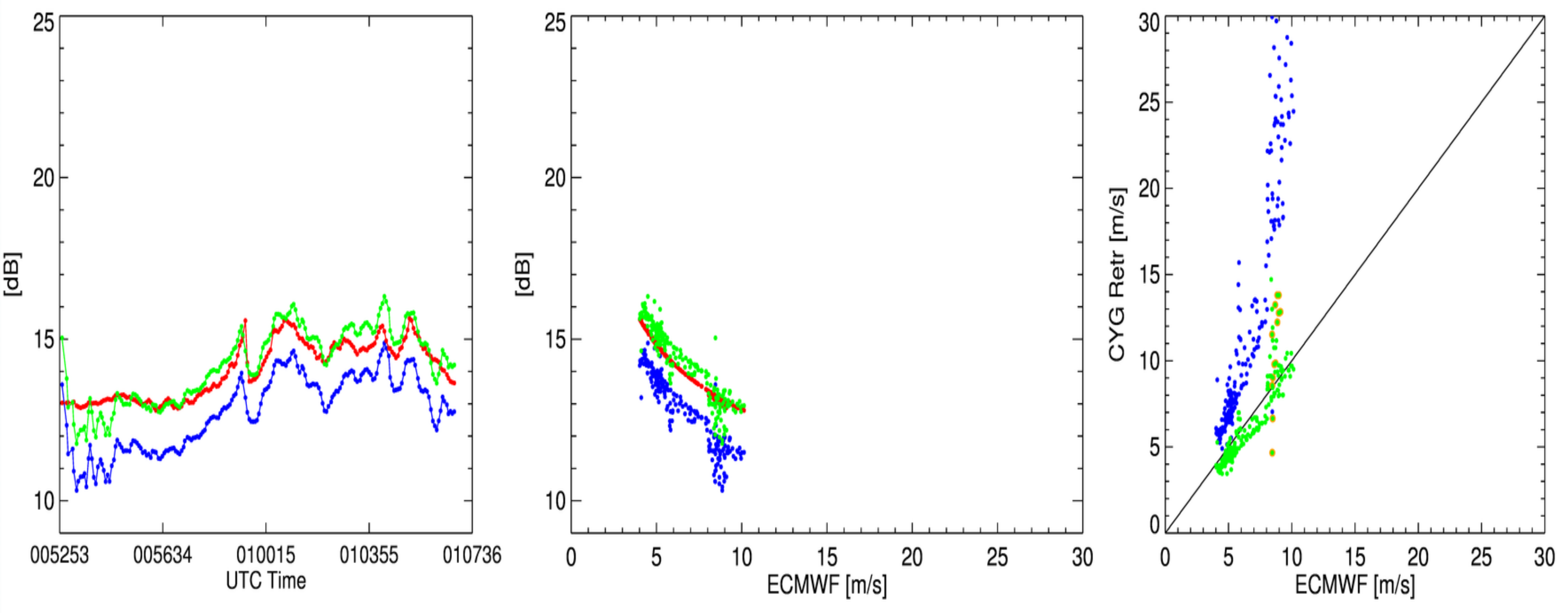
Track Debiasing Idea



━ **CYGNSS σ_0**

━ **GMF Simulated σ_0**

Track Debiasing Implementation



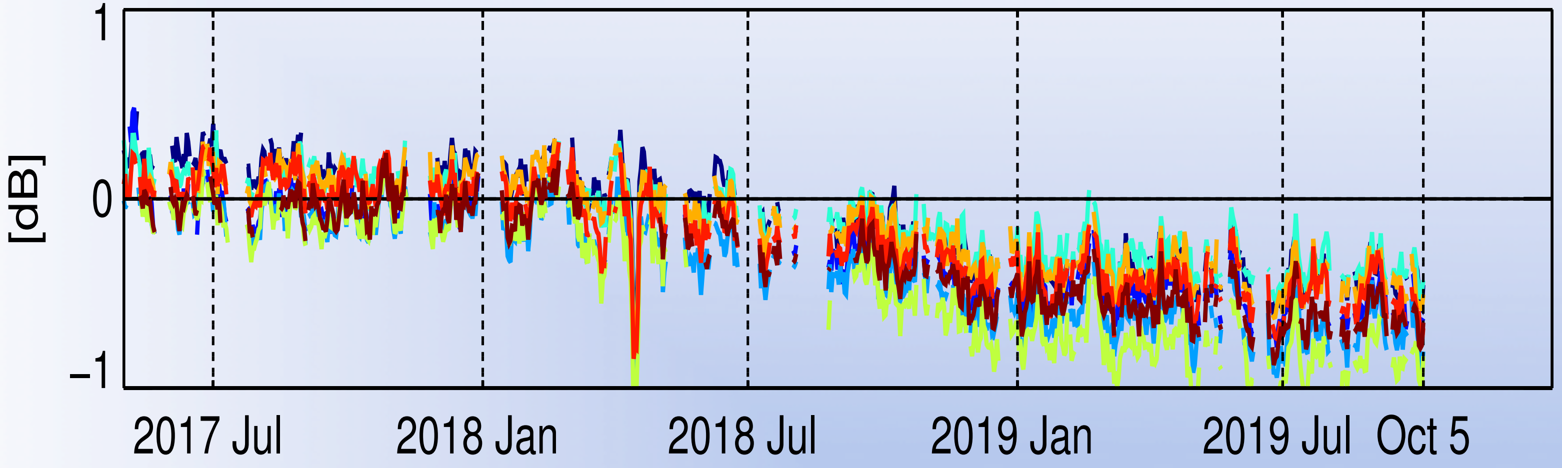
🟦 **CYGNSS σ_0**

🟥 **GMF Simulated σ_0**

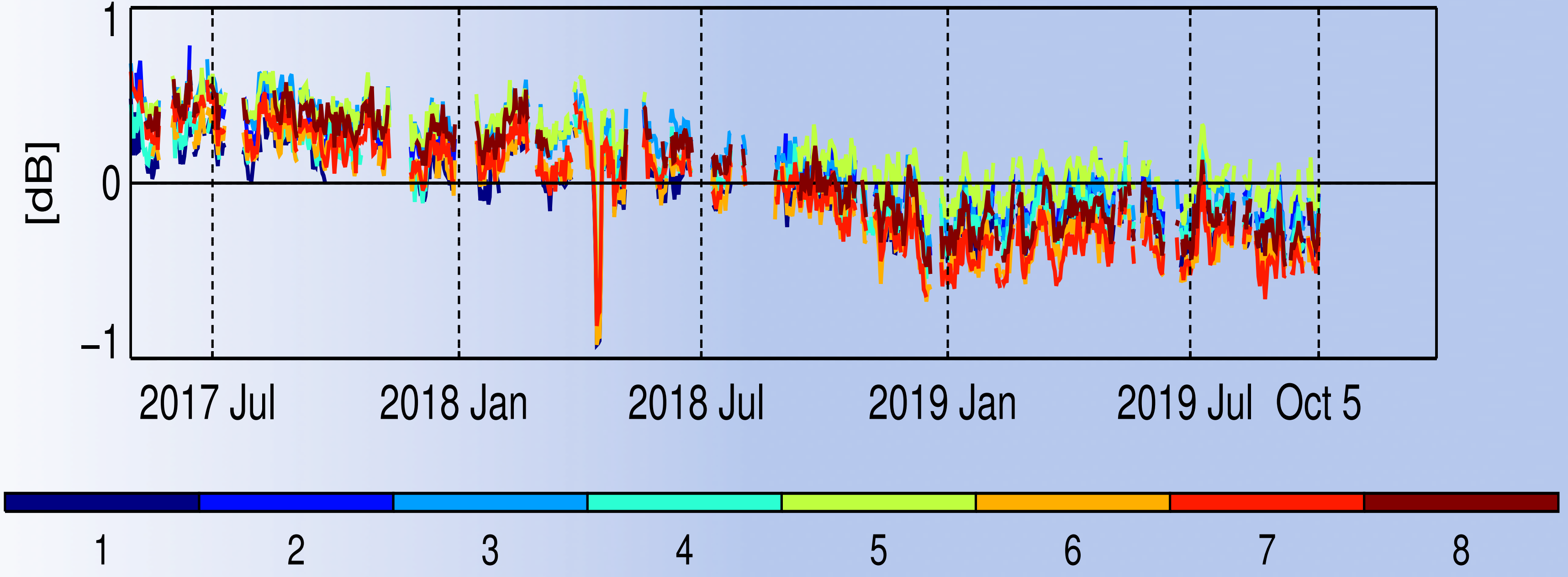
🟩 **Debiased CYGNSS σ_0**

Before Track Debiasing

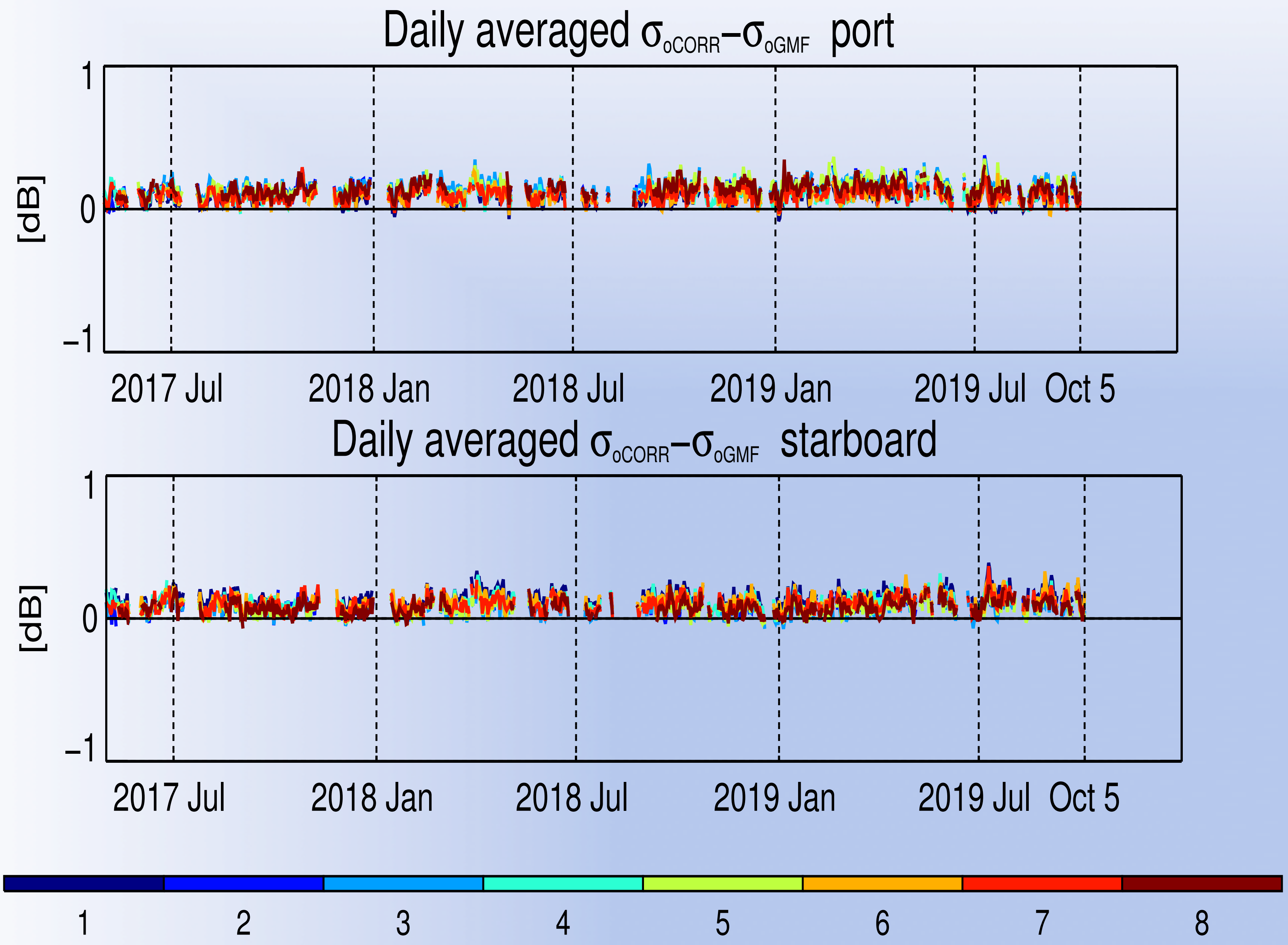
Daily averaged $\sigma_o - \sigma_{oGMF}$ port



Daily averaged $\sigma_o - \sigma_{oGMF}$ starboard



After Track Debiasing



Daily averaged $\sigma_{oCORR}-\sigma_{oGMF}$ port

Daily averaged $\sigma_{oCORR}-\sigma_{oGMF}$ starboard

NOAA CYGNSS Wind Product

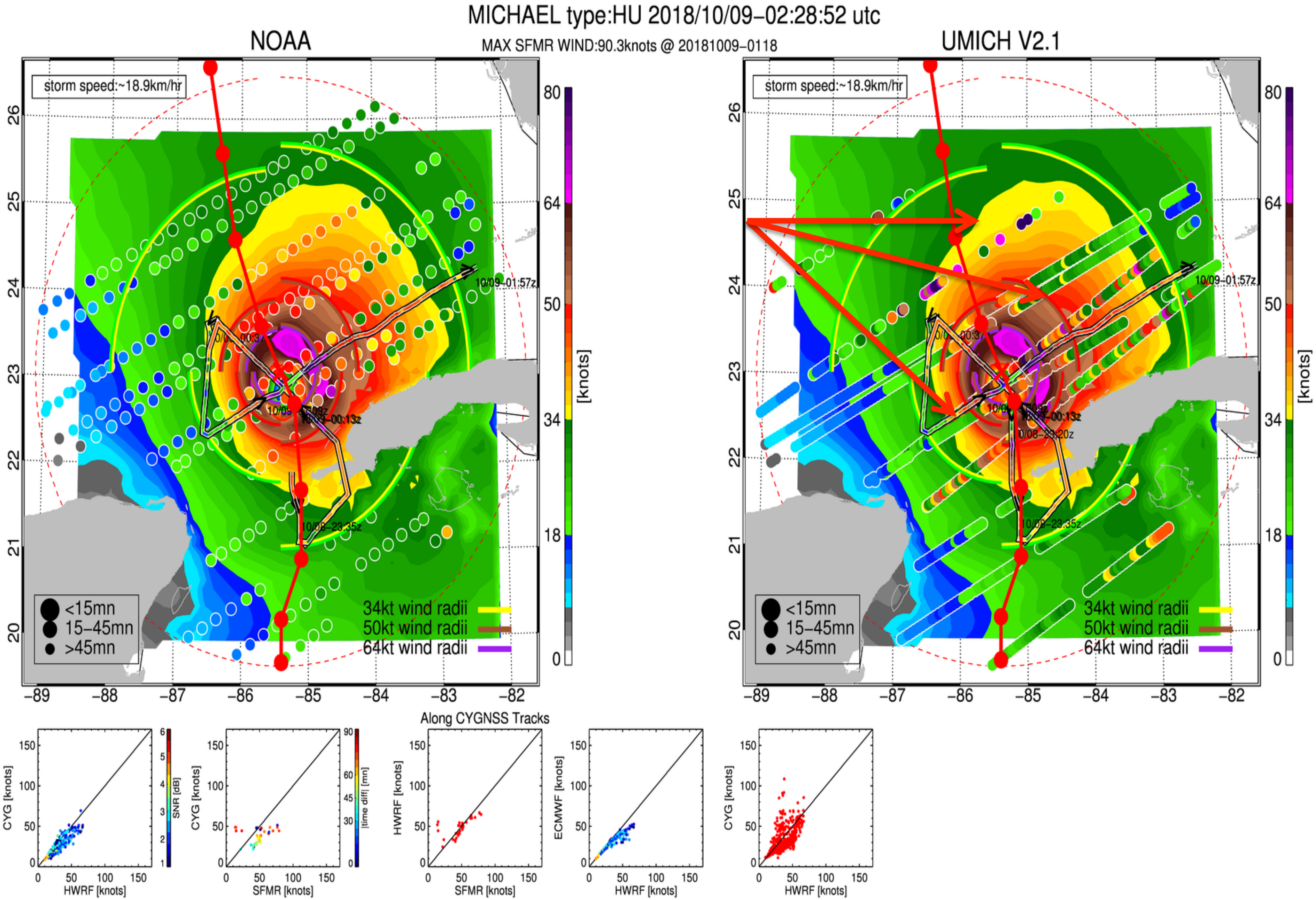
- Ver 1.1 Released on PODAAC September 28, 2020

- Ver 1.2 Is getting ready for release in May 2022. Data will be available to global community in quasi NRT (as soon as CYGNSS data is downloaded from spacecraft)
    - Utilizes some of the star tracker data
    - Improved retrieval procedure
    - Improved GMF

