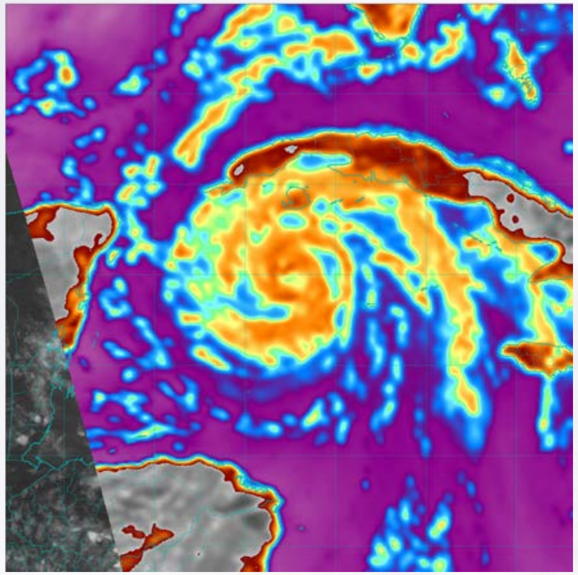
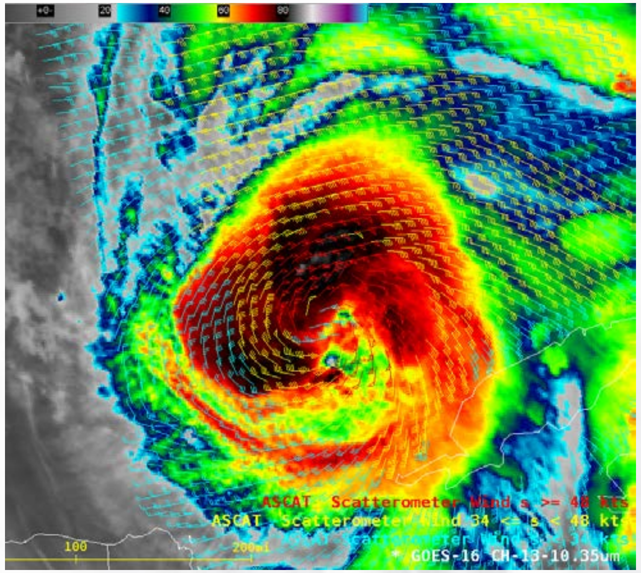
Interpretation of Microwave Imagery and Scatterometry





Brad Reinhart

National Hurricane Center

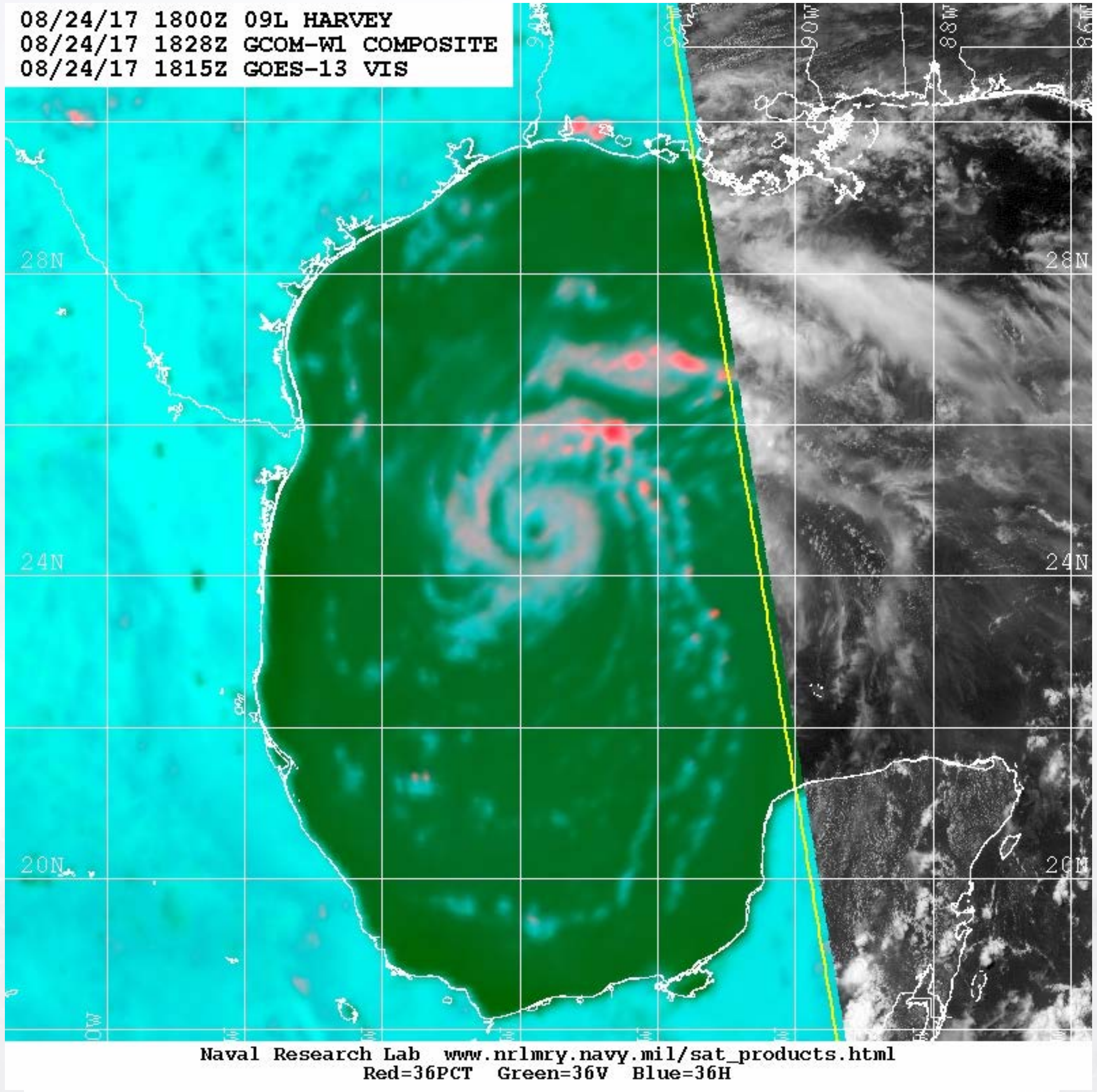
2023 WMO RA-IV Workshop on Hurricane Forecasting and Warning

