Capella Space
AMPLIFY INTELLIGENCE™

Geophysical Model Function to Retrieve Ocean Surface Wind Speeds with High-Resolution X-band Synthetic Aperture Radar (SAR) Data

Yuriy Goncharenko[1] , Christopher Jackson[2] ,Gordon Farquharson[1]

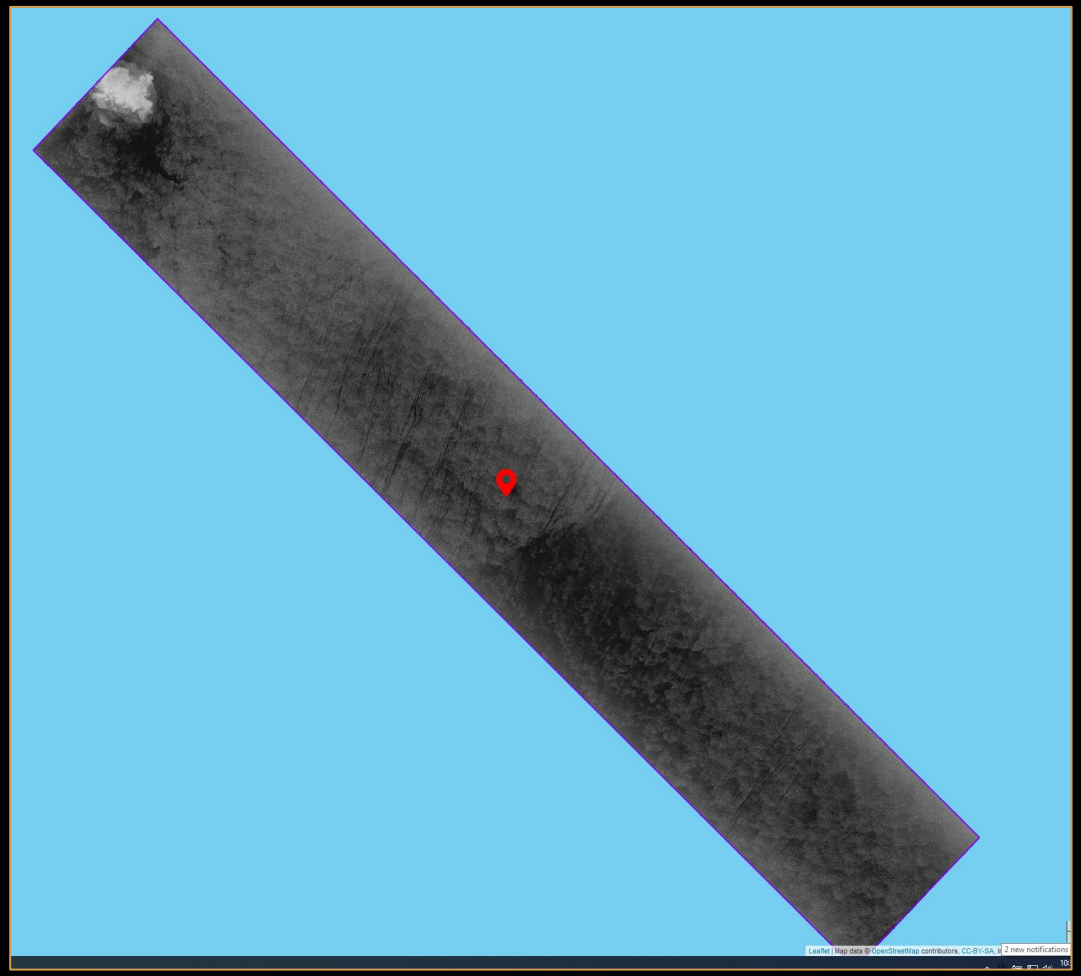
[1] – Capella Space Corporation
[2] – Global Ocean Associates

2025 International OVWST Meeting

May 07, 2025

SBIR Data Rights
Agreement Number: FA24012490008
Contractor Name: Capella Space Corp.
San Francisco, CA 94402
Expiration of SBIR Data Protection Period: 10/04/2044

Agenda

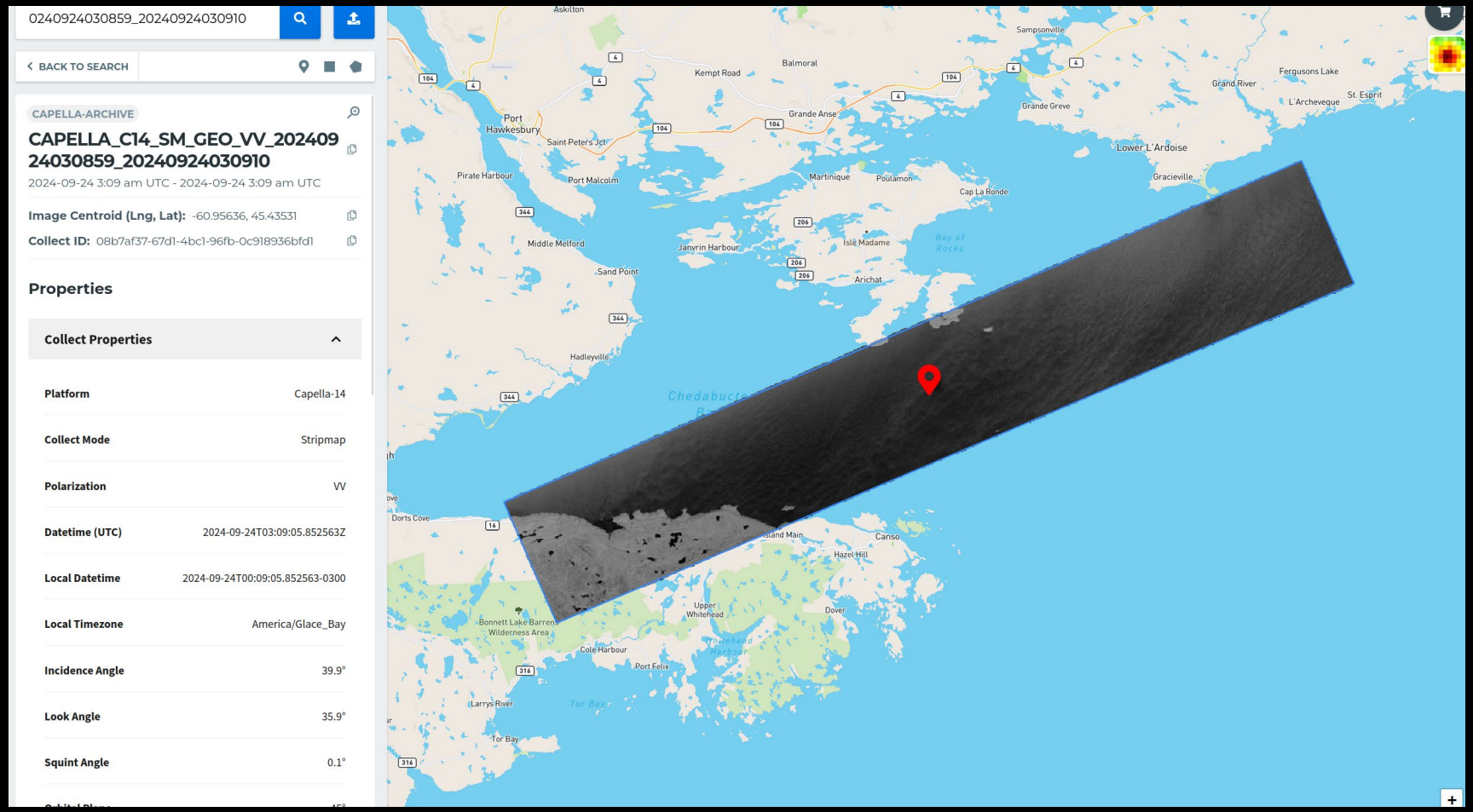


X-Band VV SAR Image of a Storm Cell
(10x 100 km scene, 10x10m resolution)