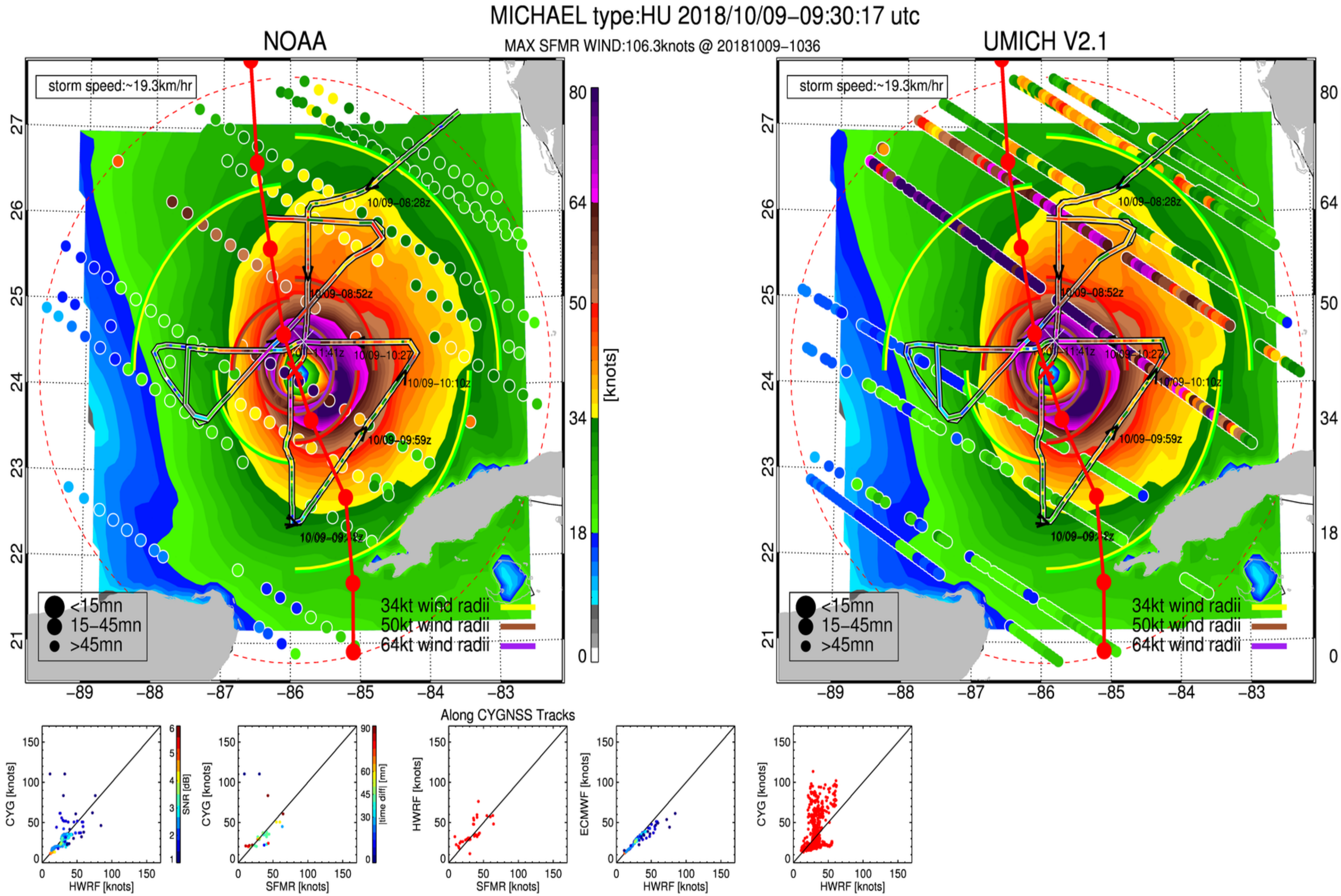
NOAA vs. Official CYGNSS Wind in Tropical Cyclones

‘TRUTH’: HWRF

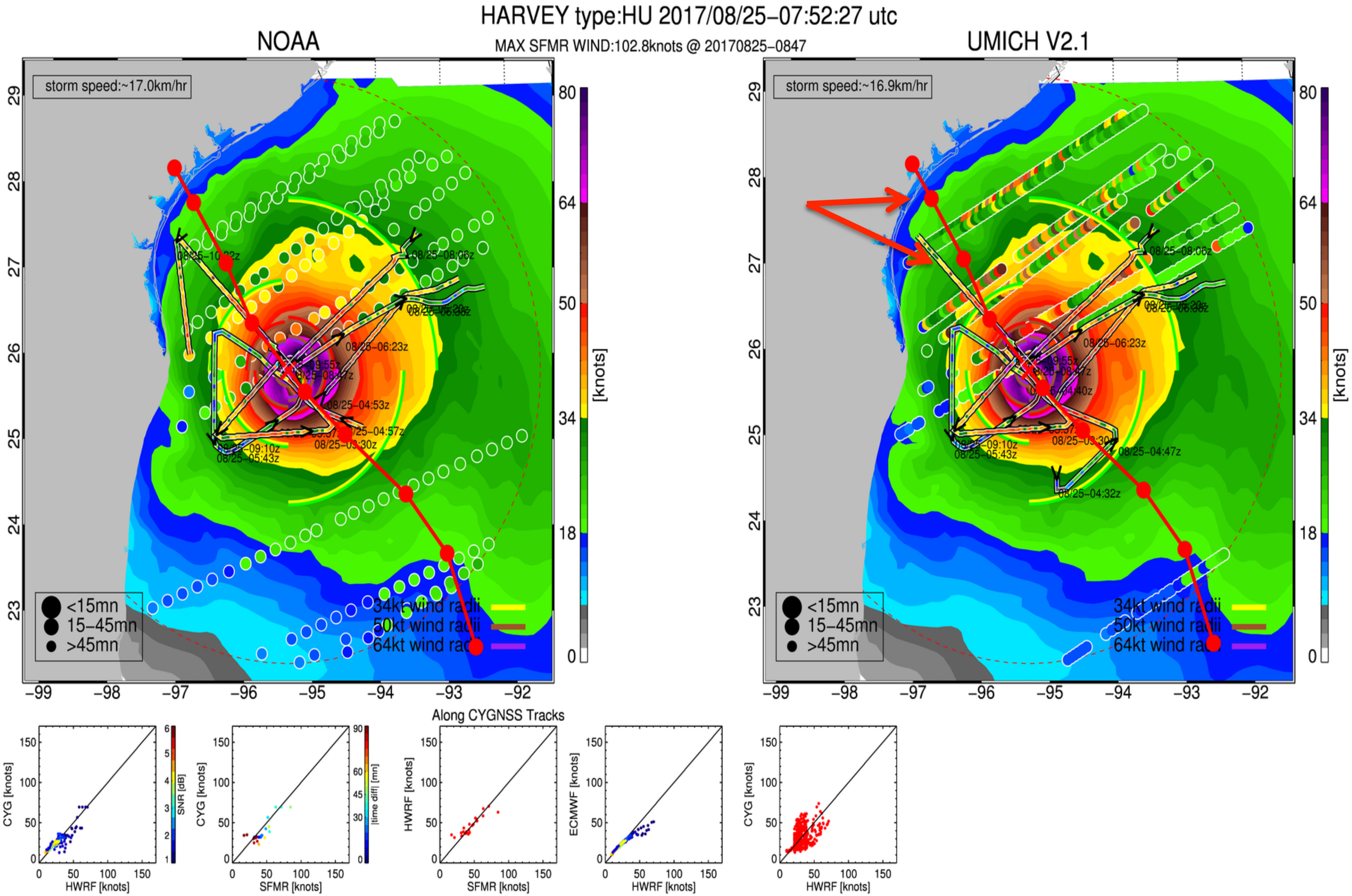
Hurricane MICHAEL



Hurricane MICHAEL

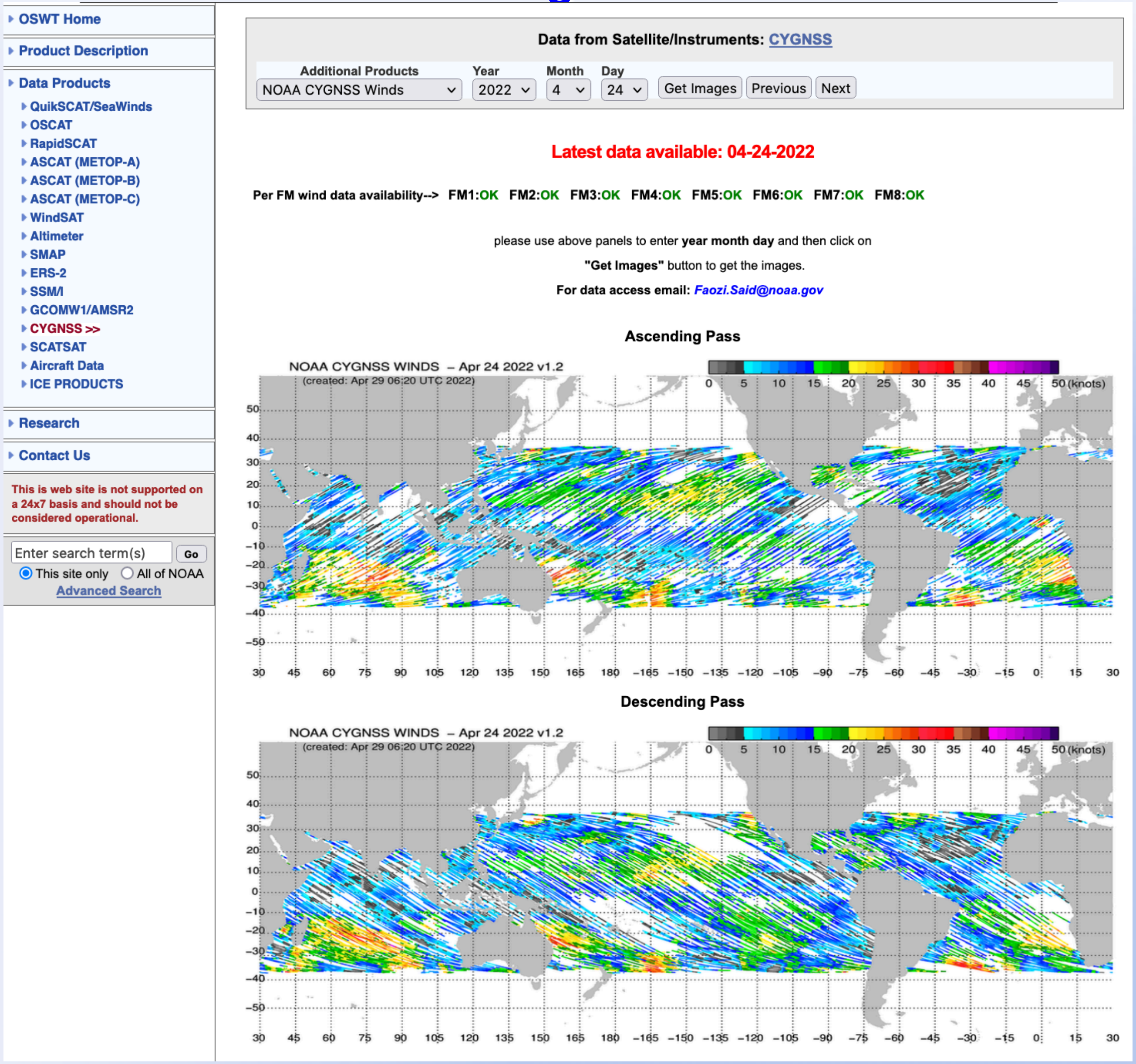


Hurricane HARVEY



NOAA CYGNSS Global Wind Web Page

https://manati.star.nesdis.noaa.gov/datasets/CYGNSSData.php



- OSWT Home
- Product Description
- Data Products
  - QuikSCAT/SeaWinds
  - OSCAT
  - RapidSCAT
  - ASCAT (METOP-A)
  - ASCAT (METOP-B)
  - ASCAT (METOP-C)
  - WindSAT
  - Altimeter
  - SMAP
  - ERS-2
  - SSM/I
  - GCOMW1/AMSR2
  - CYGNSS >>
  - SCATSAT
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- Research
- Contact Us

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Enter search term(s) Go

● This site only ○ All of NOAA

Advanced Search

Data from Satellite/Instruments: CYGNSS

Additional Products: NOAA CYGNSS Winds
Year: 2022
Month: 4
Day: 24

Latest data available: 04-24-2022

Per FM wind data availability--> FM1:OK FM2:OK FM3:OK FM4:OK FM5:OK FM6:OK FM7:OK FM8:OK

please use above panels to enter **year month day** and then click on

"Get Images" button to get the images.

For data access email: ***Faozi.Said@noaa.gov***

Ascending Pass

NOAA CYGNSS WINDS – Apr 24 2022 v1.2
(created: Apr 29 06:20 UTC 2022)

Descending Pass

NOAA CYGNSS WINDS – Apr 24 2022 v1.2
(created: Apr 29 06:20 UTC 2022)

Lessons Learned

- **Proper calibration is absolutely critical**
  - It’s relatively easy to make measurements from one sensor consistent, but making 32 independent measurements consistent is not easy
- **Sufficient information for independent validation and verification is absolutely essential** This has always been true, but needs to be re-emphasized
- **There are no short cuts to provide high quality and consistent remote sensing products** that will be utilized to support decisions that can have significant consequences to life and property
  - Small satellites have benefits, but also bring new challenges
- **GNSS-R remote sensing is not well suited for retrieving the winds in the inner core of a tropical cyclone**, but it does have promise for accurate low wind speed retrievals

Wind Vector Constellation Status

EUMETSAT

ASCAT (METOP-A, B and C)

- Open and near real-time data access
- METOP-B and METOP- C phased for overlap versus maximizing coverage in tropics
- METOP-A will cease normal operations on November 15, 2021
- ASCAT available through the EPS-SG/SCA launch

SCA (ASCAT Follow-On, EPS-SG, from ~2025)

CMA

FY-3E (launch July 4, 2021)

- OSVW measurements from WindRad (in commissioning)

NSOAS

HY2 series: HY-2B (launch 25 Oct 2018), HY-2C (launch 21 Sep 2021), HY-2D (launch 19 May 2021)

- HY-2B and HY-2C will be available via EUMETCast from 4 November 2021

CNSA + CNES

CFOSAT (launch on 29 October 2018), SWIM L2 data on EUMETCAST

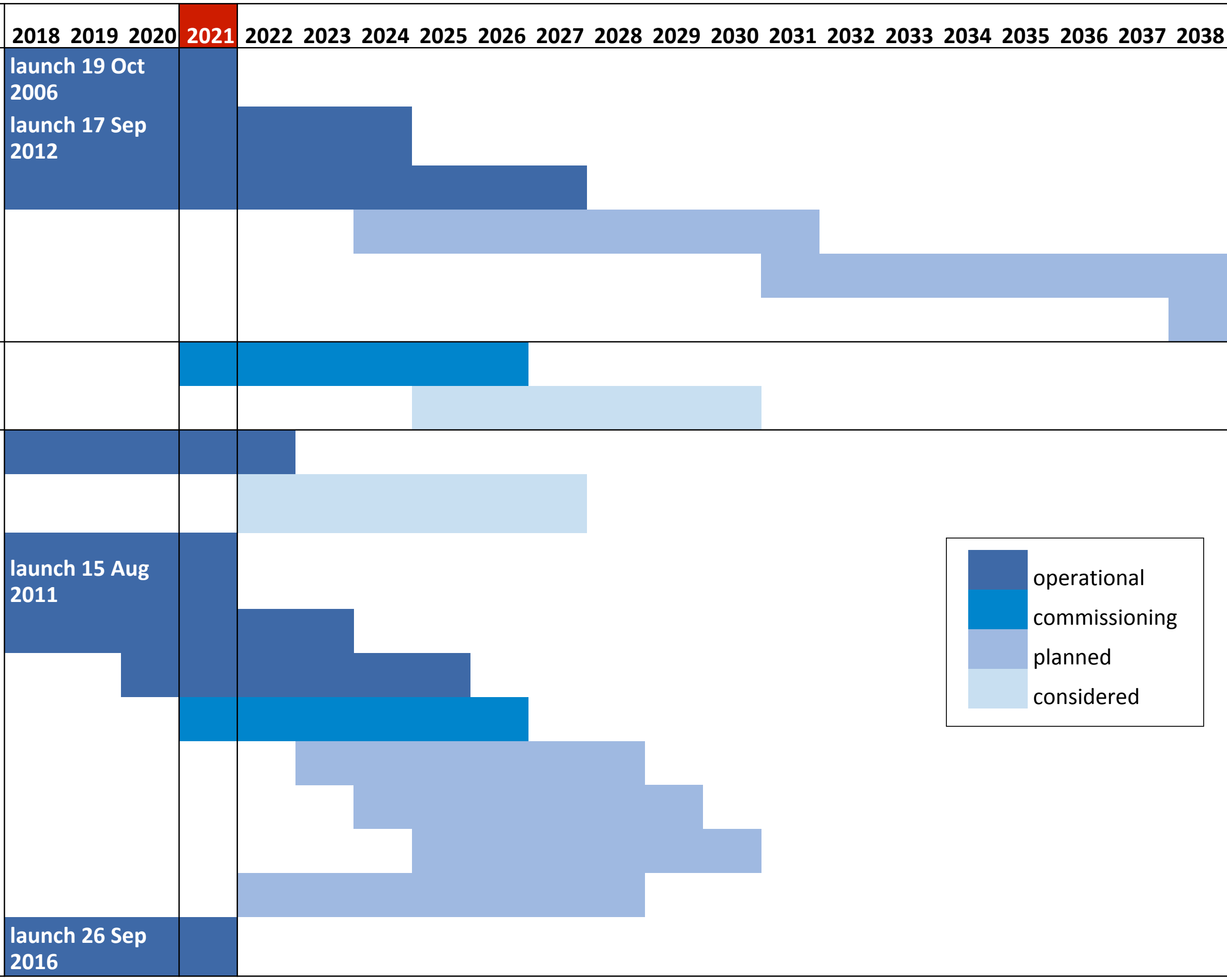
ISRO

SCATSAT-1 (launch September 26, 2016)

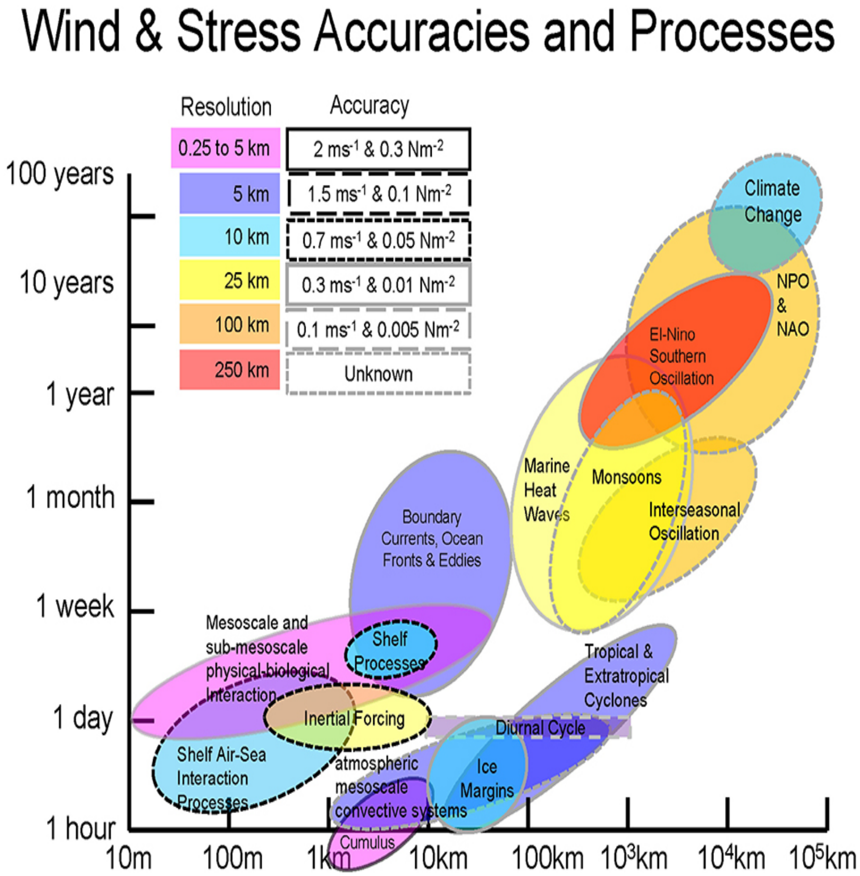
- Open and near real-time OSCAT data access from April 24, 2017 until unrecoverable anomaly on February 28, 2021
- OSCAT follow-on (OceanSat-3) now planned for Q3 / 2022 launch

The Virtual Scatterometer Constellation

	Instrument	Satellite	System	Orbit
C-band	ASCAT	Metop-A	fixed fan beam	08:46 desc
	ASCAT	Metop-B		09:30 desc
	ASCAT	Metop-C		09:30 desc
	SCA	Metop-SG-B1		09:30 desc
	SCA	Metop-SG-B2		09:30 desc
	SCA	Metop-SG-B3		09:30 desc
C-/Ku-band	WindRAD	FY-3E	conical scanning	05:30 desc
	WindRAD	FY-3I		05:30 desc
Ku-band	SCAT (CFOSAT)	CFOSAT	rotating fan beam	07:00 desc
	SCAT (CFOSAT)	CFOSAT follow-on		07:00 desc
	SCAT (HY-2A)	HY-2A	conical scanning	06:00 desc
	SCAT (HY-2A)	HY-2B		06:00 desc
	SCAT (HY-2A)	HY-2C		66 °
	SCAT (HY-2A)	HY-2D		66 °
	SCAT (HY-2A)	HY-2E		06:00 desc
	SCAT (HY-2A)	HY-2F		66 °
	SCAT (HY-2A)	HY-2G		66 °
	OSCAT	OceanSat-3		12:00 desc
	OSCAT	ScatSat-1		08:45 desc



Observing System Requirements



Wind & Stress Accuracies and Processes

Figure: OceanObs'19 White Paper
https://doi.org/10.3389/fmars.2019.00443

What is really needed?