Outline

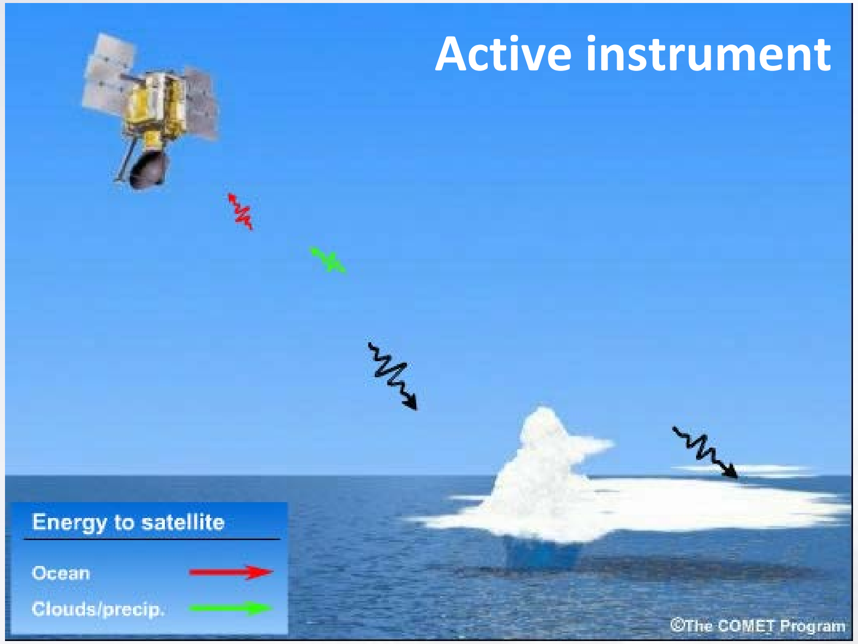
- Introduction to remote sensing
  - *Active vs. passive instruments*
  - *Geostationary vs. polar-orbiting satellites*
- Passive microwave imagery
  - *85-91 GHz and 37 GHz imagery*
  - *Data interpretation and TC applications*
- Active microwave sensors
  - *Scatterometers*
  - *Synthetic aperture radar*
- Exercise