Ocean Surface Wind Collection Mode: Current Mode

Collection Mode:

- Side-looking stripmap;
- ***10 km x 70 km*** or ***10 km x 100 km*** scene size (up to 200 km long);
- 10 x 10 m resolution;
- NESZ: -28 to -35 dB;

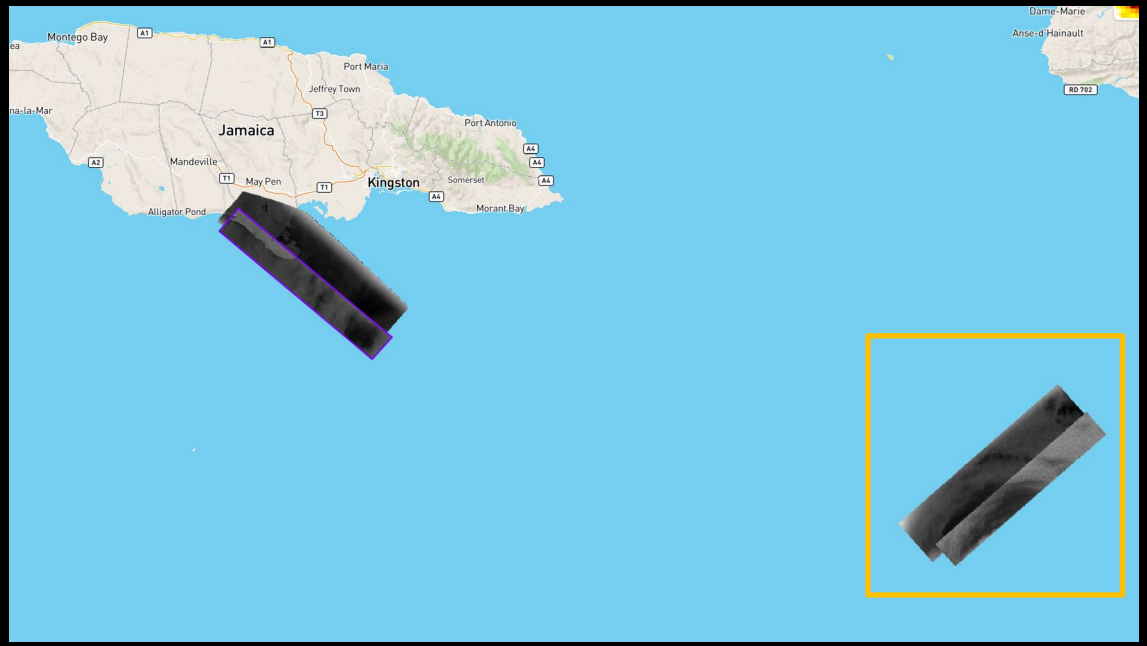


NOAA buoy 44488 (red pin) - east of Chedabucto Bay

Ocean Surface Wind Collection Mode: Potential

(Potential) Collection Mode:

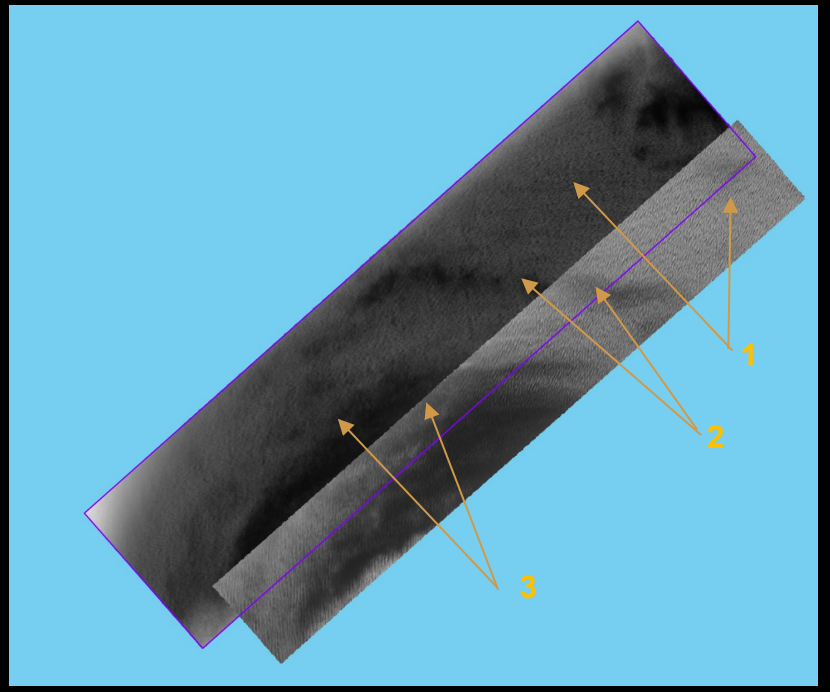
- Forward and aft looking stripmaps;
- Two ***10 km x 120 km*** scenes;
- Up to 70 degrees azimuth angle difference
- 10 x 10 m resolution;
- NESZ: -28 to -35 dB;



July 3, 2024, Hurricane Beryl

Images were taken with different squint (+23 and -23 deg.) at 09:25:14.9Z and 09:26:50.4Z (1.5 minutes apart)
(1) NRCS is different due to 46 deg azimuth angle difference between collects.
(2) This feature is OK aligned between both collects.
(3) This feature is 3-5 km off. Either:

- Significant change in wind direction occurred;
- Overlayed projection of rain is different for both collects;
- Features could just move fast: 90 s * 50 m/s = 4500 m



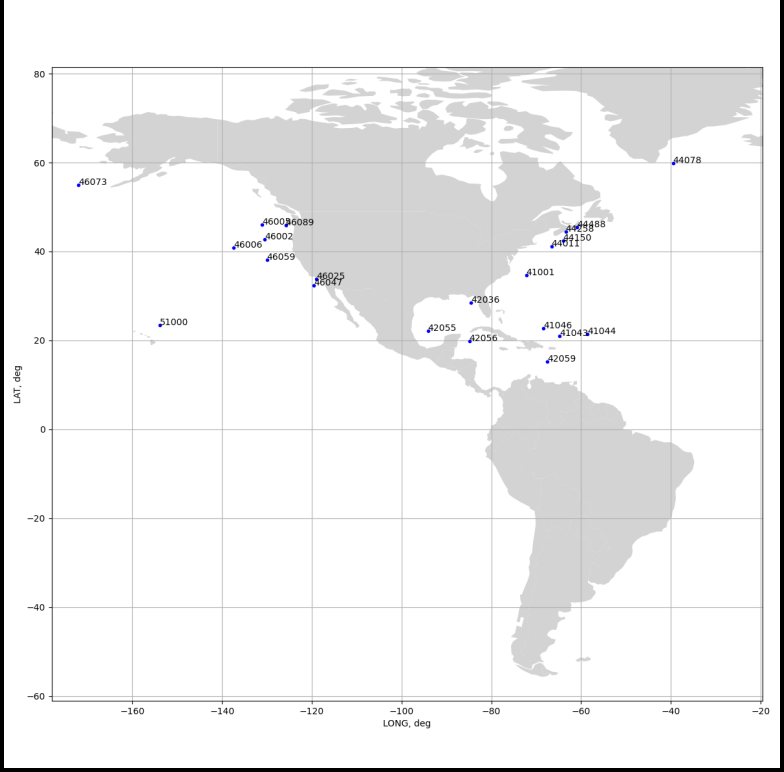
Description of a Data Set: Locations and Observed Wind