Discussion of observing system requirements for **accuracy and resolution(space and time)**:

- Observation requirements vary greatly depending on the spatial and temporal scales of phenomena that need to be captured in a model.
- Sampling requirements in space and time are driven by the need to capture the variability

Minimum Constellation

- At least 3 scatterometers in orbits designed to roughly meet WMO requirements (observations every 6 hours)
- One instrument in a non-sun-synchronous orbit for sampling the diurnal cycle, better mid-latitude sampling and provide inter-calibration

Requirements for the OSVW Constellation

Instruments

Spaceborne scatterometers (C-, Ku-band) are the trusted reference standard to provide global ocean surface **wind vector** data.

Other remote sensing techniques have demonstrated varying capabilities at retrieving ocean surface winds:

- Microwave radiometers: Multi-frequency / Polarimetric / L-band
- Synthetic Aperture Radar (SAR)
- GNSS-R
- HF radars (regional coverage but frequent temporal refresh)

How do these other techniques compare with microwave scatterometry and where do they fit within the OSVW observing system portfolio?

Applications

- Weather forecasting: nowcasting (analysis) + short range
- Climate observing / analysis (seasonal, inter-annual and longer time scales)
- Ocean dynamics...

Needs analysis of:

- Global statistics
- Geographical distribution / temporal sampling
- Spatial resolution (**actual** versus gridding resolution)
- Performance in the extremes (low (< 3m/s) and strong wind speeds (> 30m/s))
- Dependency on ancillary data

Need a standard set of metrics + validation methodologies.

Cross-calibration of missions, Cal/Val and data product standards

Ongoing efforts in the OVWST community on the quality assessment of data products and wind retrievals:

- Wind retrievals during extreme winds (what is really being measured?)
- GMF development and validation
- Comparison of wind retrieval algorithms
- Assessment of rain effects in the tropics (particularly relevant for Ku-band instruments / radiometers)
- Spatial scaling effects
- Generation of a quality-controlled wind reference dataset linking dropsondes / buoys / SFMR (plane-based measurements) / SAR data
- Cross validation of C-band and Ku-band retrievals

Recent activities / highlights:

- CEOS OSVW-VC special sessions @ IGARSS'21 :
  - Status and Recent Progress
  - Consolidation of Standards and Metrics for Optimized Scientific and Operational Applications
- IOVWST'21

Cross-cutting activities / synergies:

- Within CGMS: Ocean Surface Wind Task Group (OSW TG) in the CGMS IWWG that coordinates actions/recommendations with GSICS, CEOS, the IOVWST and other relevant entities
- Within WGCV: formed Working Team to consolidate standards and metrics; preparation of draft work plan; shared datasets for intercalibration and consolidation of standards and metrics

Future focus

We need to clearly articulate:

- What we need to measure (speed and direction?) and why?
- How often do we need to measure this? Times of the day?
- Under what environmental conditions do we need to measure it?
- What real spatial resolution is required?
    - One cannot resolve features that occur over spatial scales of kilometers with a measurement footprint of 40km

Why is this important?

- There are many competing technologies making various claims to be able to provide ocean wind products.
- We need to be able to **objectively evaluate** these technologies based on a solid foundation based on data and facts.
- We need to **differentiate** products that are developed to retrieve the **actual winds versus** products that are tuned to infer the **maximum wind speeds**.

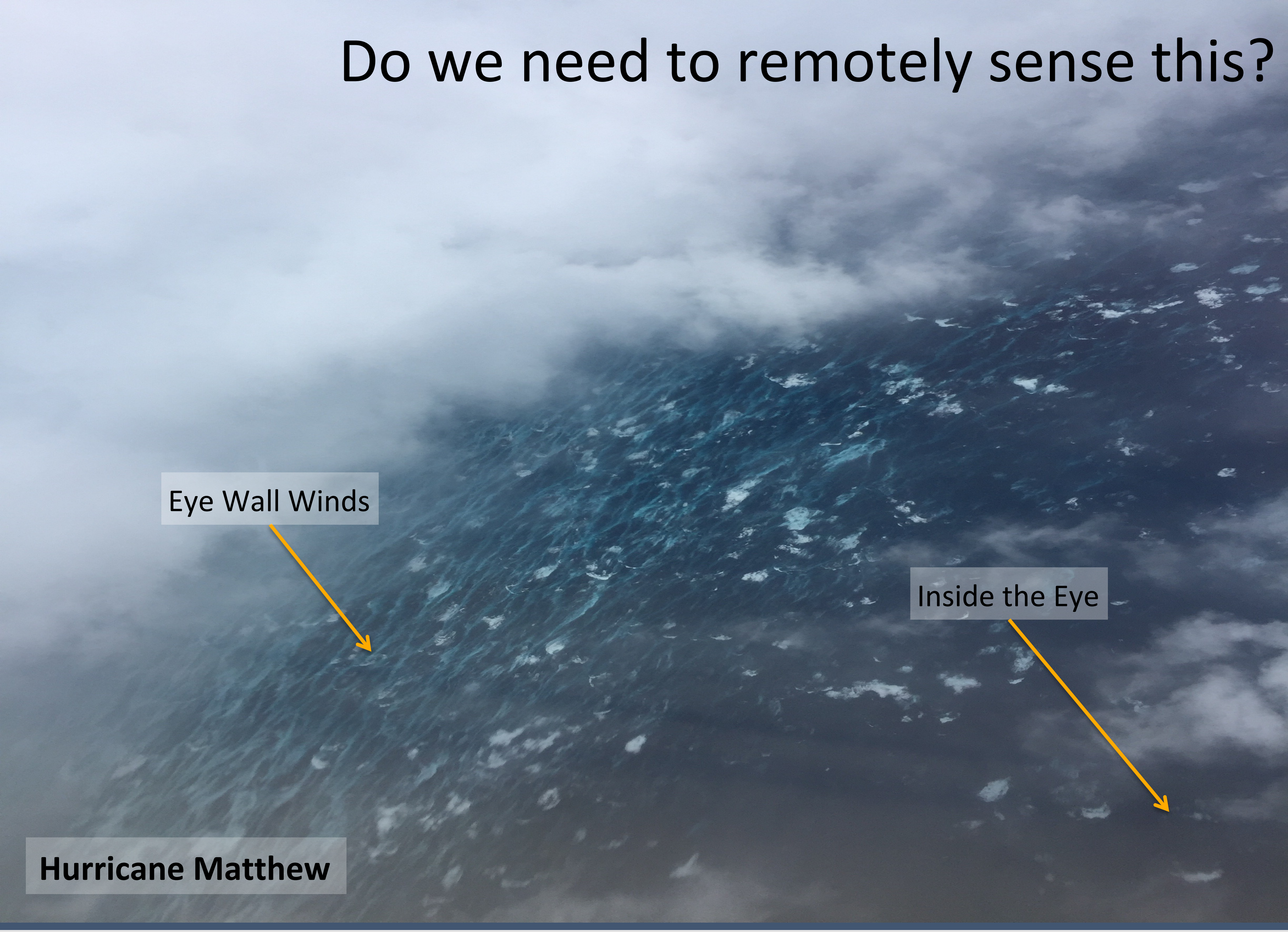
What Should NOAA Do?

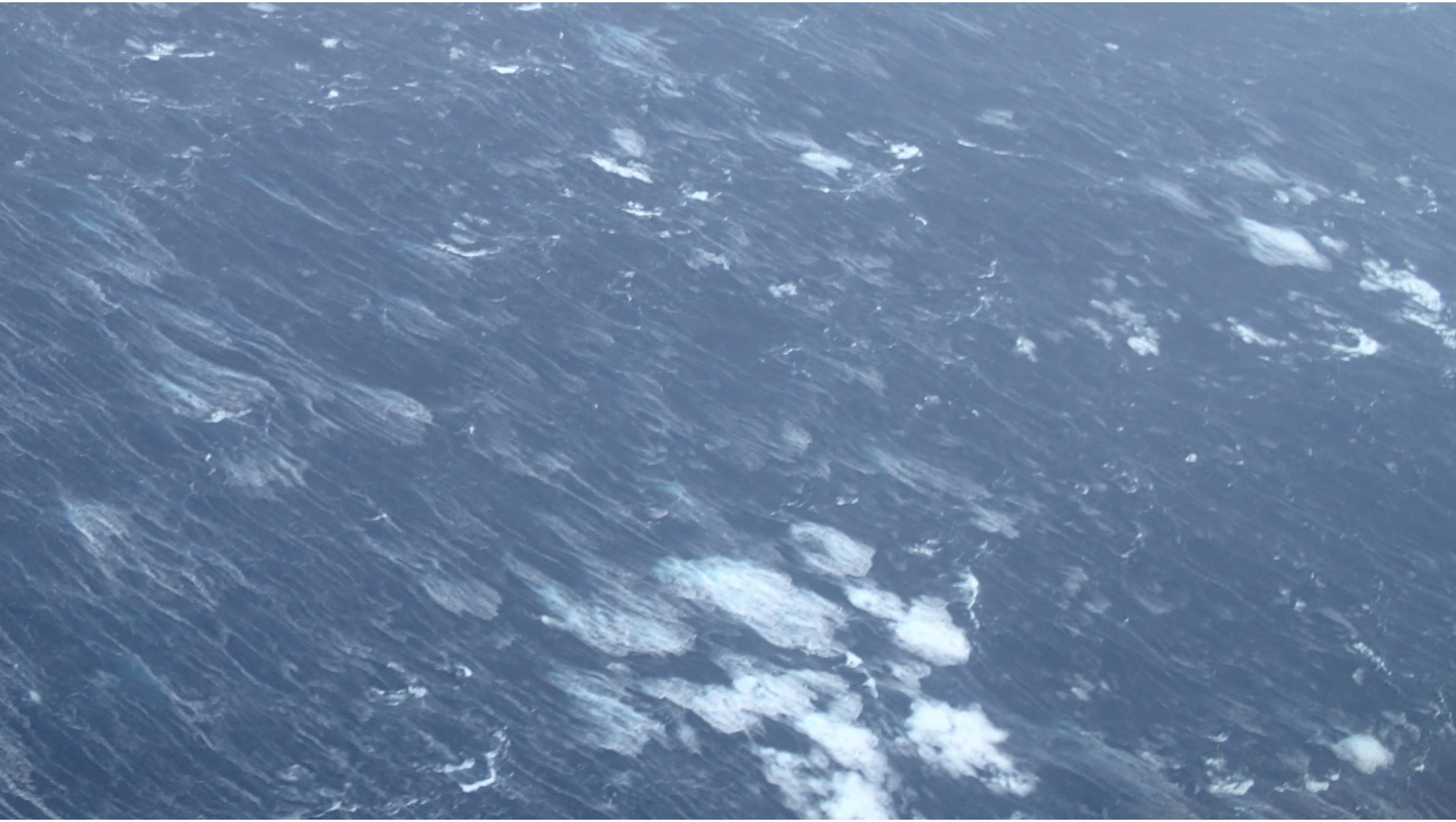
- Satellite OSVW is a critical observable for NOAA (real-time and climate time scales)
  - We now totally depend upon EUMETSAT and ISRO to partially meet requirements
- NOAA should **contribute** to the virtual OSVW constellation
  - Target under sampled orbit crossing times to achieve 6 hourly revisit times
  - Pursue proven and mature methodologies to support operational requirements (i.e. scatterometry)

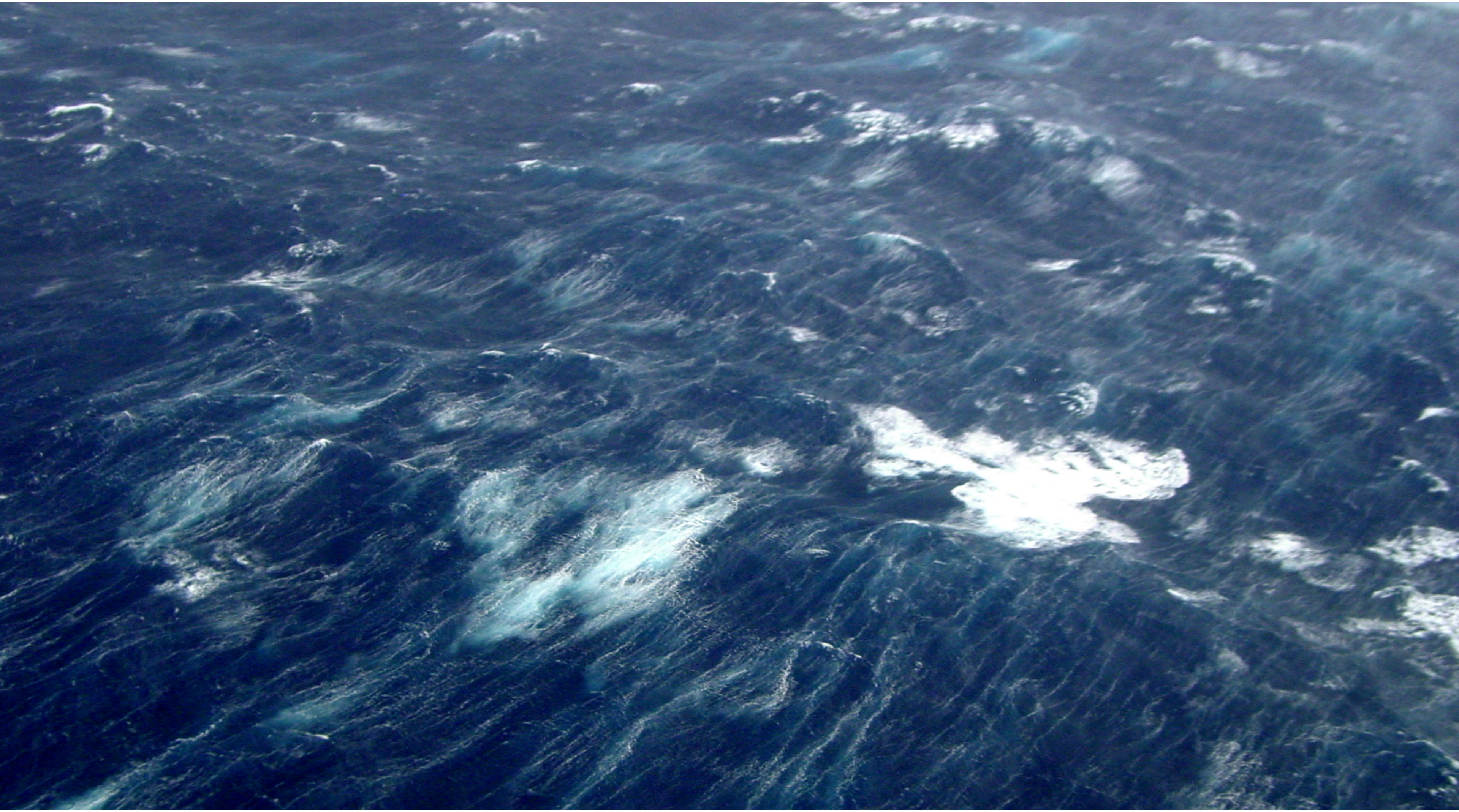
Be wary of shiny objects!