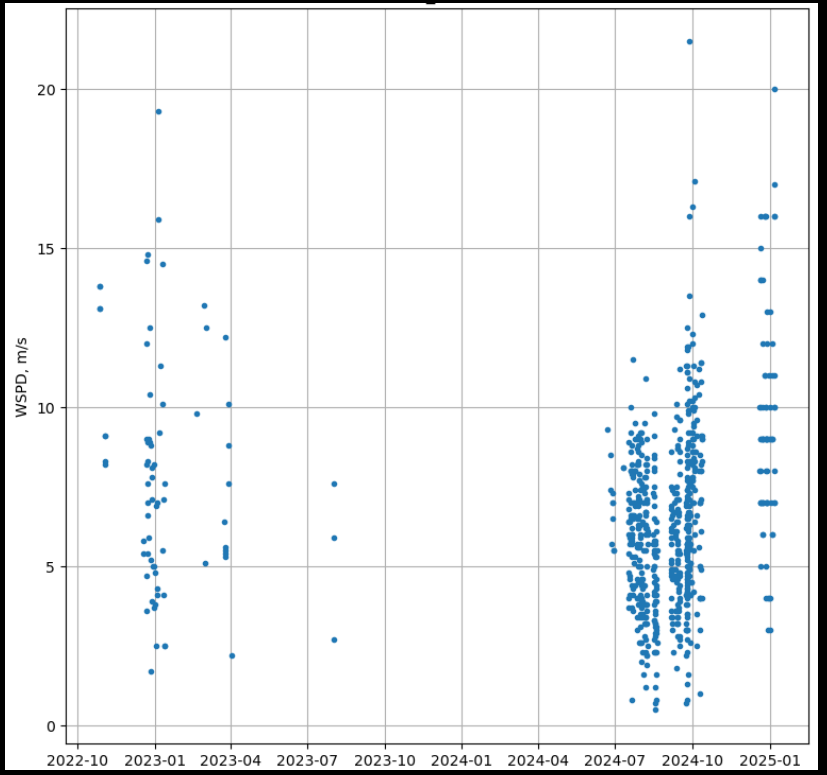
Data set:

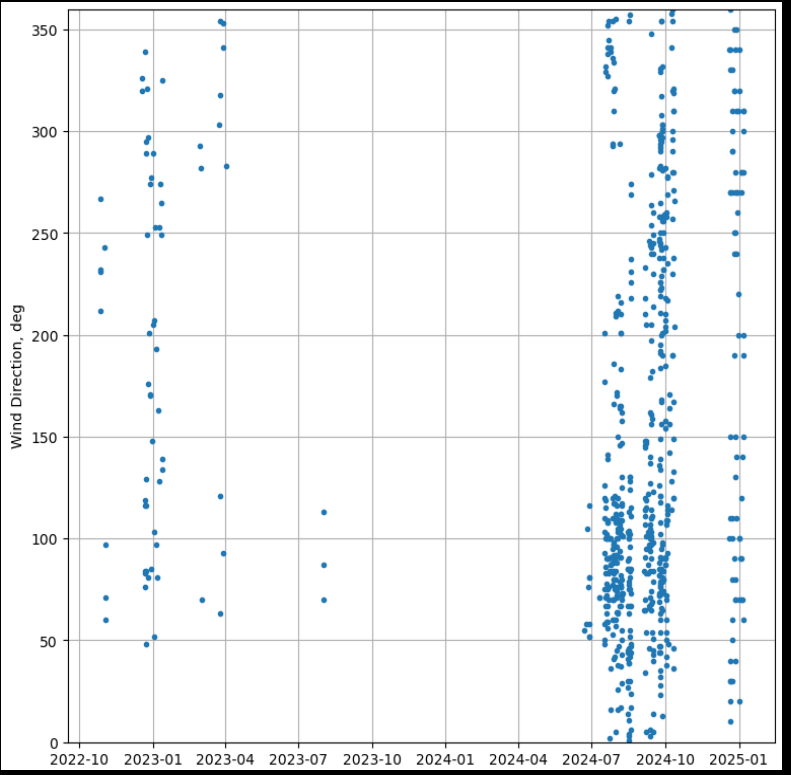
- 394 VV-polarized 10 km x 70 km stripmap images featuring a NOAA weather buoy at the scene center point.
- The dataset was taken over 28 NOAA weather buoys located in the Atlantic, East Pacific and Central Pacific

Observed wind speed and relative wind direction

The data taken in 2025 was not quality controlled, therefore some quantization is visible



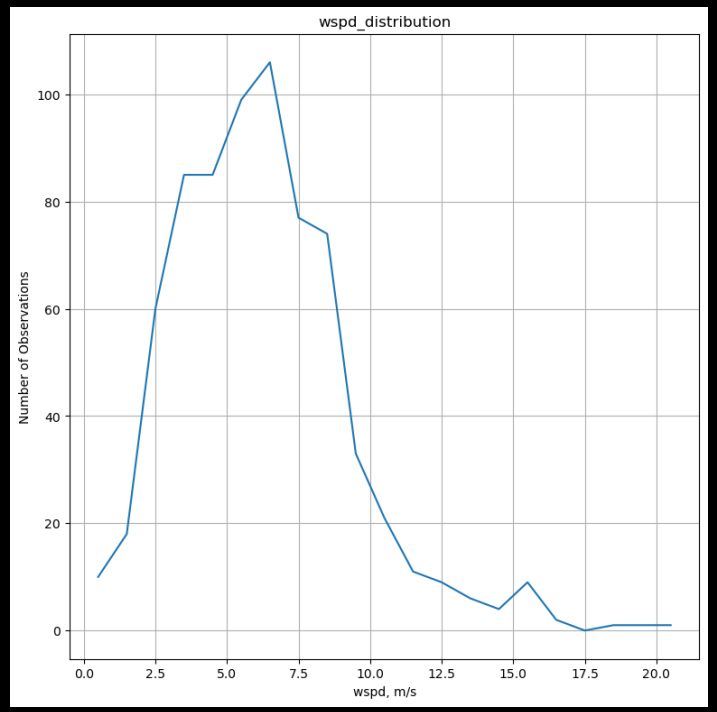


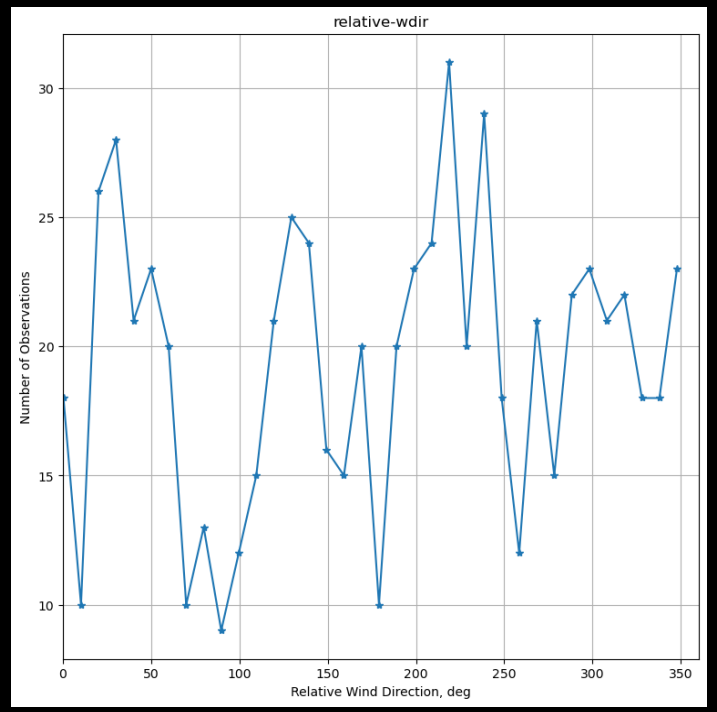


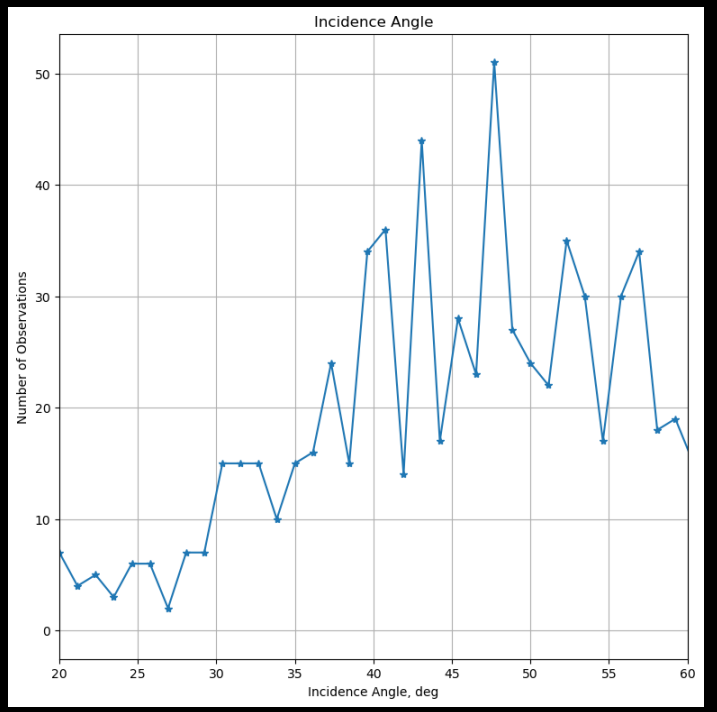
Description of a Data Set: Statistics

Data set:

- Enough data for wind speed < 11 m/s;
- Good angular diversity for relative wind direction;
- Incidence angle from 20 to 60 deg was covered, but most of the data is in 35 to 60 deg incidence angle range;



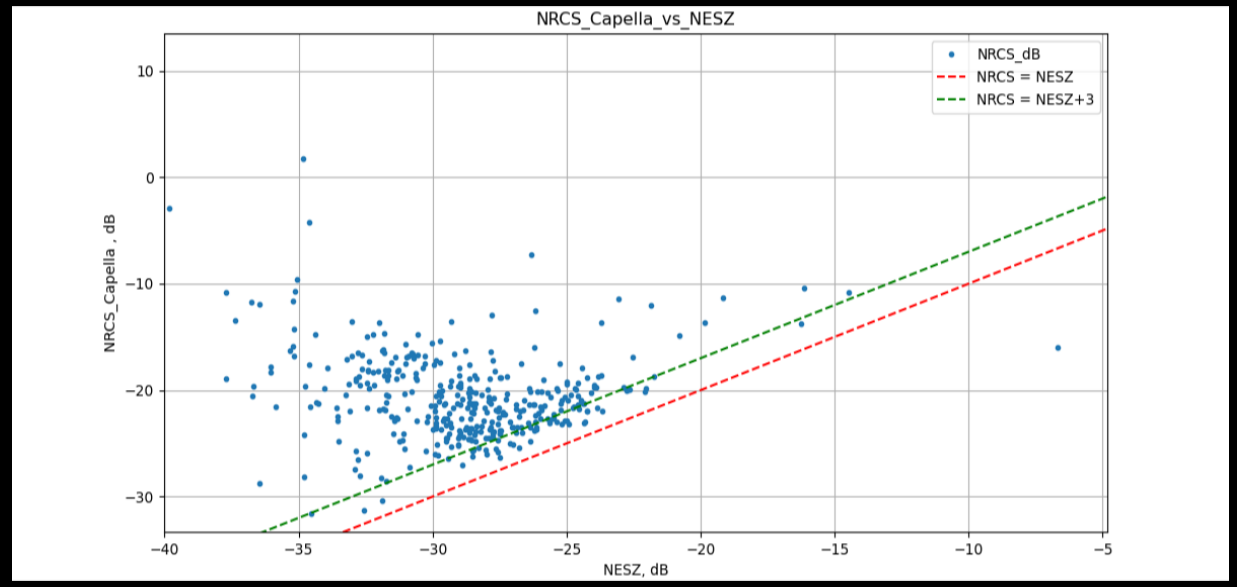




Description of a Data Set: Quality Control

Noise Level:

- Scenes with NRCS less than NESZ + 3dB were excluded

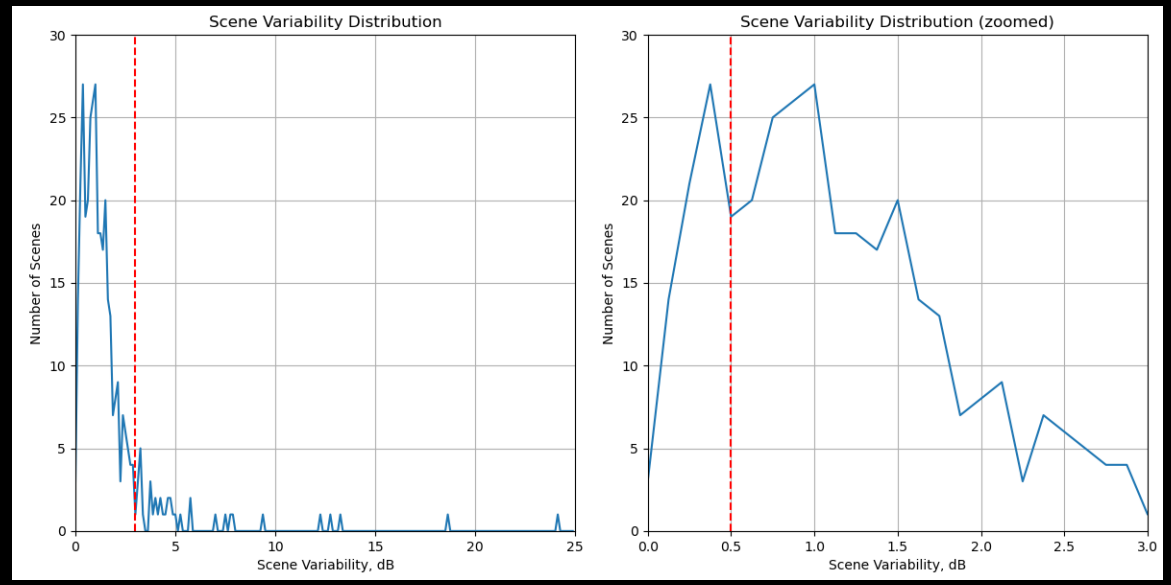


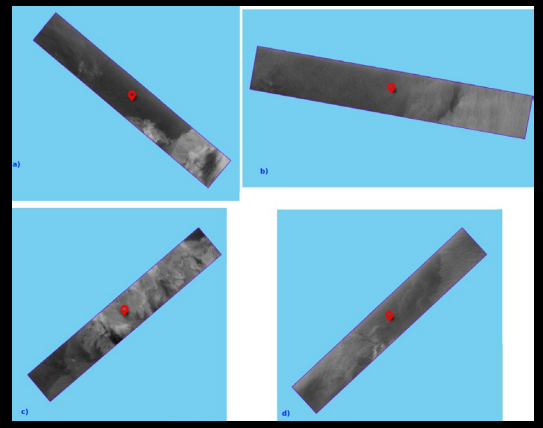
Result:

- Almost 20% of collects were removed from the further analysis

Scene Variability:

- Scenes with NRCS variability of more than 3dB were excluded



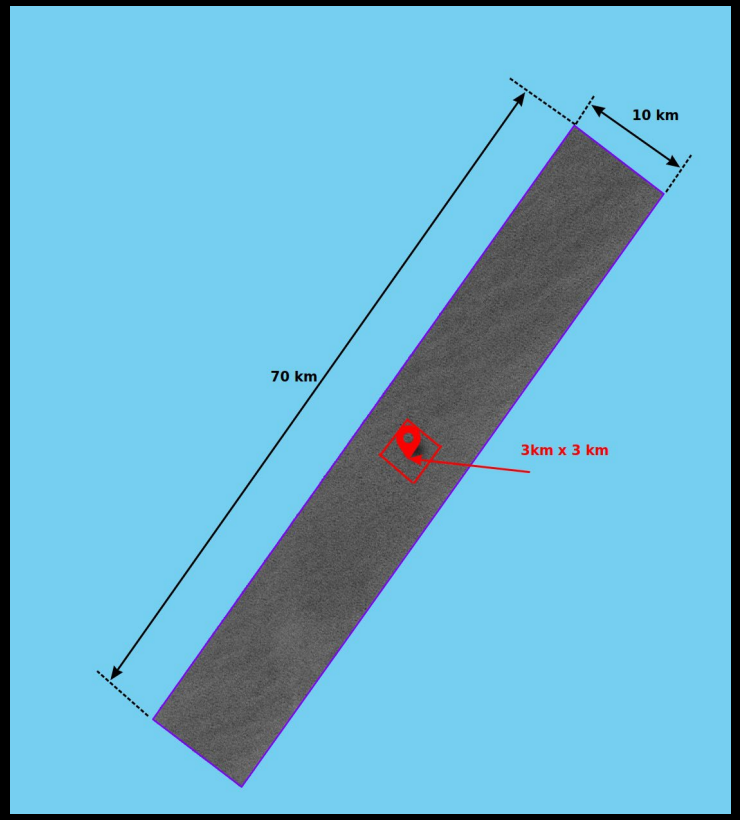


a) 2024-09-05 18:48:47, buoy 42055, scene variability: 9.5 dB;
b) 2024-07-17 12:18:04, buoy 46006, scene variability: 4.9 dB;
c) 2024-07-22 02:20:02, buoy 42056, scene variability: 7.8 dB;
d) 2024-07-20 06:40:42, buoy 51000, scene variability: 4.1 dB.

GMF Development

Input Data: For all SAR images which passed QA check:

- Measured NRCS was averaged over 3 x 3 km area (red box) around the NOAA buoy (red pin)
- Wind speed and wind direction was measured by NOAA buoy.



Generic Representation of Co-Pol GMF:

$$z(v,\varphi,\theta) = B_0^p(v,\theta)(1 + B_1(v,\theta) * cos\,\varphi + B_2(v,\theta) * cos\,2\varphi)$$

Z – Normalized radar cross section (NRCS);
v – wind speed;
ϕ - angle between wind speed vector and radar look direction;
θ – incidence angle;
B0, B1 and B2 – tuning coefficients: The term B0 represents the isotropic term, B1 the upwind/downwind amplitude, and B2 the upwind crosswind amplitude.

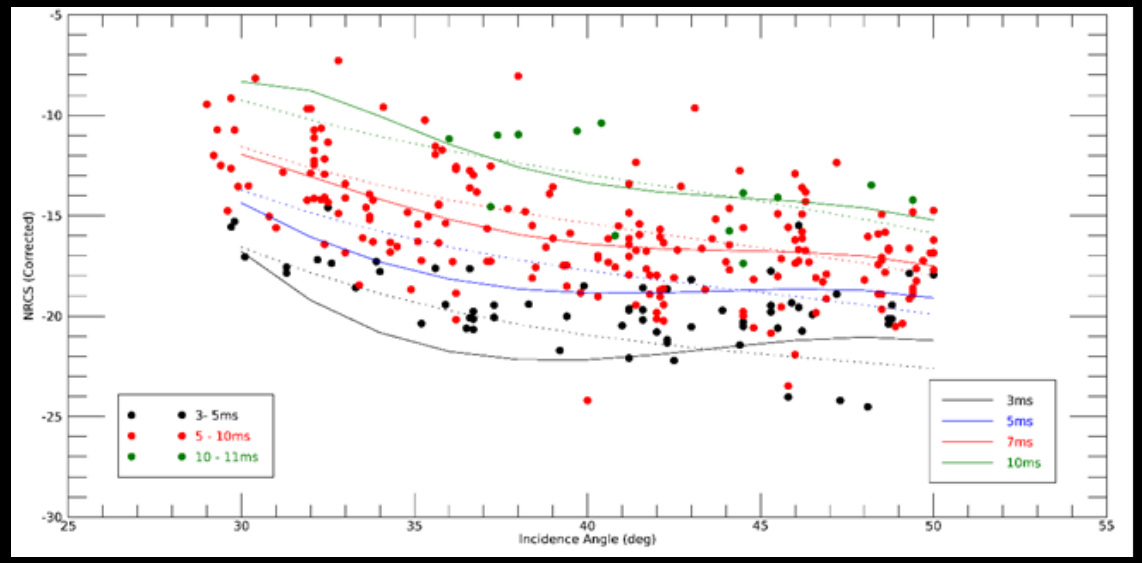
B0, B1 and B2 each contain a series of coefficients which are fit (tuned) for the application (or sensor system).

- XMOD2: 32 coefficients total.
- CMOD5: "only" 23 coefficients.

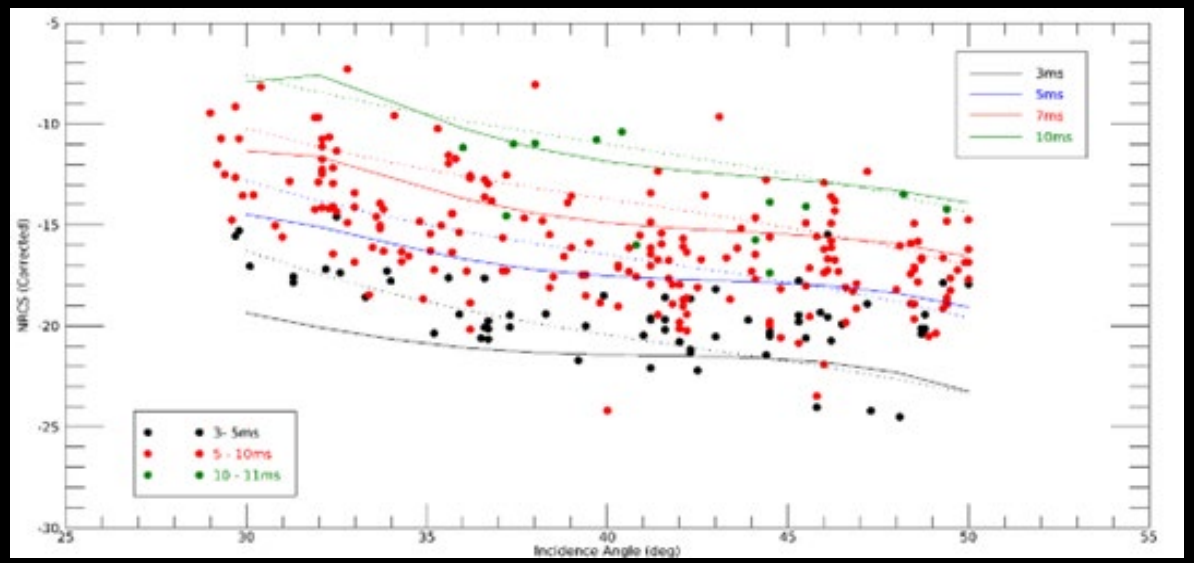
GMF tunning:

- MPFIT function (available in both IDL and Python) was used.
- MPFIT uses the Levenberg-Marquardt technique iteratively adjusting the model parameters to identify the best least-square fit between measured and modelled NRCS.
- XMOD2 were used as a start point