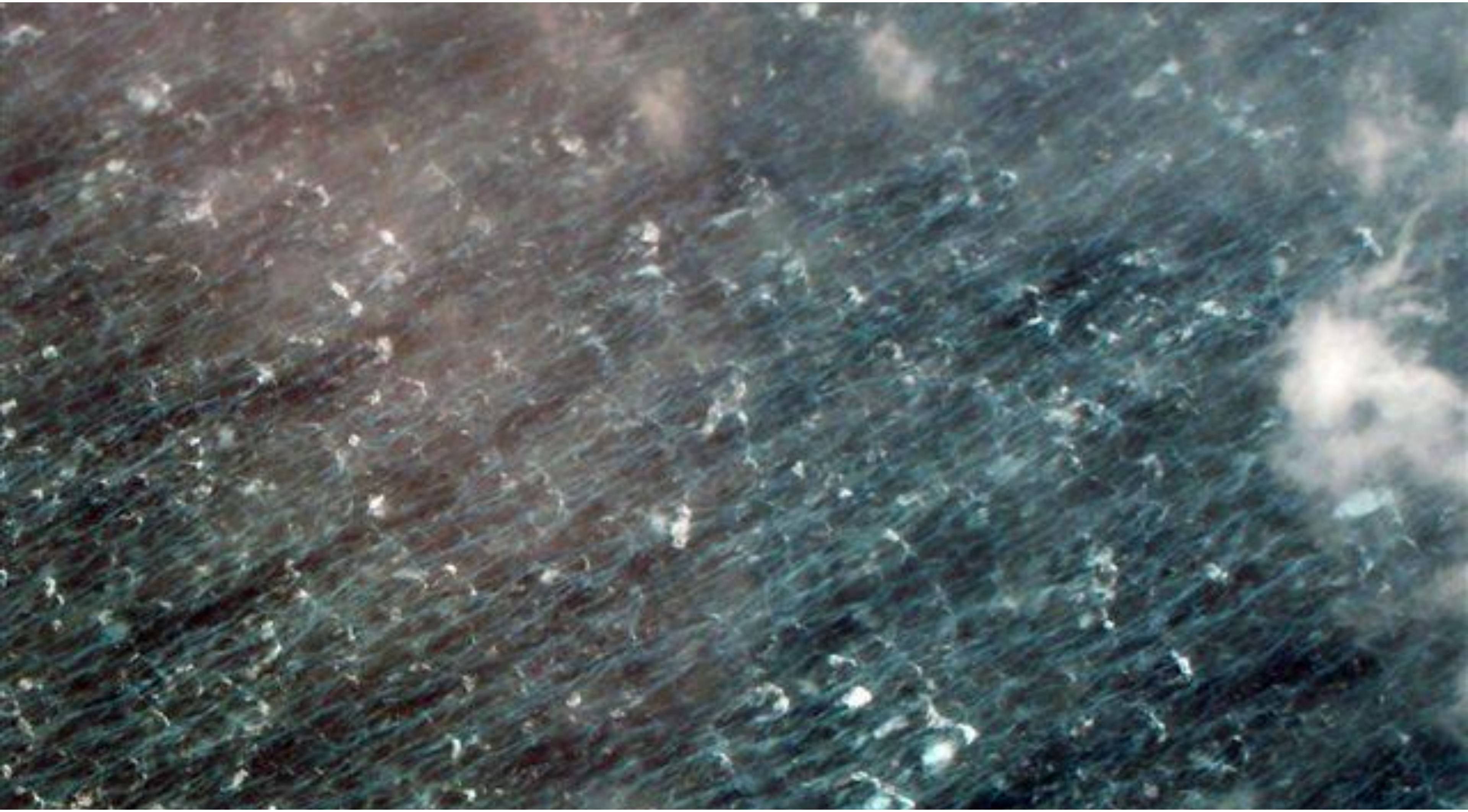
A statement in a glossy brochure does not directly translate to a validated and verified product that has the accuracy and consistency to support operational decision making

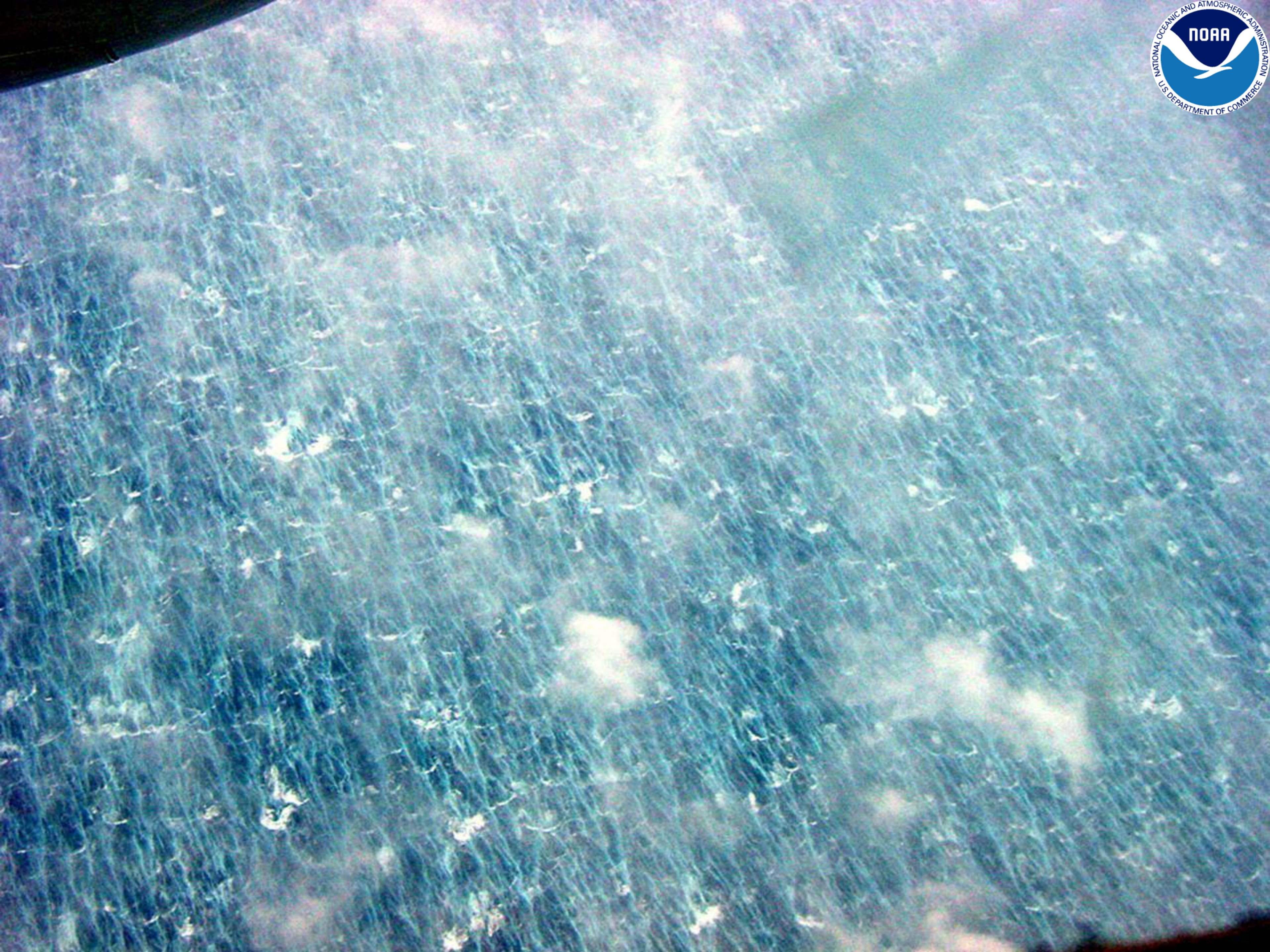
Do we need to remotely sense this?











ASCAT UHR Examples

Retrieving winds and ice in the coastal zone

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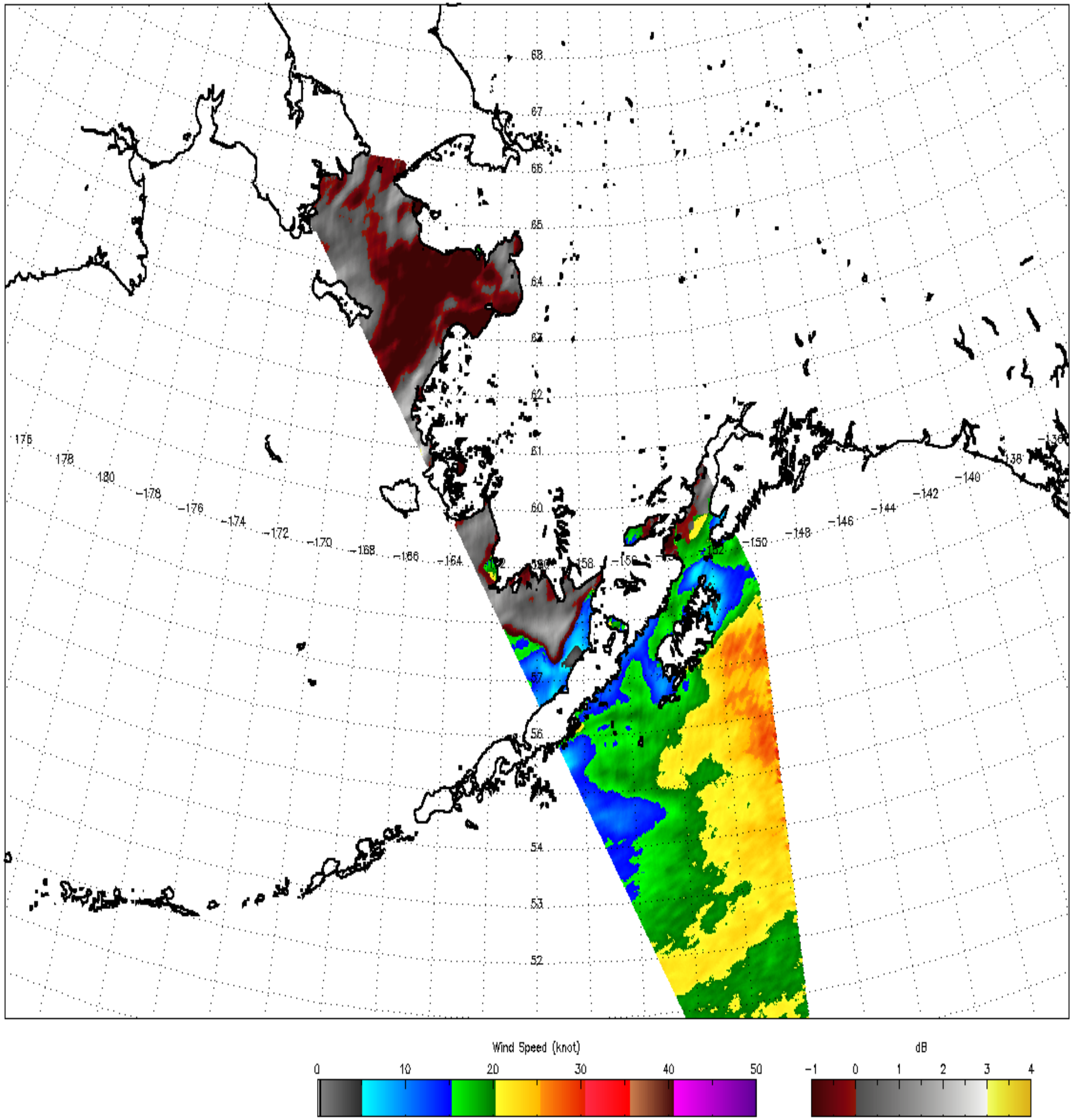

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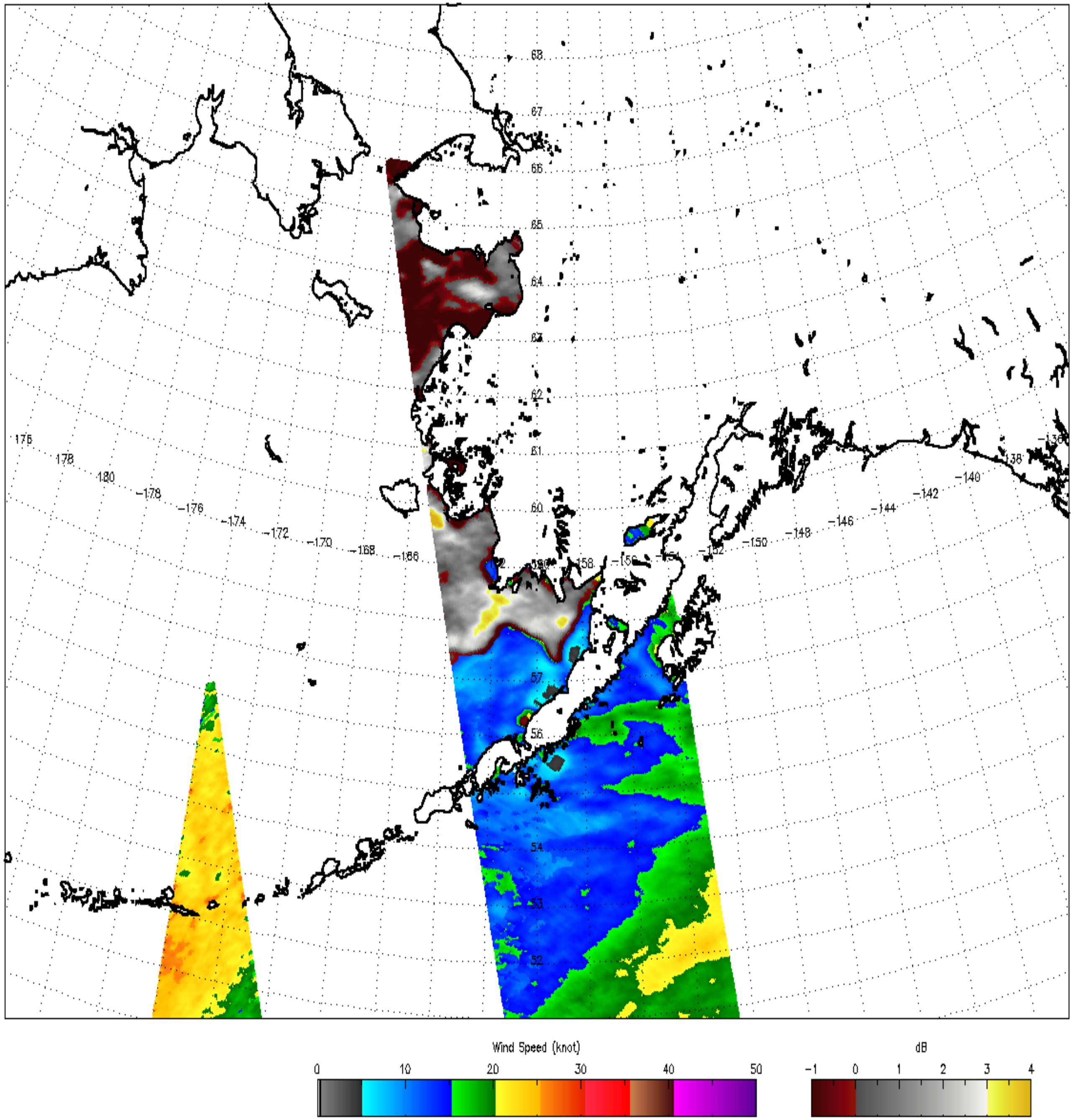

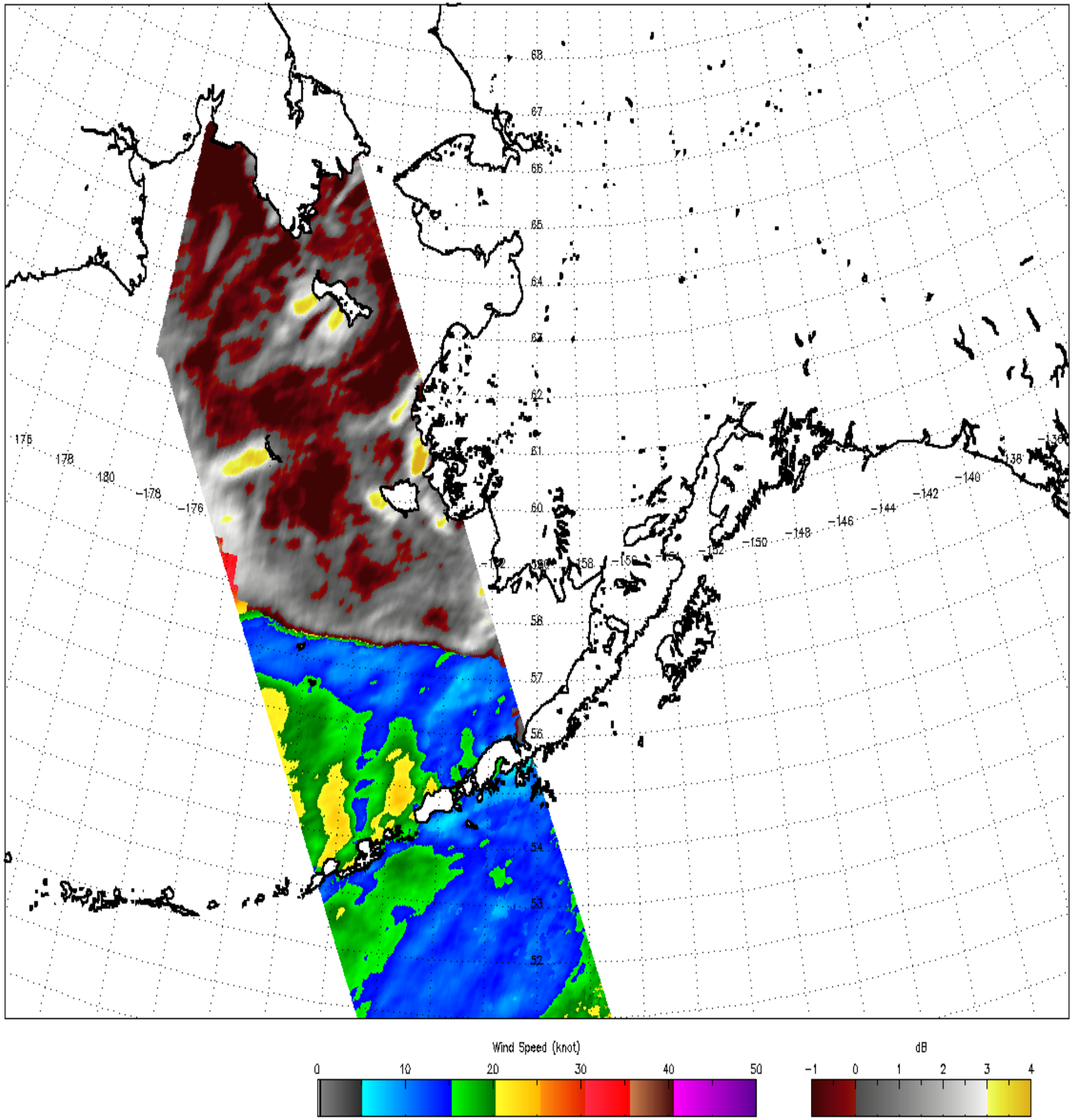

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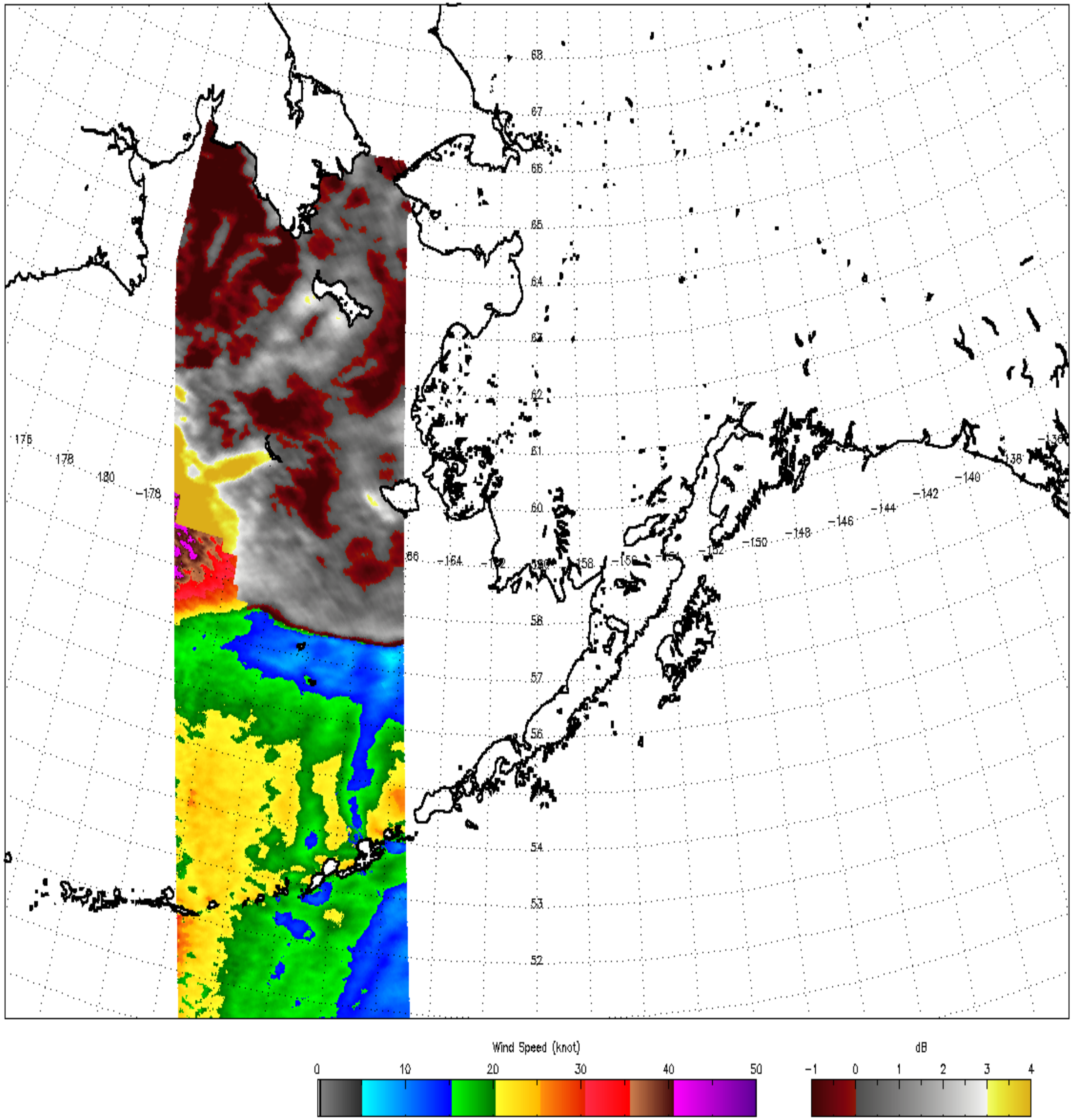

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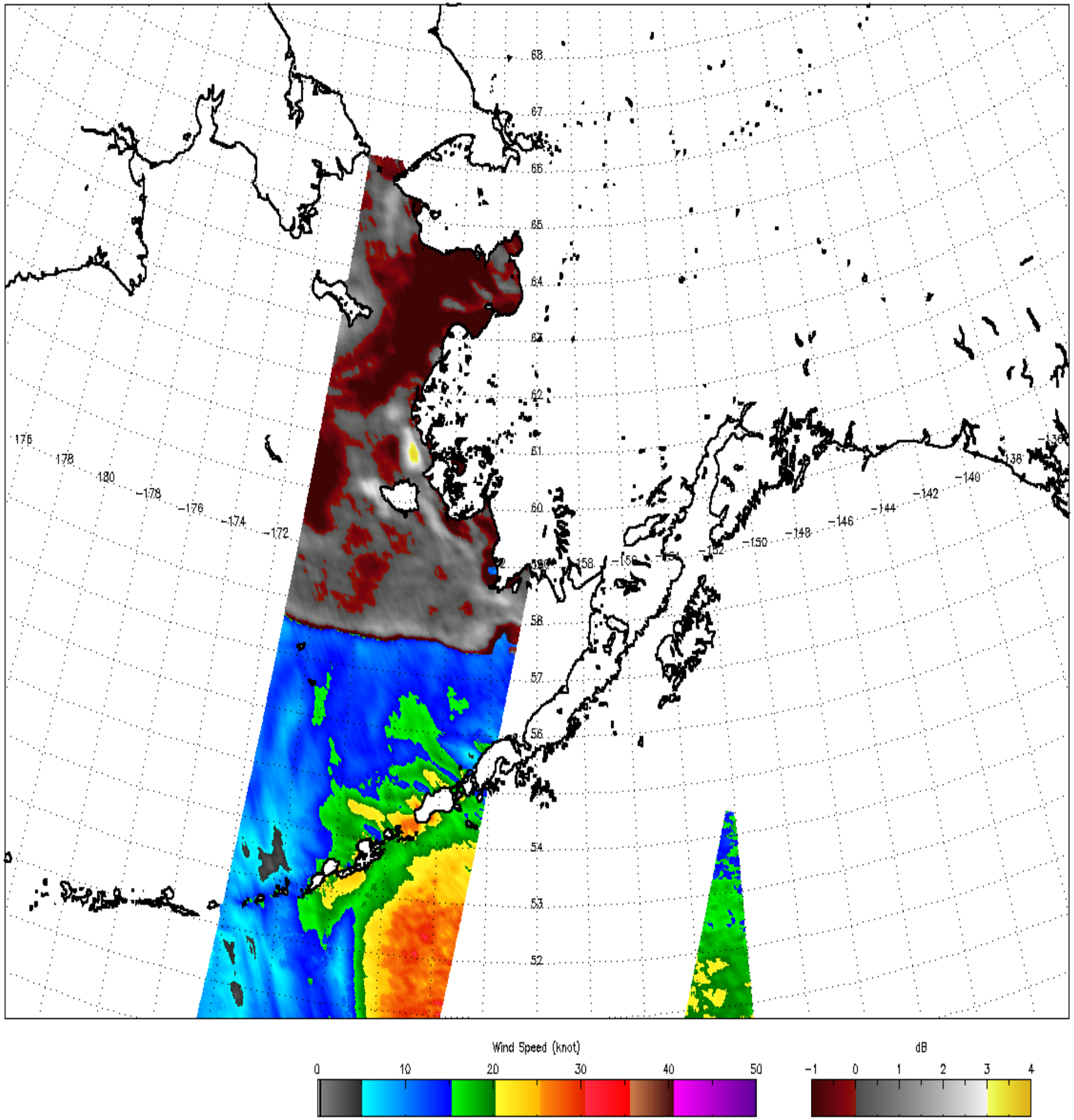

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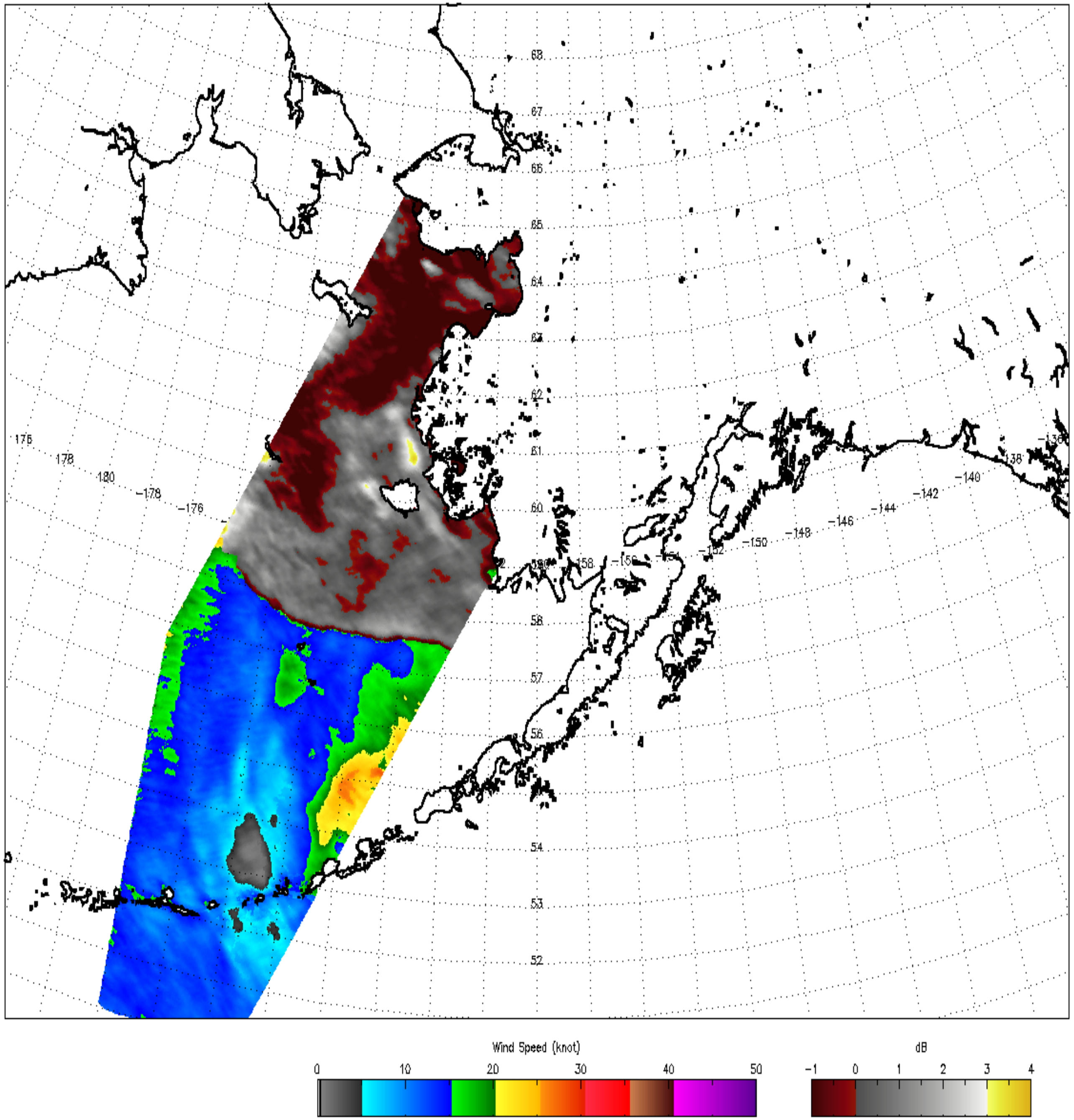

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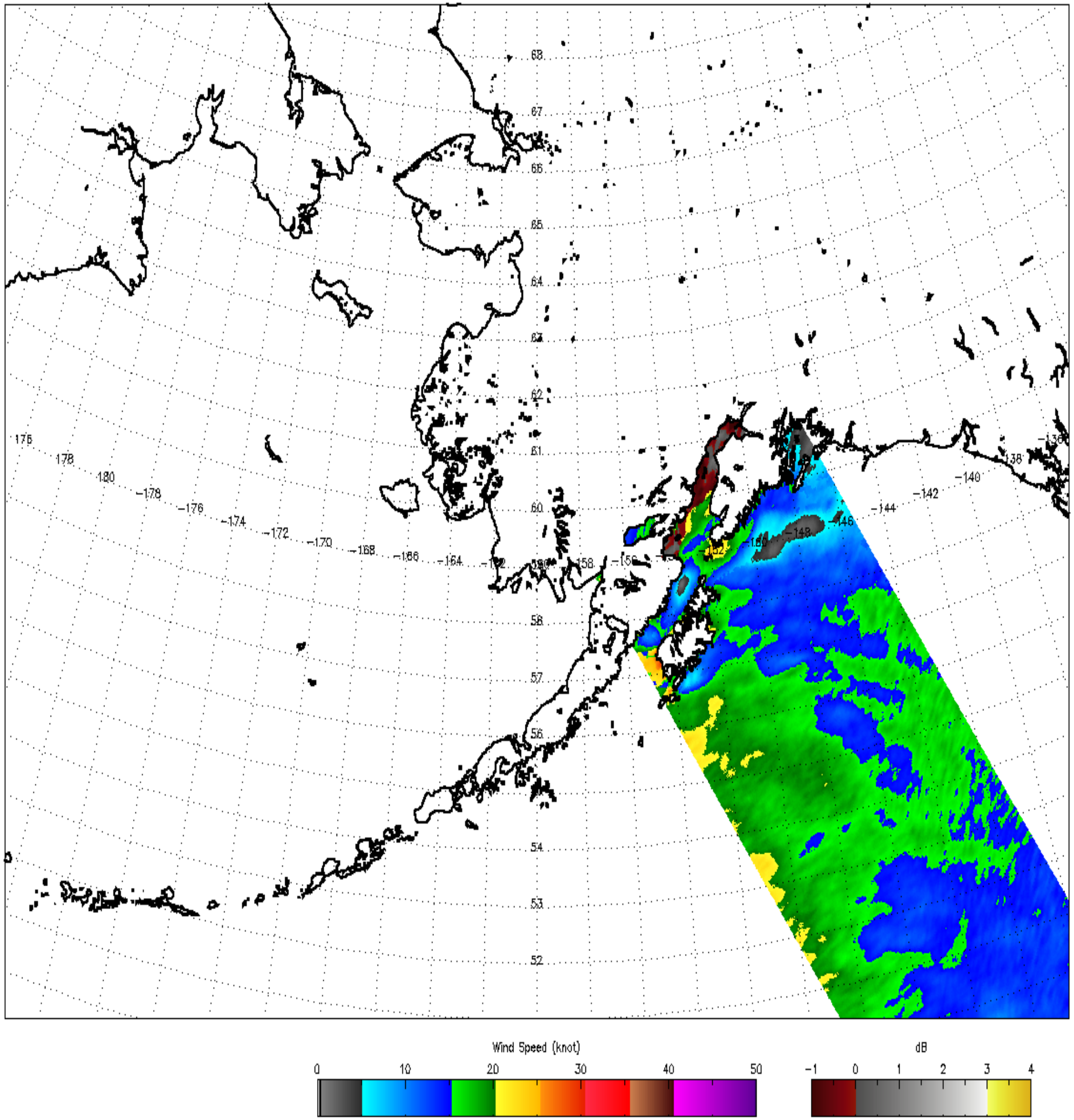

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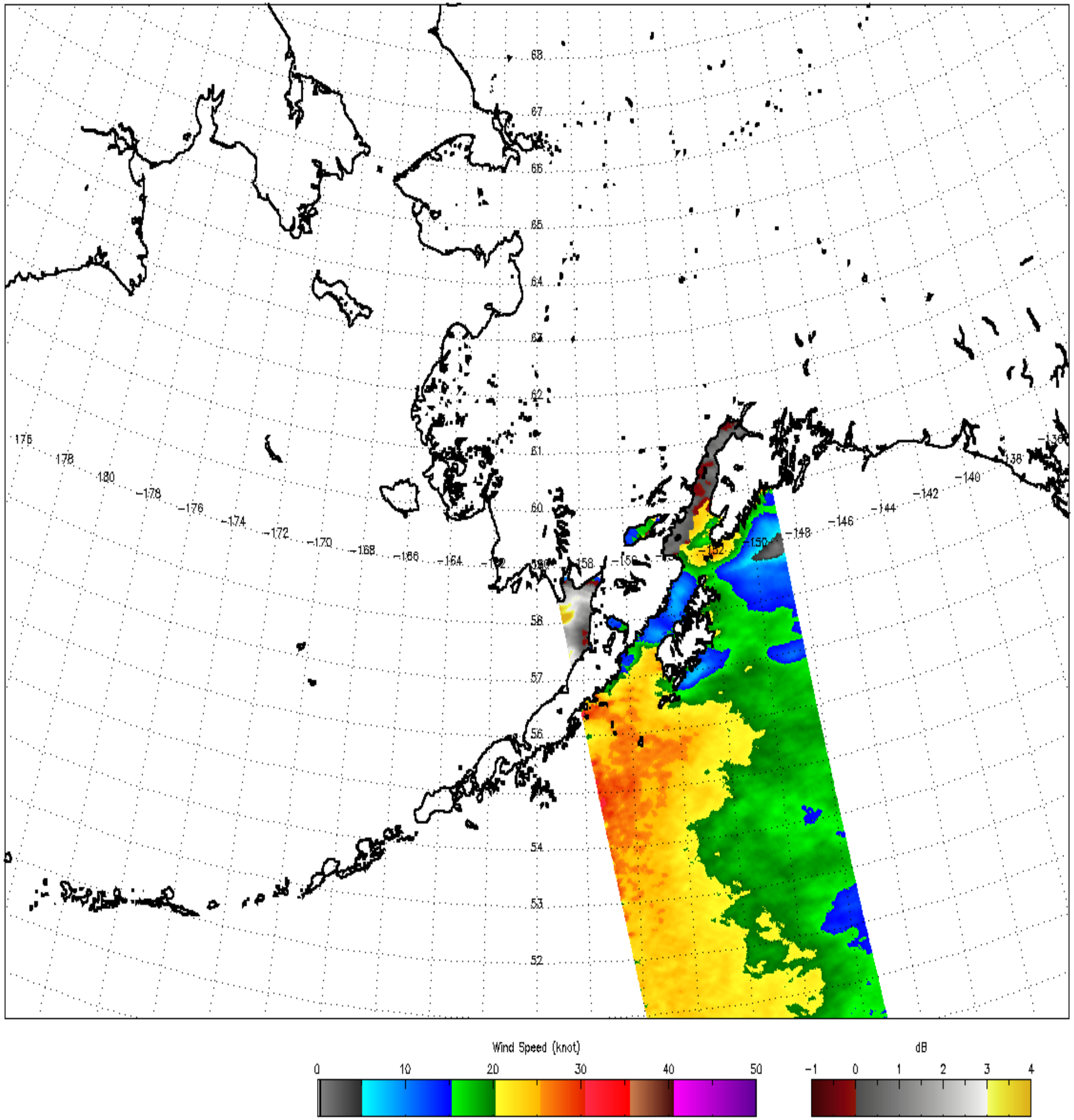