GMF Development



B0 Coefficient



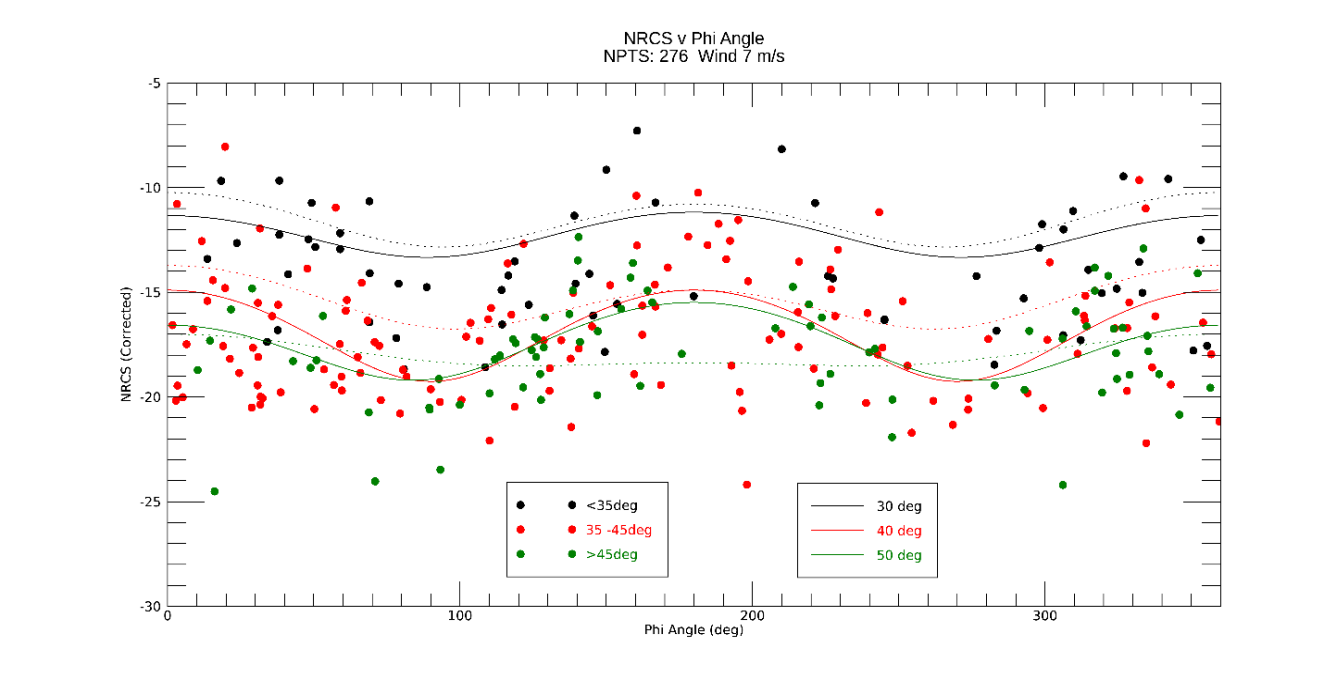
Full model (B0, B1, B2)

Dashed lines: XMOD2 GMF, solid lines XMOD-C(apella)

Remarks:

- B0: Most likely over-tunning effects for 3 m/s wind.
- B0: Bumps at 45-50 deg incidence angle for 3-7 m/s wind: NRCS at higher incidence angles is, usually, smaller, so system noise effects might be more visible
- Much more data is needed to perform accurate fitting.

GMF Development: Full Model Results for 7 m/s Wind

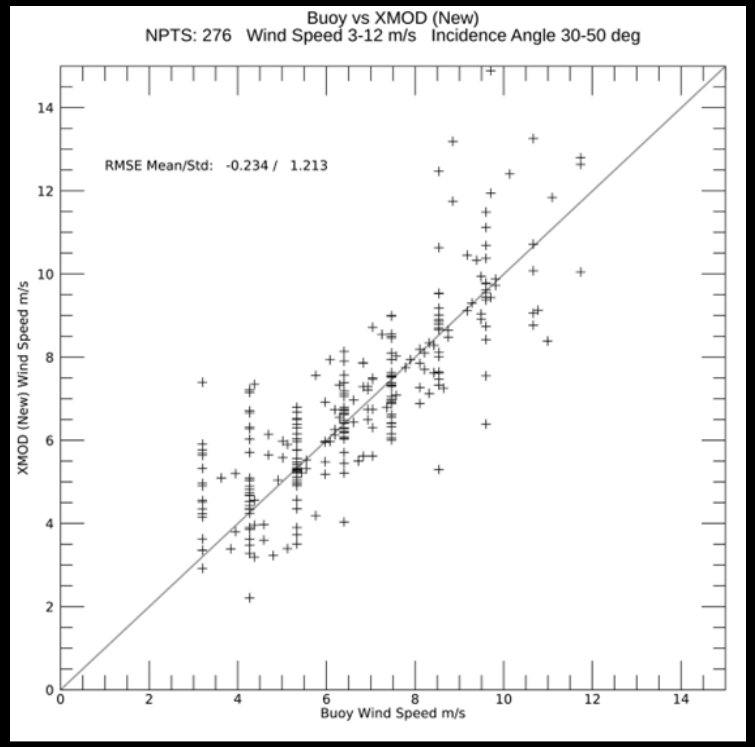


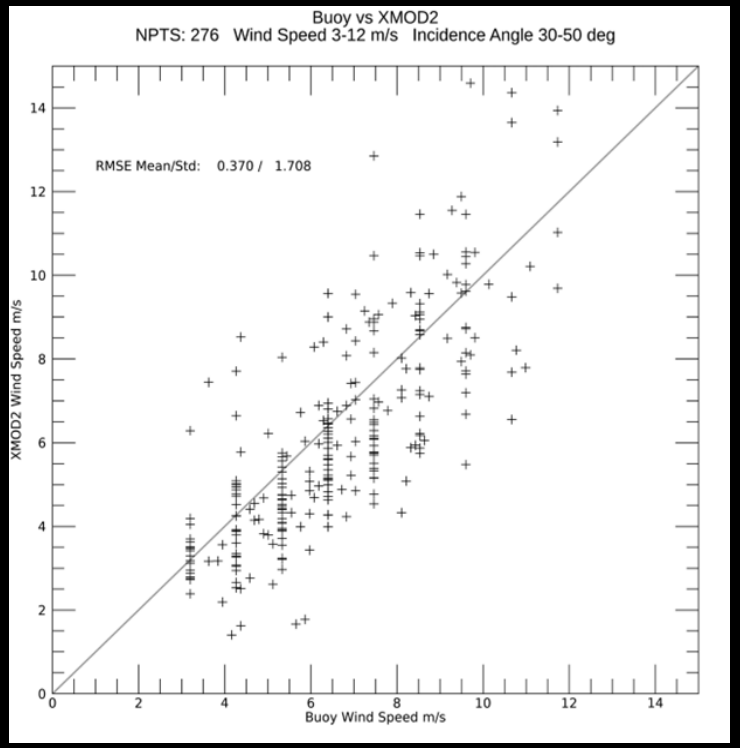
Full model result for 7 m/s wind speed.
Dashed lines: XMOD2 GMF, solid lines XMOD-C(apella)

Remarks:

- For higher NRCS the XMOD-C follows XMOD2 very closely.
- For NRCS less than –15 dB XMOD-C(apella) shows much better angular sensitivity:
  - The XMOD-C shape is closer to CMOD5 then to XMOD2
  - Perhaps Capella's low NESZ increased the dynamic range?
  - Result of limited data set?

GMF Development: Model Performance



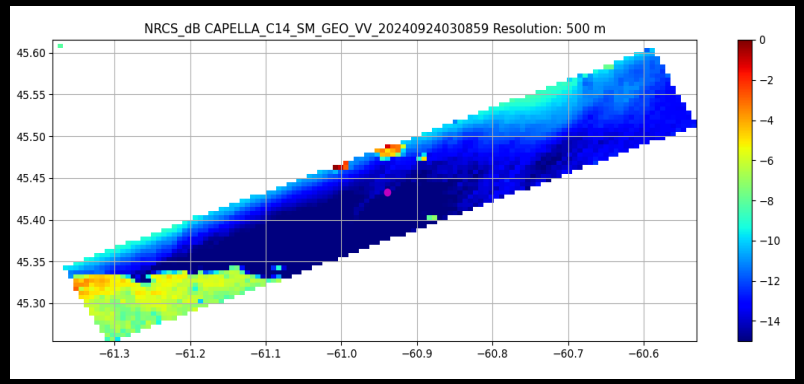


Model	Residual Mean (m/s)	RSME
XMOD-C(apella)	-0.23	1.21
XMOD2: Capella Data	0.37	1.71
XMOD2: TSX Data	-0.32	1.44