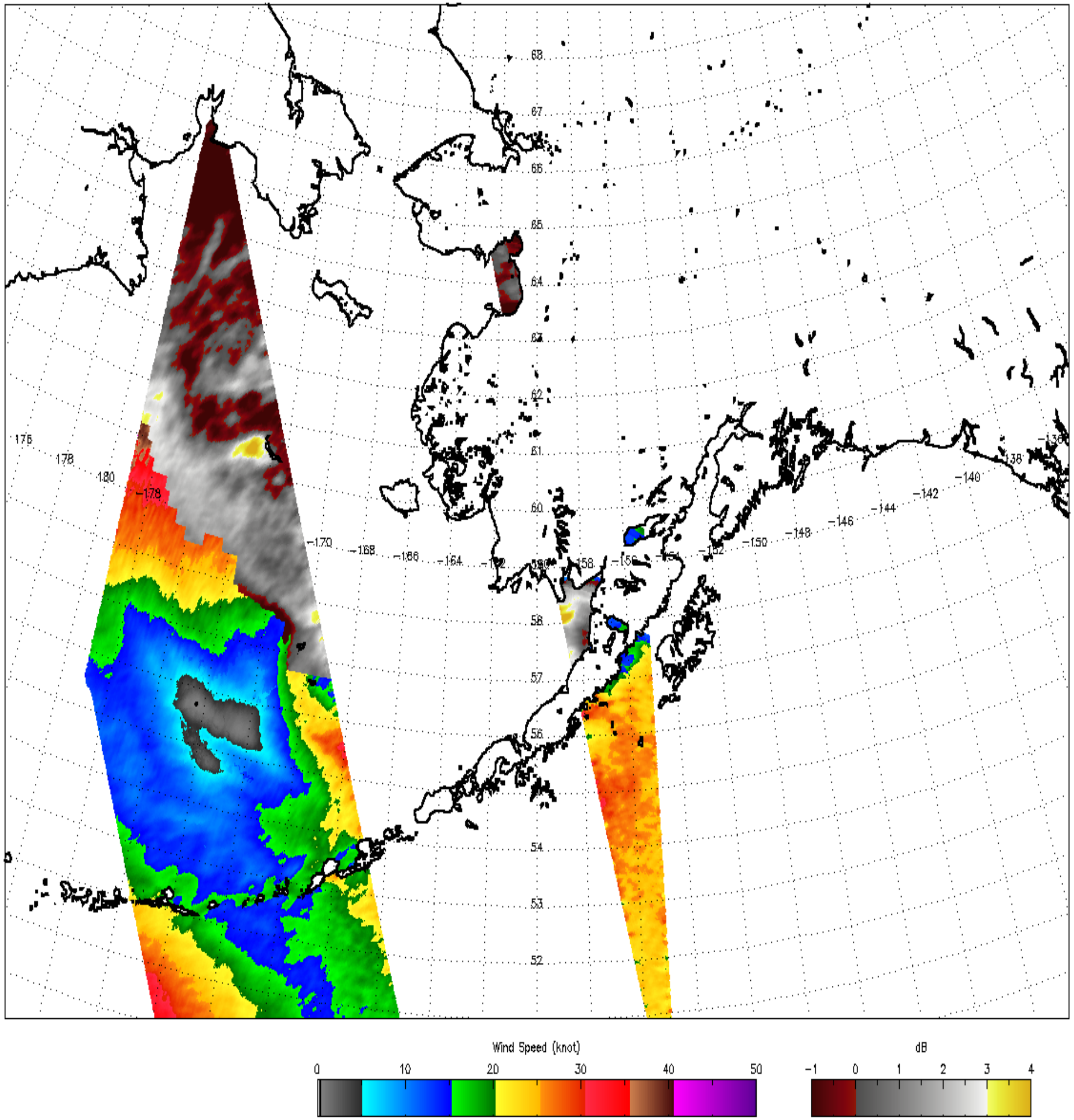

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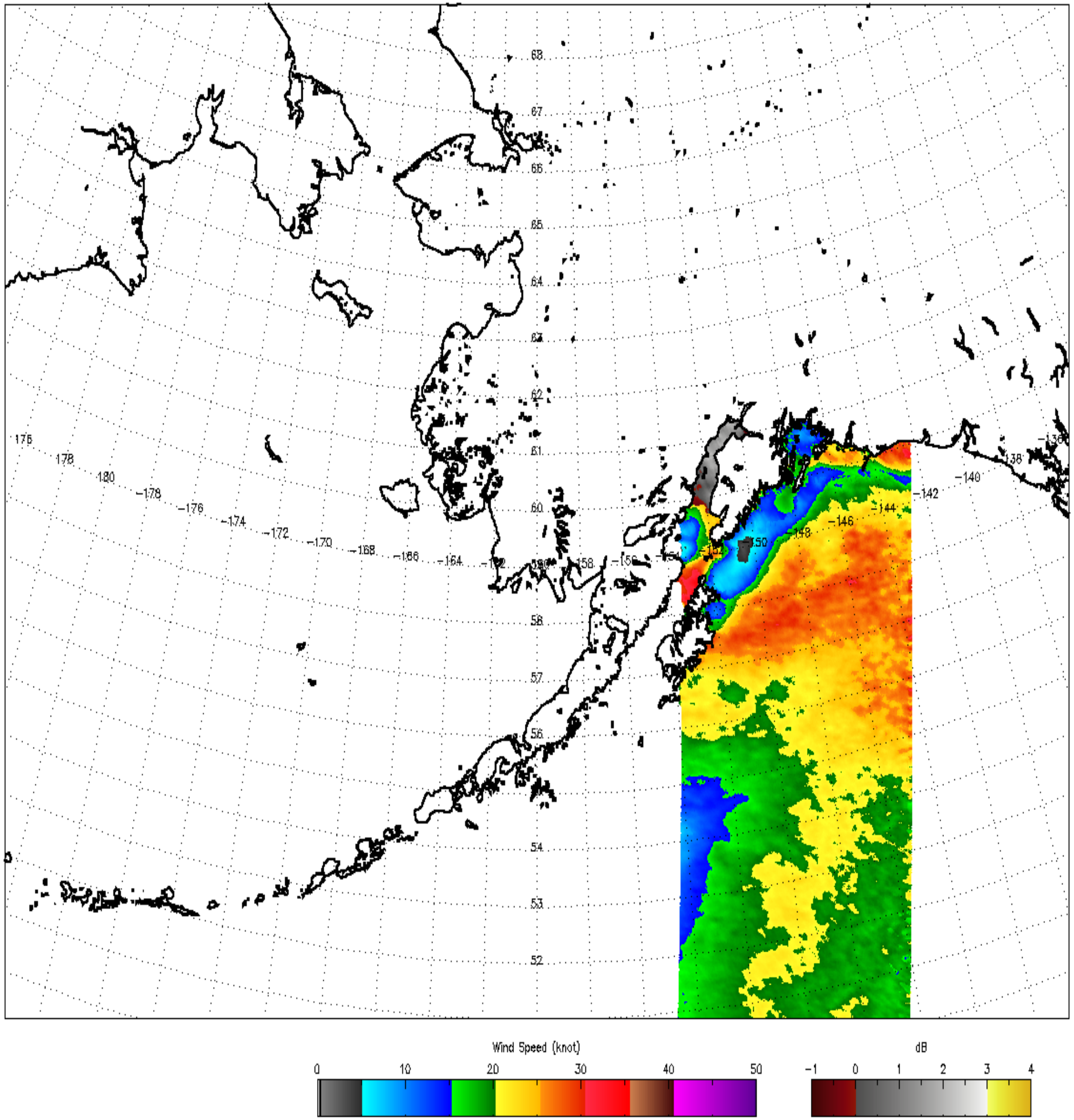

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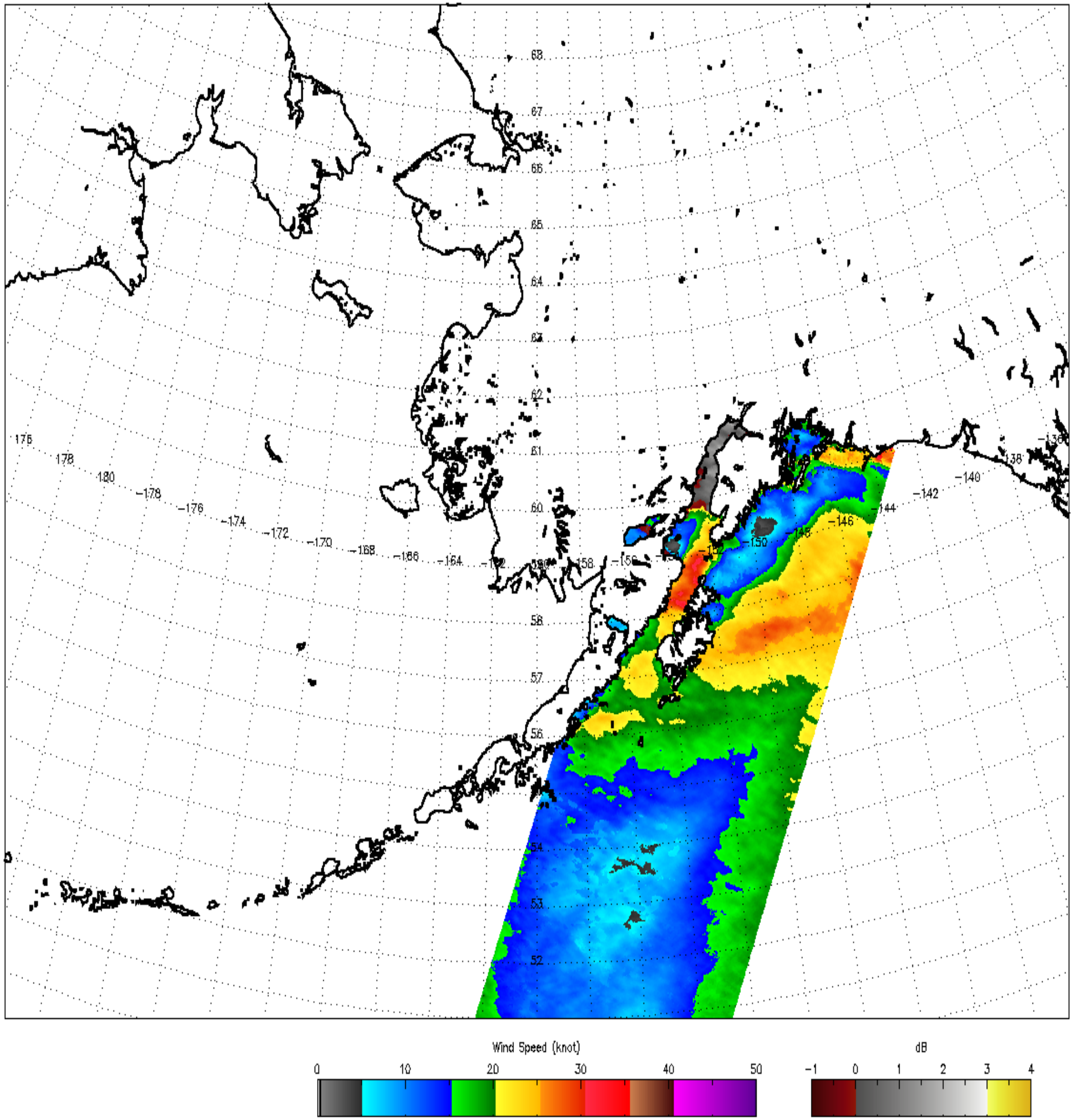

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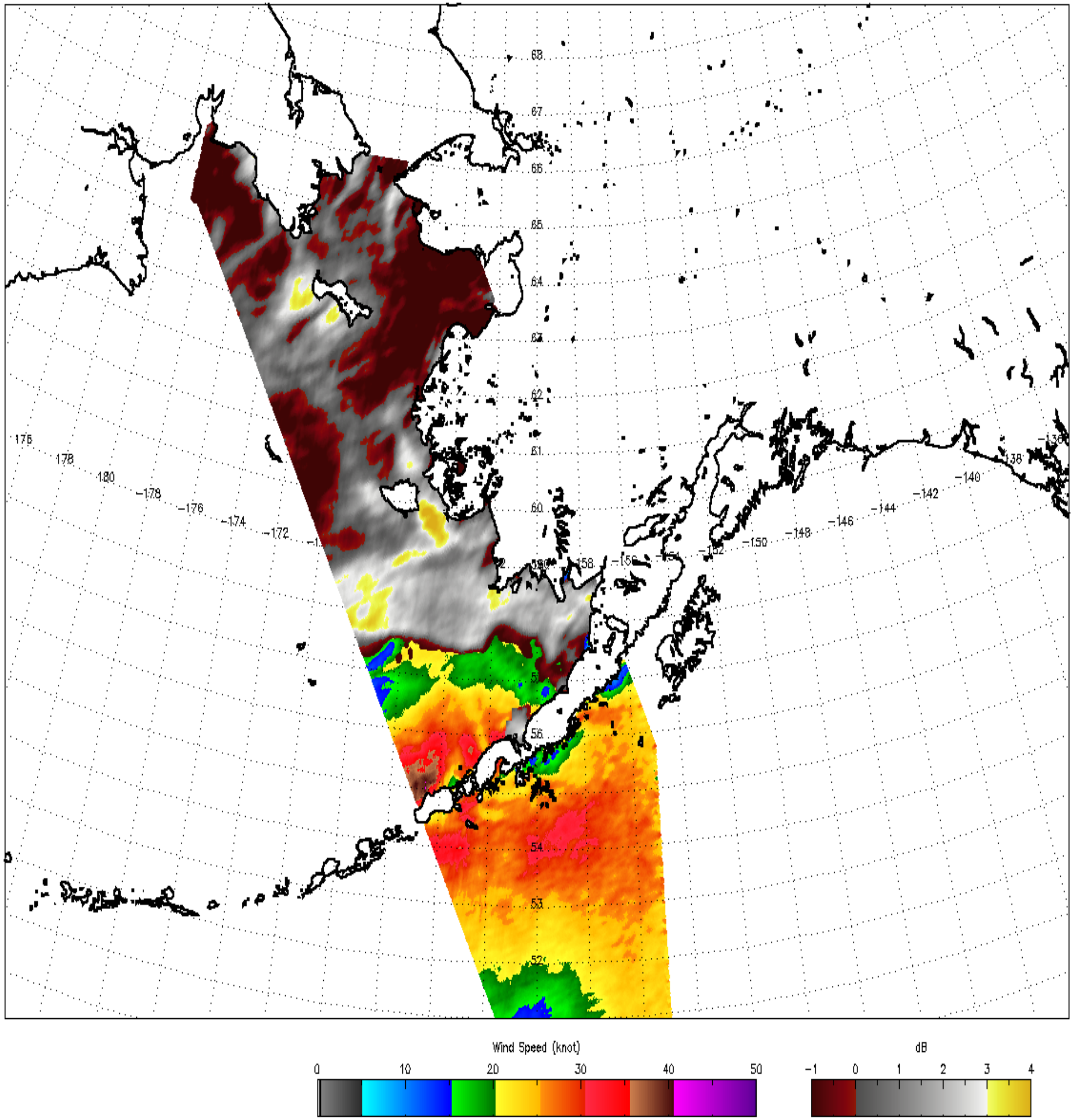

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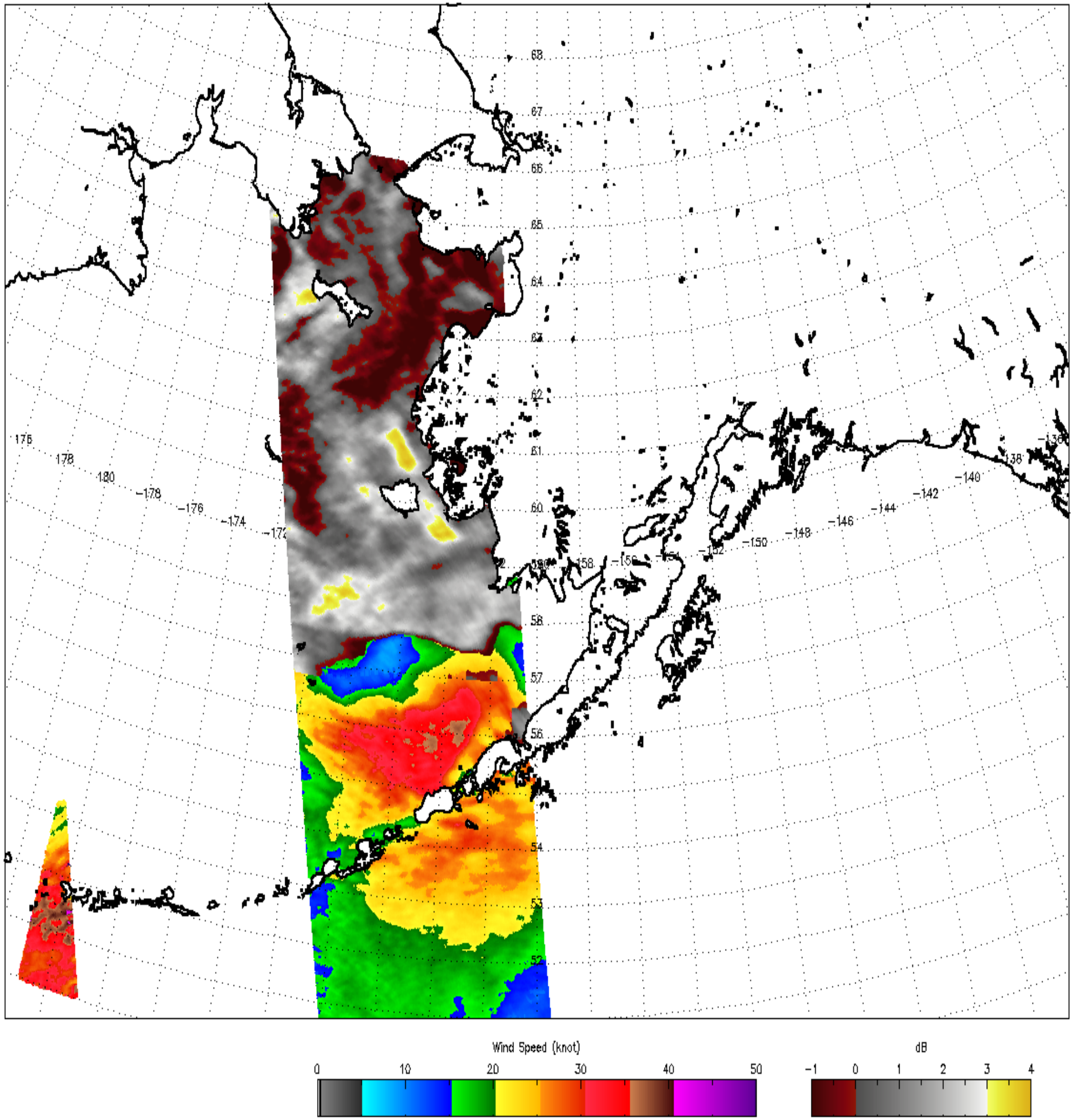

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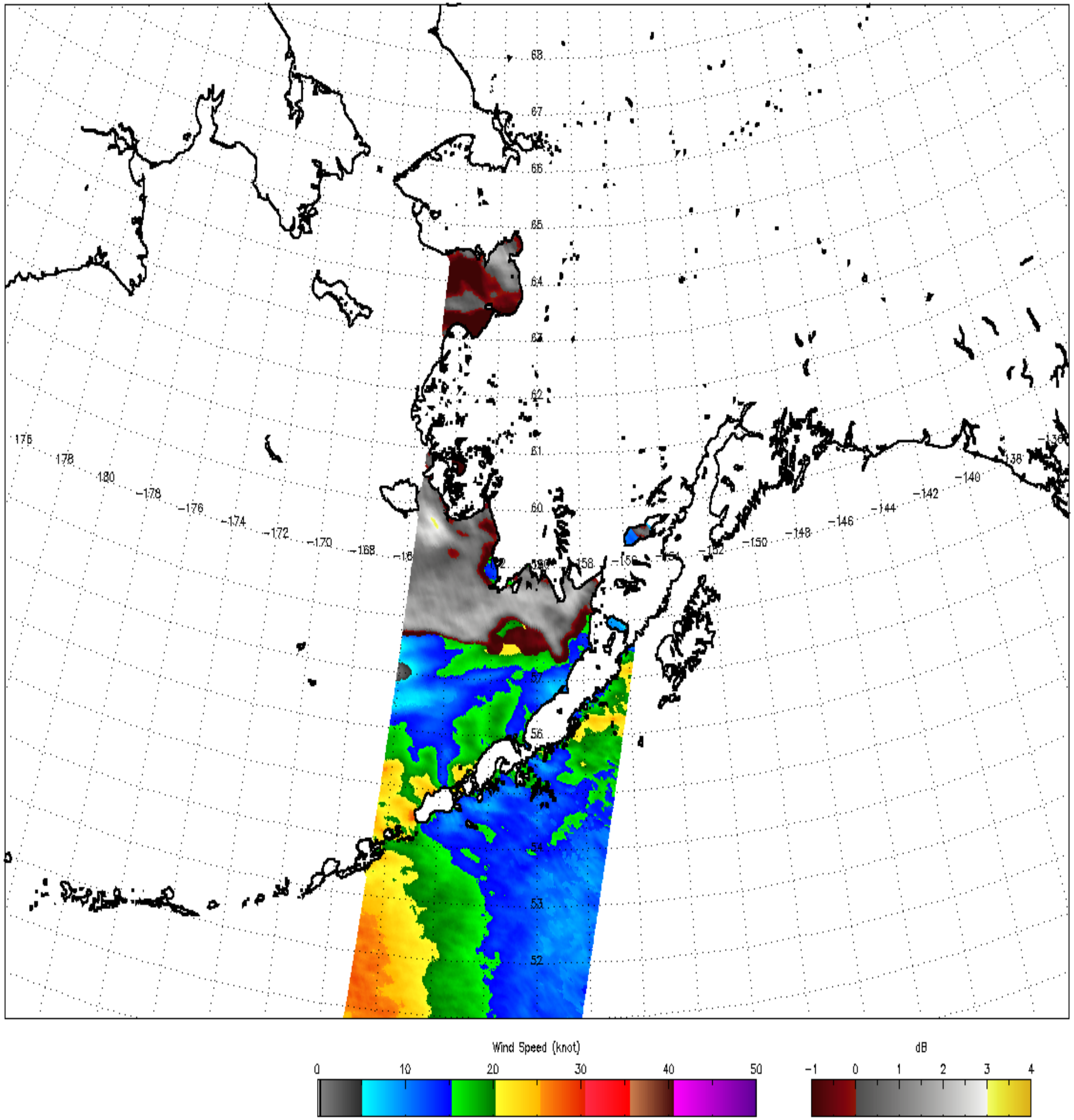

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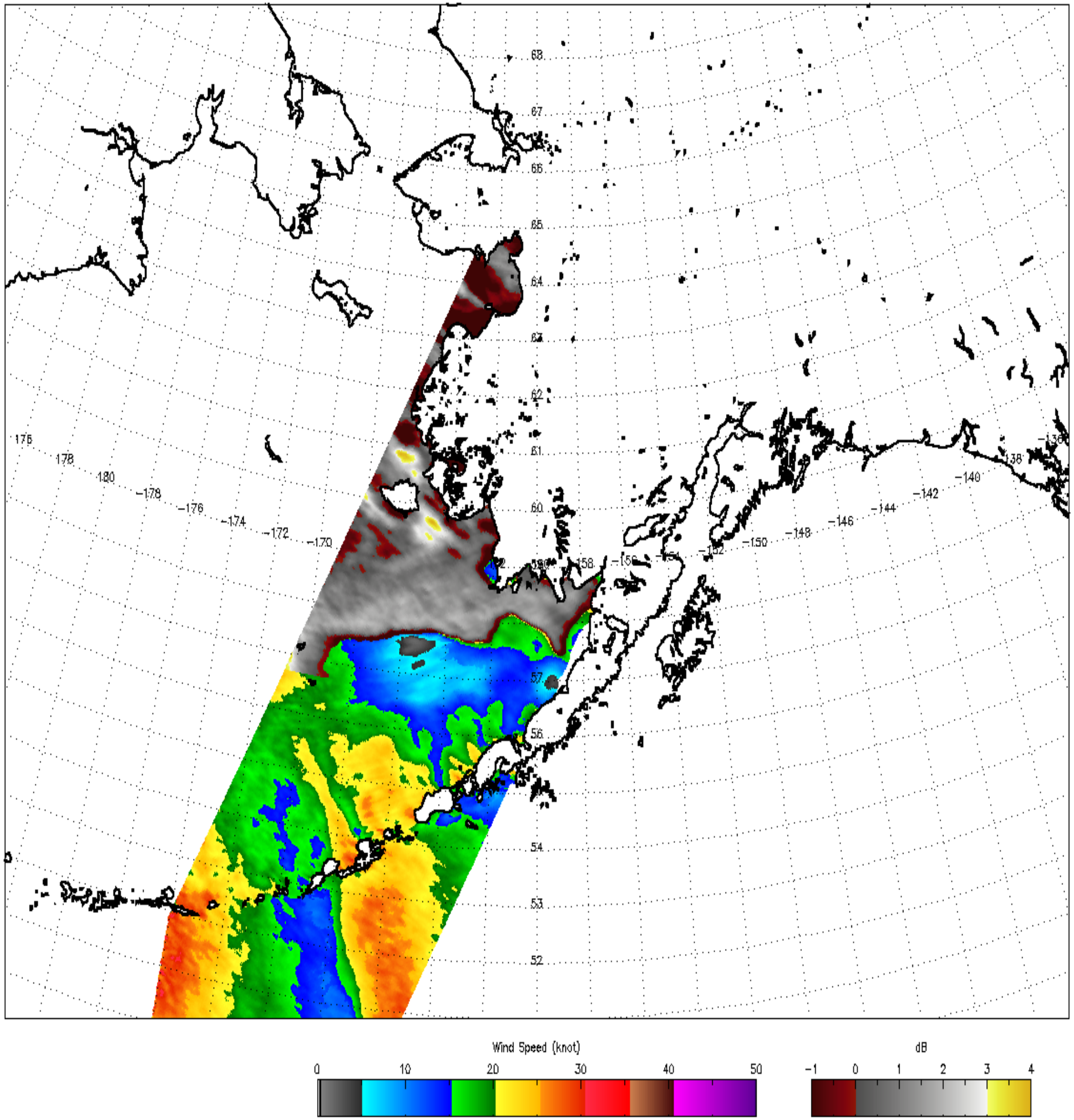

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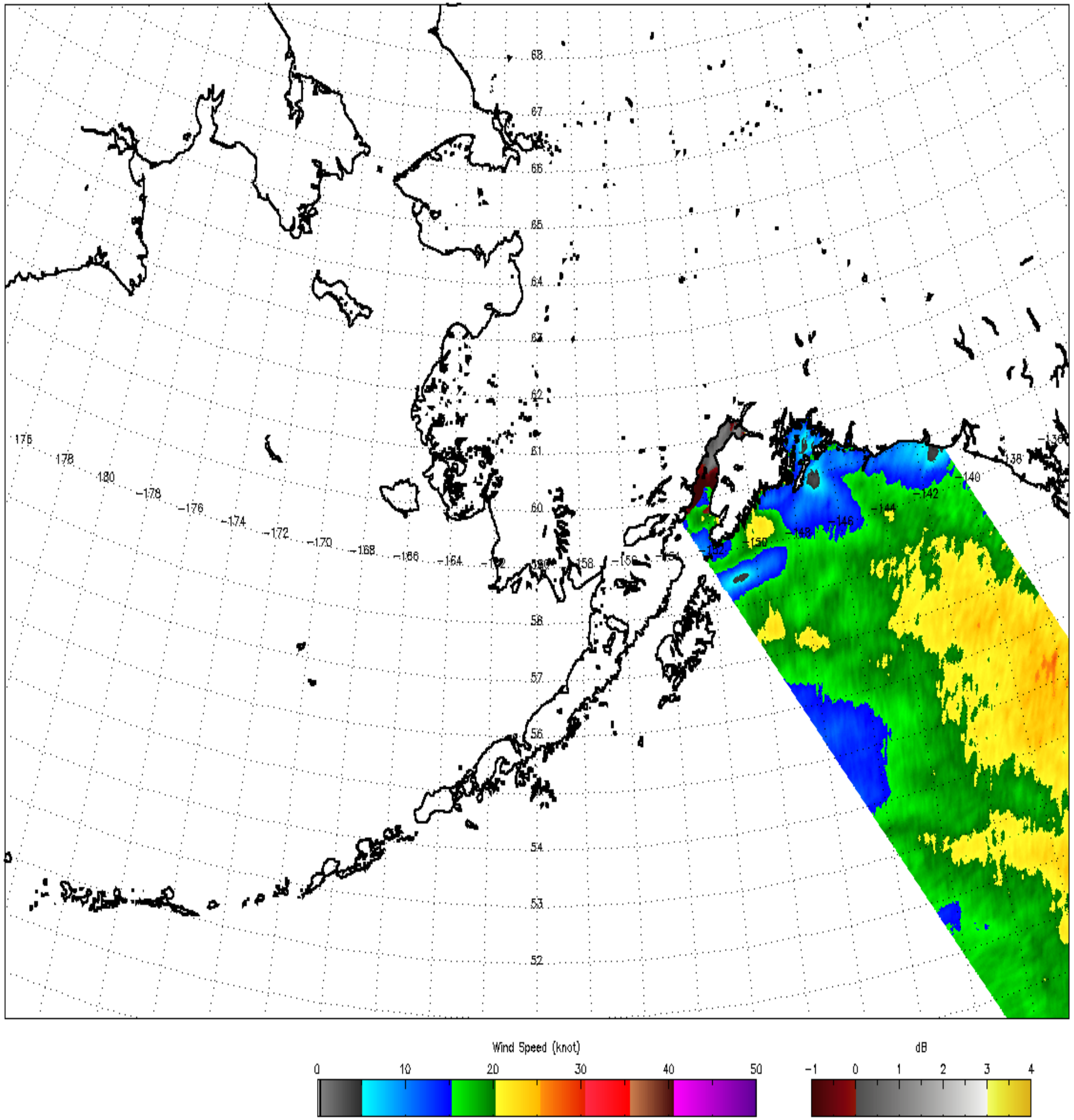

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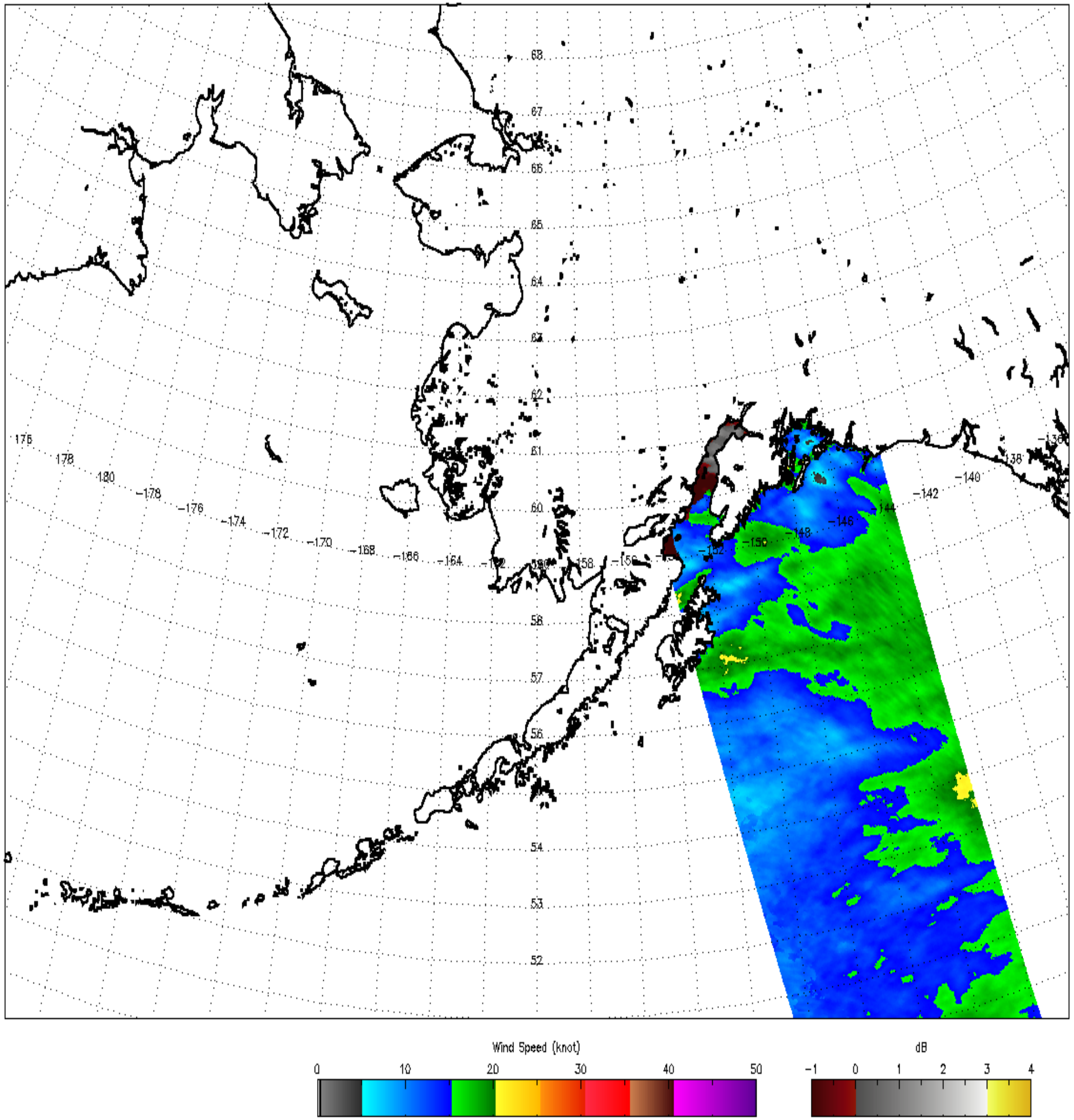