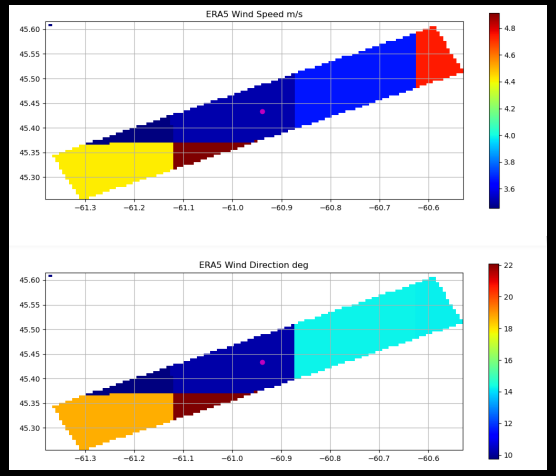
Retrieval Pipeline

- Current Capella sensor operates either in VV or HH polarizations, therefore we cannot perform unambiguous OSVW retrieval
- We use ECMWF ERA5 model to get wind direction

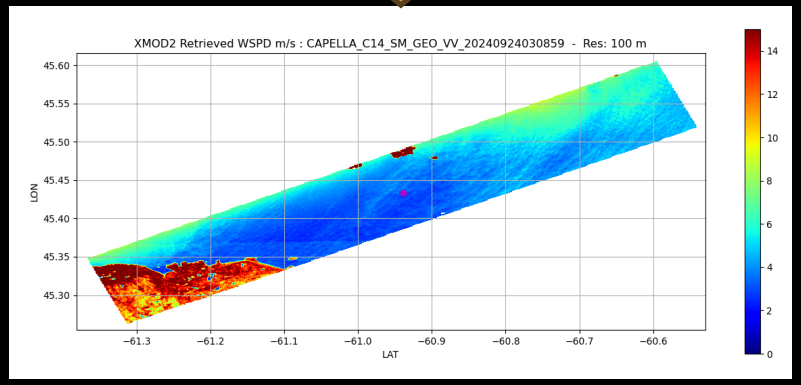
Calibrated NRCS



ERA5 Wind Direction

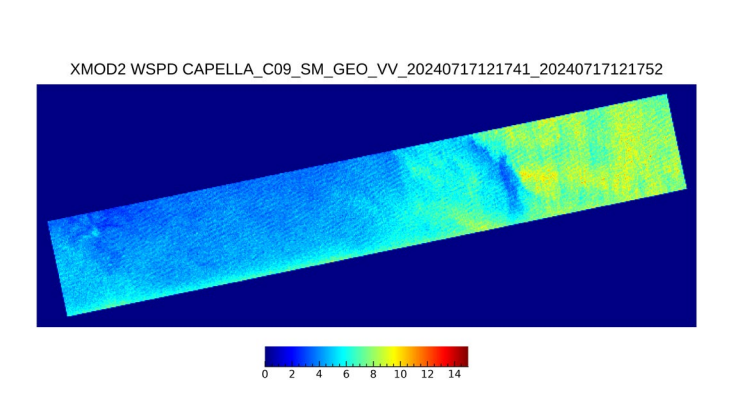


XMOD2 GMF

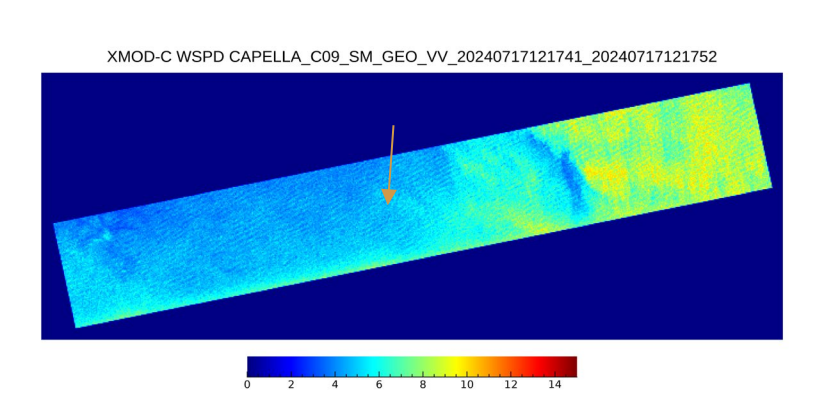


Retrieval Results (I)

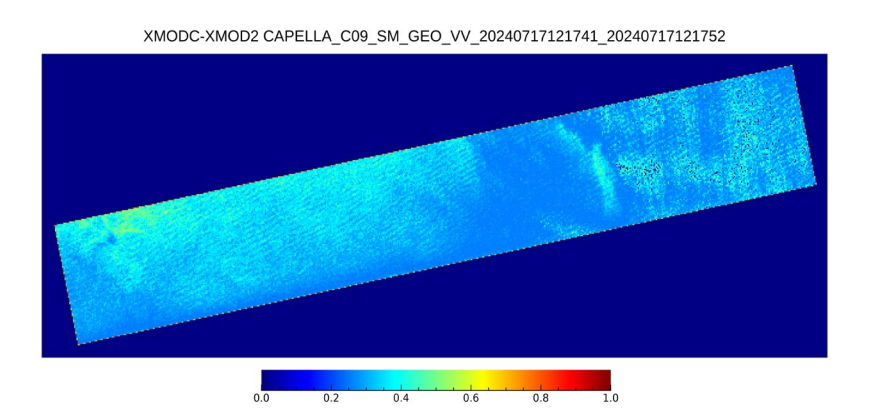
XMOD2



XMOD-C



XMOD-C - XMOD2

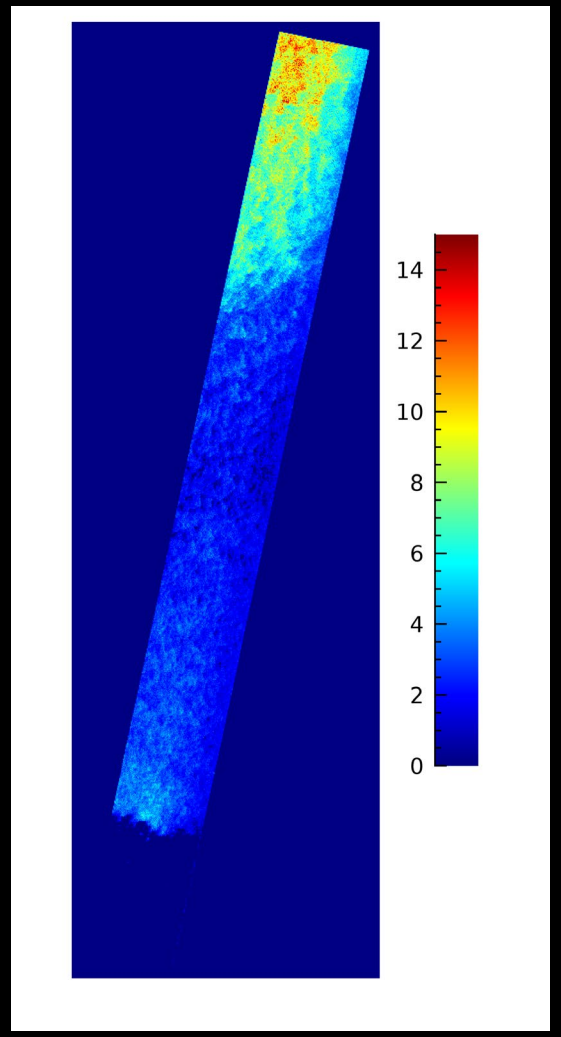


Capella-9, 2024-07-17T12:18:04.825Z, buoy_id: 46006, wspd: 7.3 m/s, wdir: 177.0 deg