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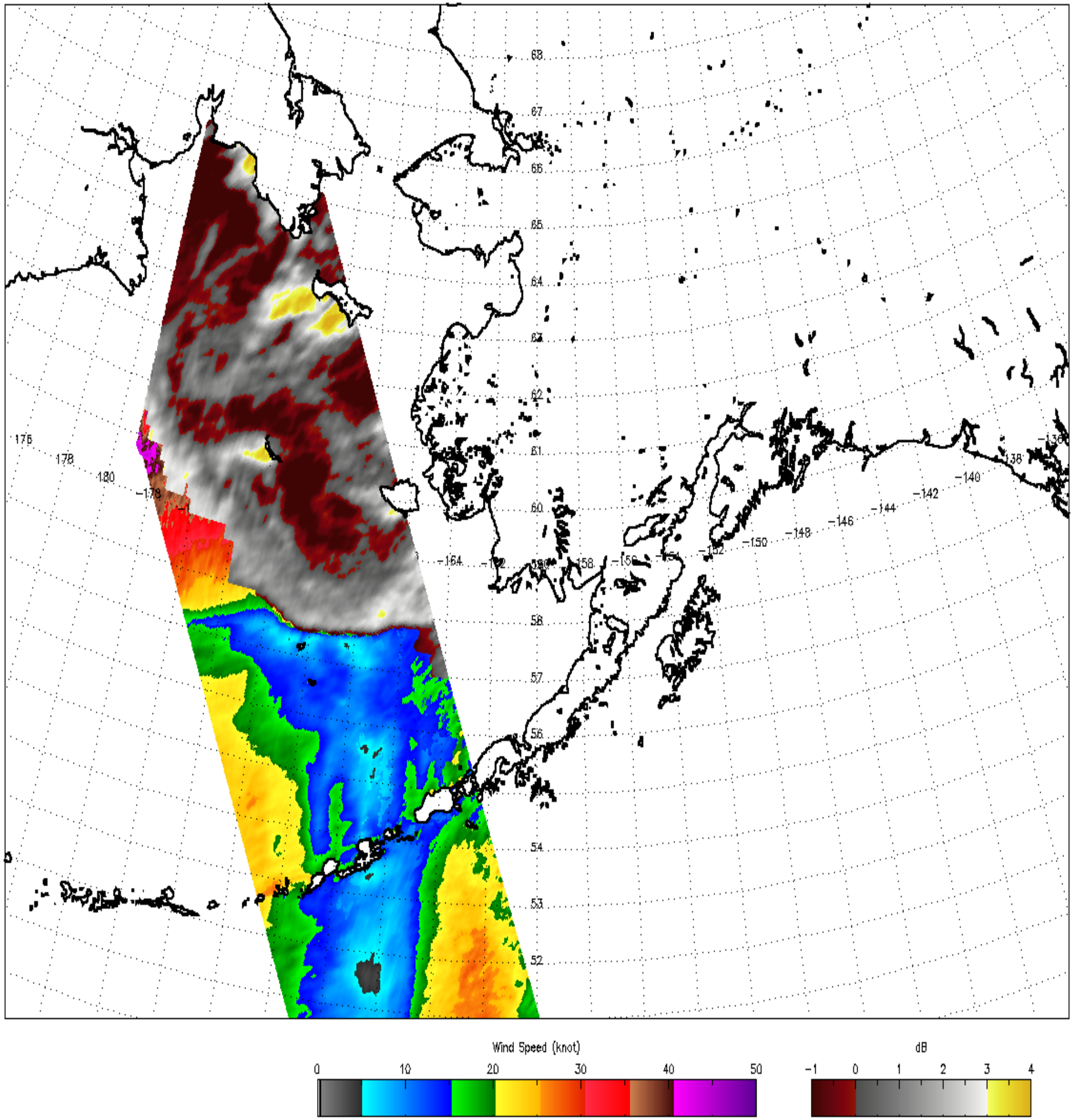

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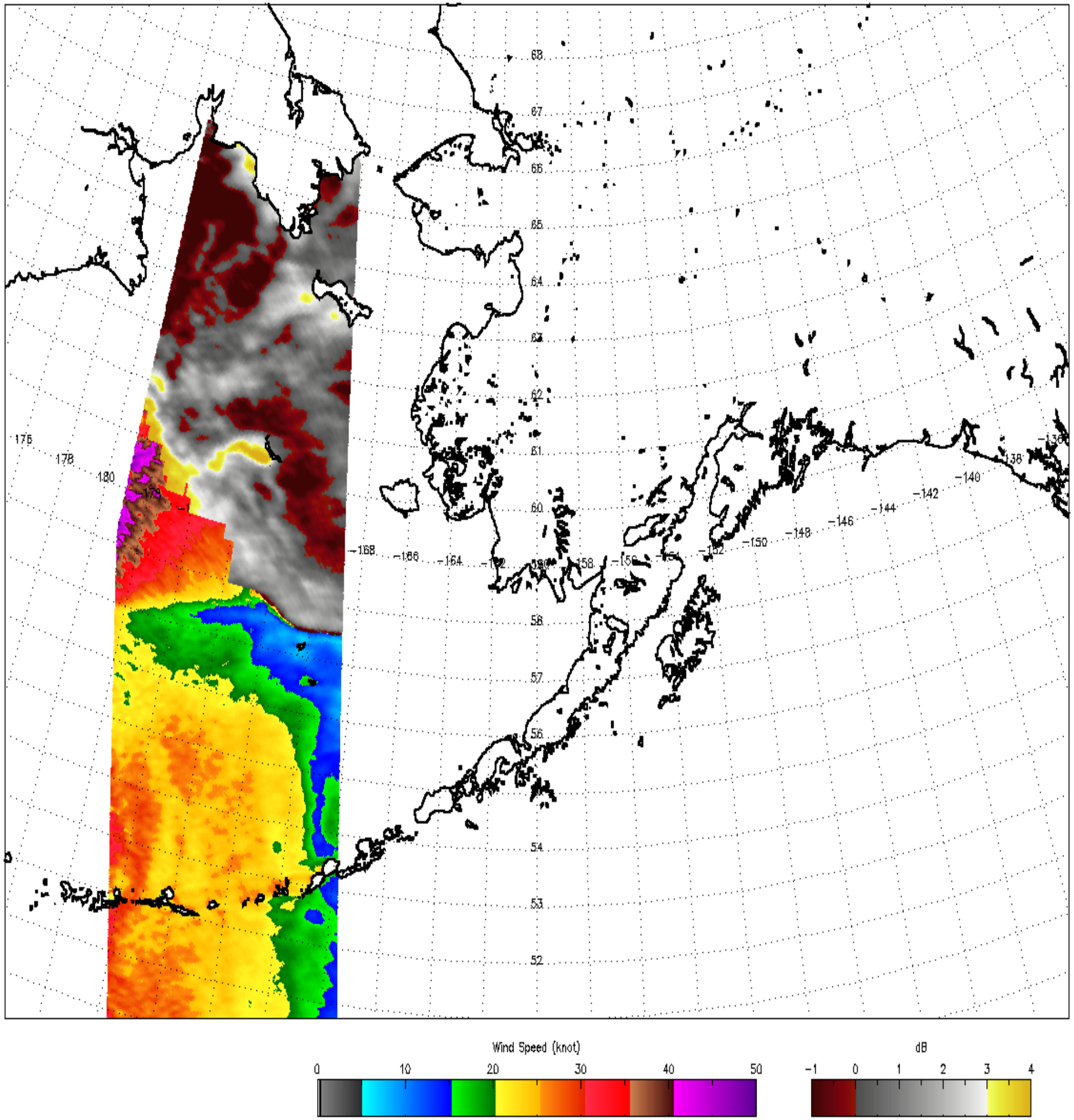

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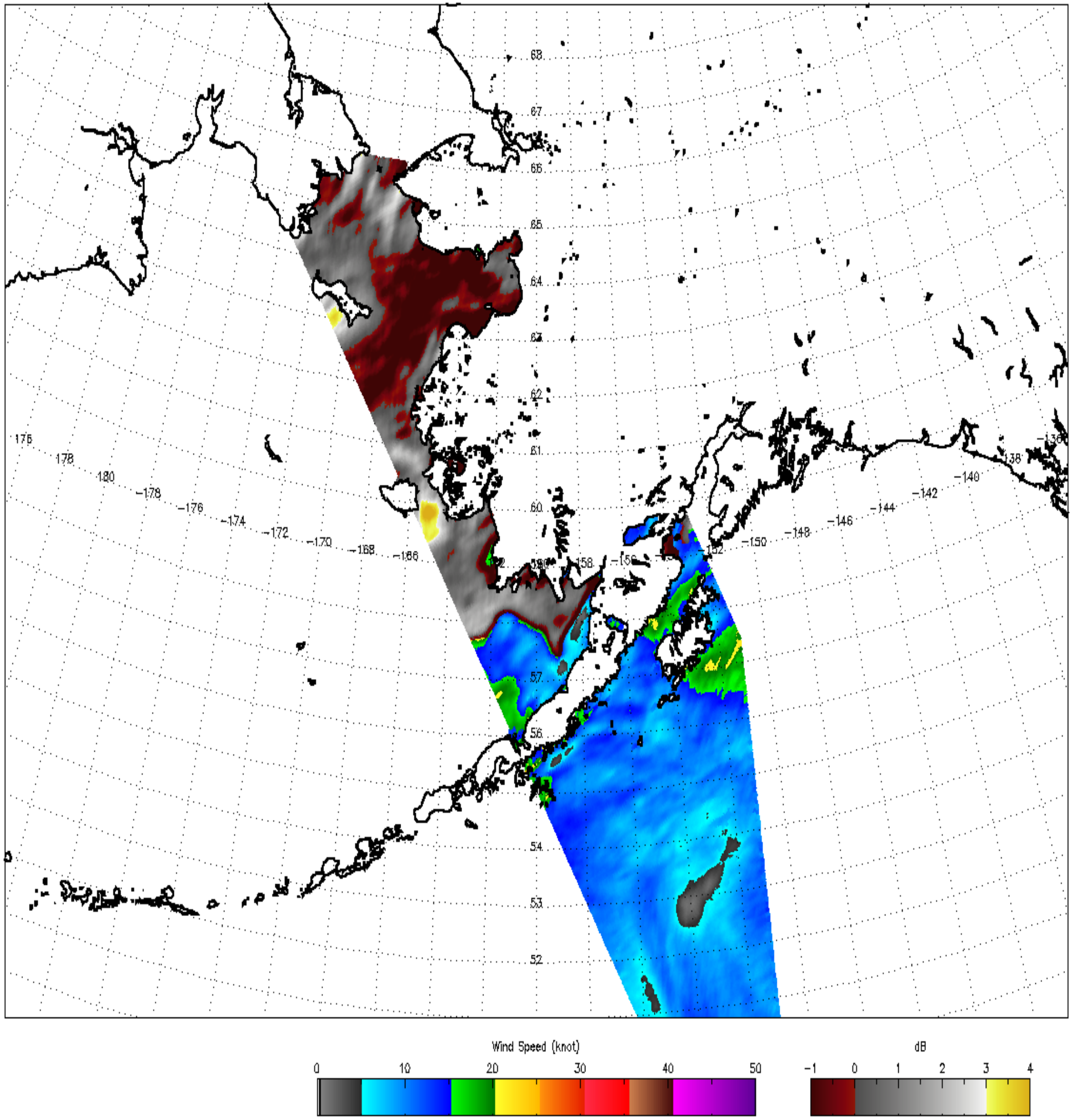

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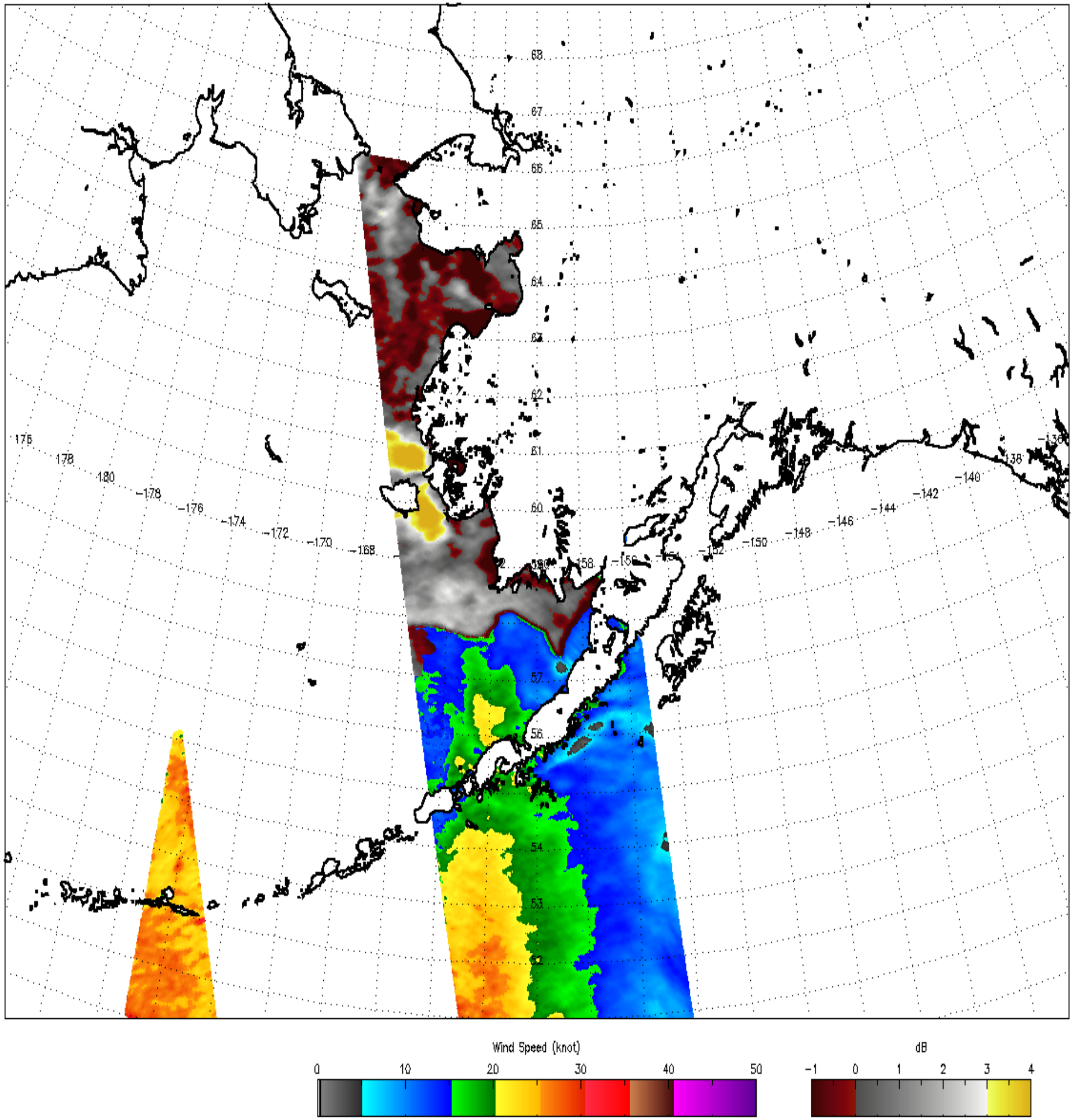

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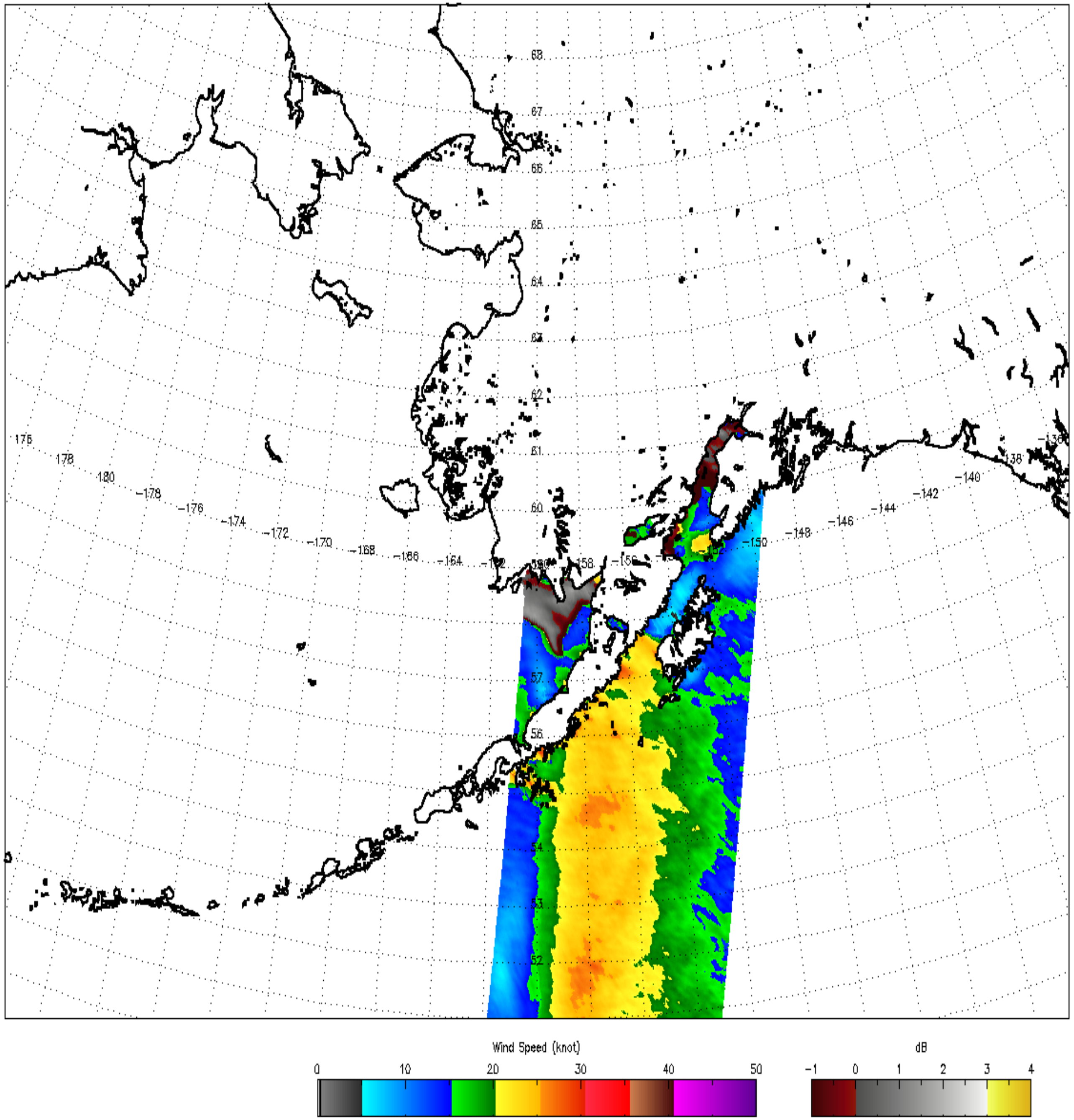

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