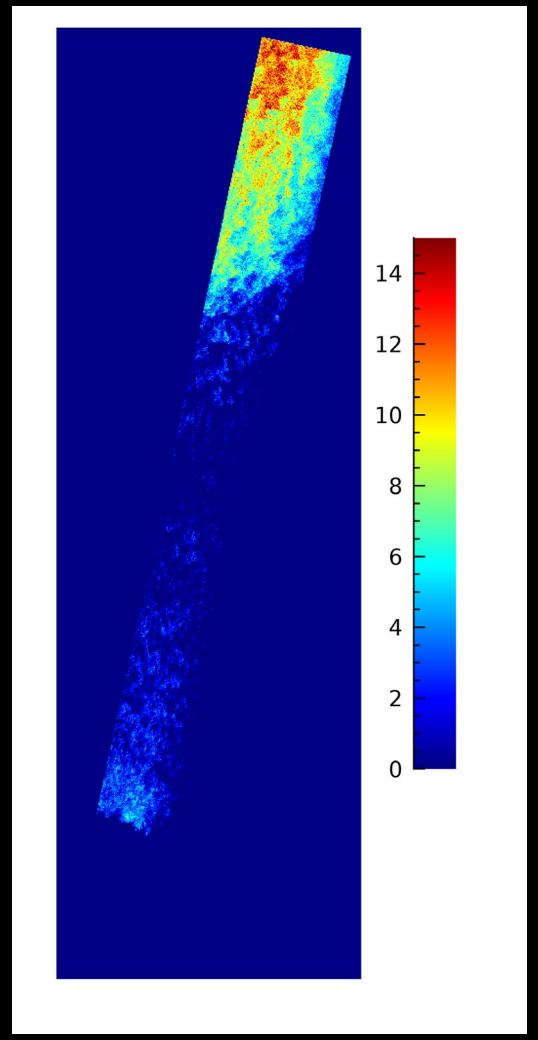
XMOD2	XMOD-C	Buoy
6.3 m/s	6.8 m/s	7.3 m/s (3 min earlier)

Retrieval Results (II)

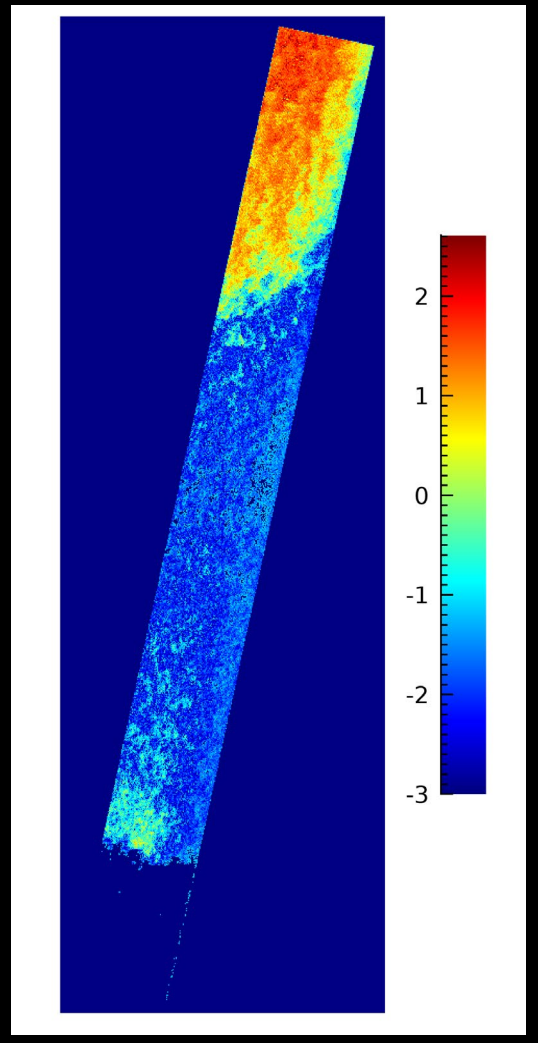
XMOD2



XMOD-C



XMOD-C - XMOD2



Capella-8, 2023-01-04T00:05:14.809Z, buoy_id: 44078, wspd: 4.3 m/s, wdir: 253.0 deg

XMOD2	XMOD-C	Buoy
3.5 m/s	1.7 m/s	4.3 m/s (10 min later)

CONCLUSION: GMF Improvement – Possible Ways

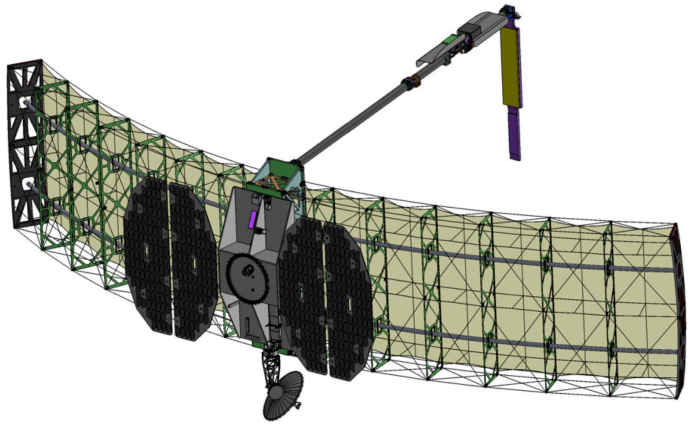
- More data (high wind speed data in particular) helps to avoid overfitting
- Not sure if weather model data is more useful that buoy for our case: an entire 10 km x 100 km scene (4,000 of 500 m x 500 m tiles or 100 3 km x 3 km tiles) all have same incidence angle and are within a couple of 0.2 x 0.2 deg model cell)
  - Would synthetic data (based on observed scene variability) work?
- AI GMF model might work better than XMOD-like one

Post Scriptum: COSAS Requirements

- **Co**mmercial **SA**R **S**catterometer for OSVW and TCI monitoring.
- Capella's material-solution was funded under the SDA SBIR Phase I & II COSAS contract.
  - Phase II successfully completed 2024
- As a Multi-Mission Pathfinder our C-Band WFOV Sensor is design to address both the Weather Intelligence and Wide Area (Maritime) Search capabilities gaps.

Parameter	Value	Units	Comments
Measurement Uncertainty: Wind Speed	N/A	m/s	N/A or best effort for wind speed 5-10 m/s
Measurement Uncertainty: Wind Speed	≤ 2	m/s	For wind speed 10-25 m/s
Measurement Uncertainty: Wind Speed	N/A	m/s	Best effort for wind speed 25-60 m/s
Measurement Uncertainty: Wind Direction	N/A	deg	For wind speed 5-10 m/s
Measurement Uncertainty: Wind Direction	≤ 15	deg	For wind speed 10-30 m/s
Measurement Uncertainty: Wind Direction	N/A	deg	For wind speed > 30 m/s
Refresh	< 6	hours	Max time to revisit the storm center + 100 km all direction
Latency	3	hours	Time elapsed from sensor to DoD data processing center
Horizontal Spatial Resolution	≤ 5	km	Radius of the smallest wind vector cell (WVC)
Accuracy (Radiometric Calibration)	1	dB	
Precision (Noise-Equivalent NRCS)	< -30	dB	

C-Band Sensor Summary



- Total mass: ~ 200 kg;
- Designed to fit Space-X rideshare;
- 10x2 m deployable TenSAR mesh antenna;
- C-band;
- VV/VH polarization;
- 2 kW peak transmit power;
- Passive electronic beam steering

COSAS OSVW mode:

- Minimum Ground Resolution:
  - Nominal: 1.5 x 1.5 km (depends on look angle)
  - Coarse: 5 x 5 km.
- Look angle range:
  - 25-55 degrees;
- Swath Width:
  - 200 km (ScanSAR mode)
- Swath Length:
  - 200 km (nominal)
  - 400 km (thermal/power limitations)
- NESZ:
  - Nominal: < –32 dBm2
  - Coarse: < –37 dBm2
- Minimum retrieved wind speed:
  - Nominal mode: 12 m/s
  - Coarse mode: 7 m/s

SVDT Medium Resolution mode:

- Ground Resolution:
  - 5 x 5 m
- Look angle range:
  - 25-55 degrees;
- Swath Width:
  - 70 km (regular stripmap mode)
- Swath Length:
  - 200 km (nominal)
- NESZ:
  - < –10 dBm2