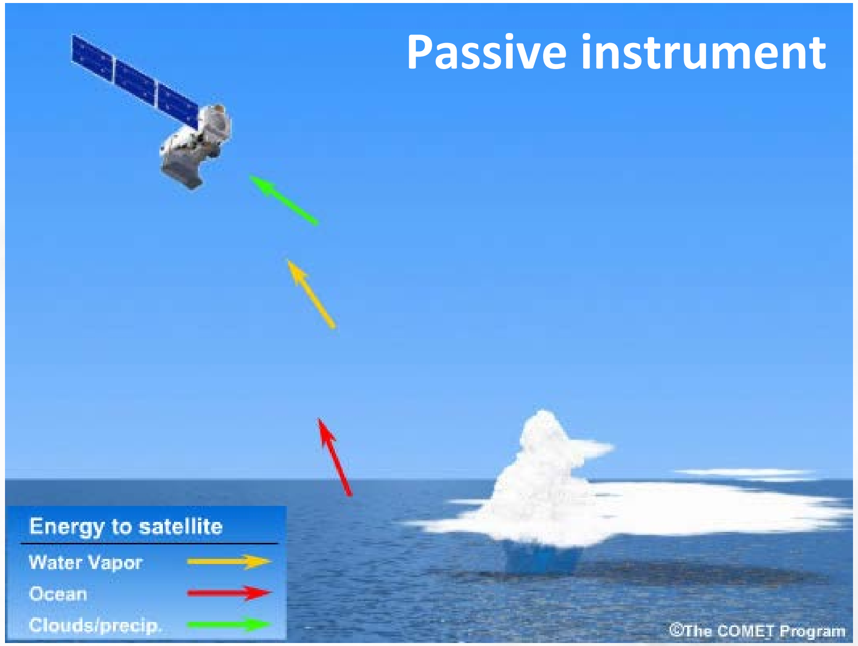
** Acknowledgement to COMET, Navy/NRL, FNMOC, and NASA for many of the images shown here*

Why use microwave imagery?



Measuring Electromagnetic Energy





Active Instruments

- Send out pulses of radiation, usually at microwave frequencies
- Measure radiation returned to the sensor
- Examples: Surface-based and airborne radars and scatterometers

Passive Instruments

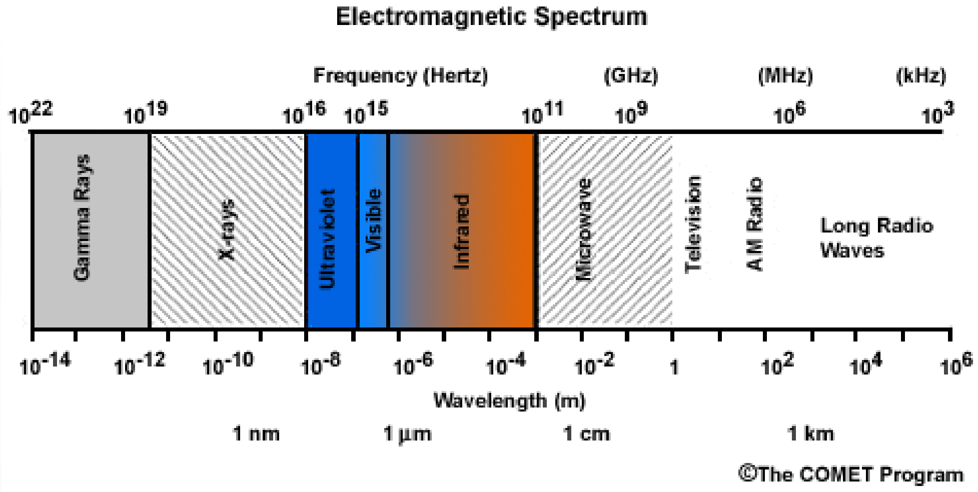
- Receive radiation leaving the earth-atmosphere system
- Measure emitted and scattered infrared and microwave radiation

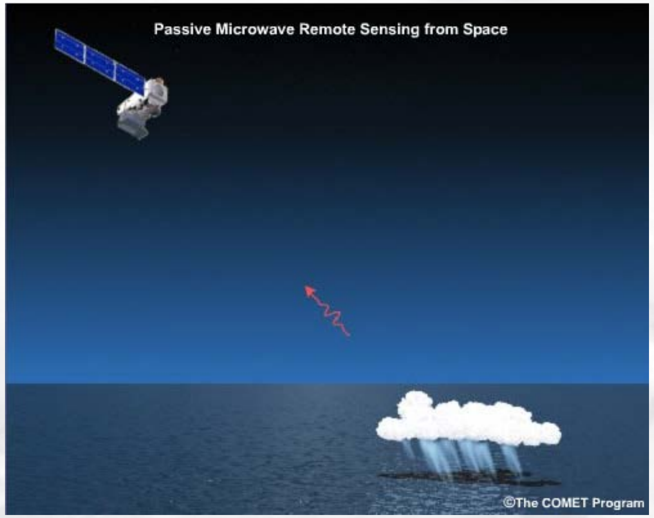
Passive Microwave Sensors

- Passive microwave sensors measure emitted energy from 19 to 200 GHz

- Emissivity is a measure of the energy radiated from an object

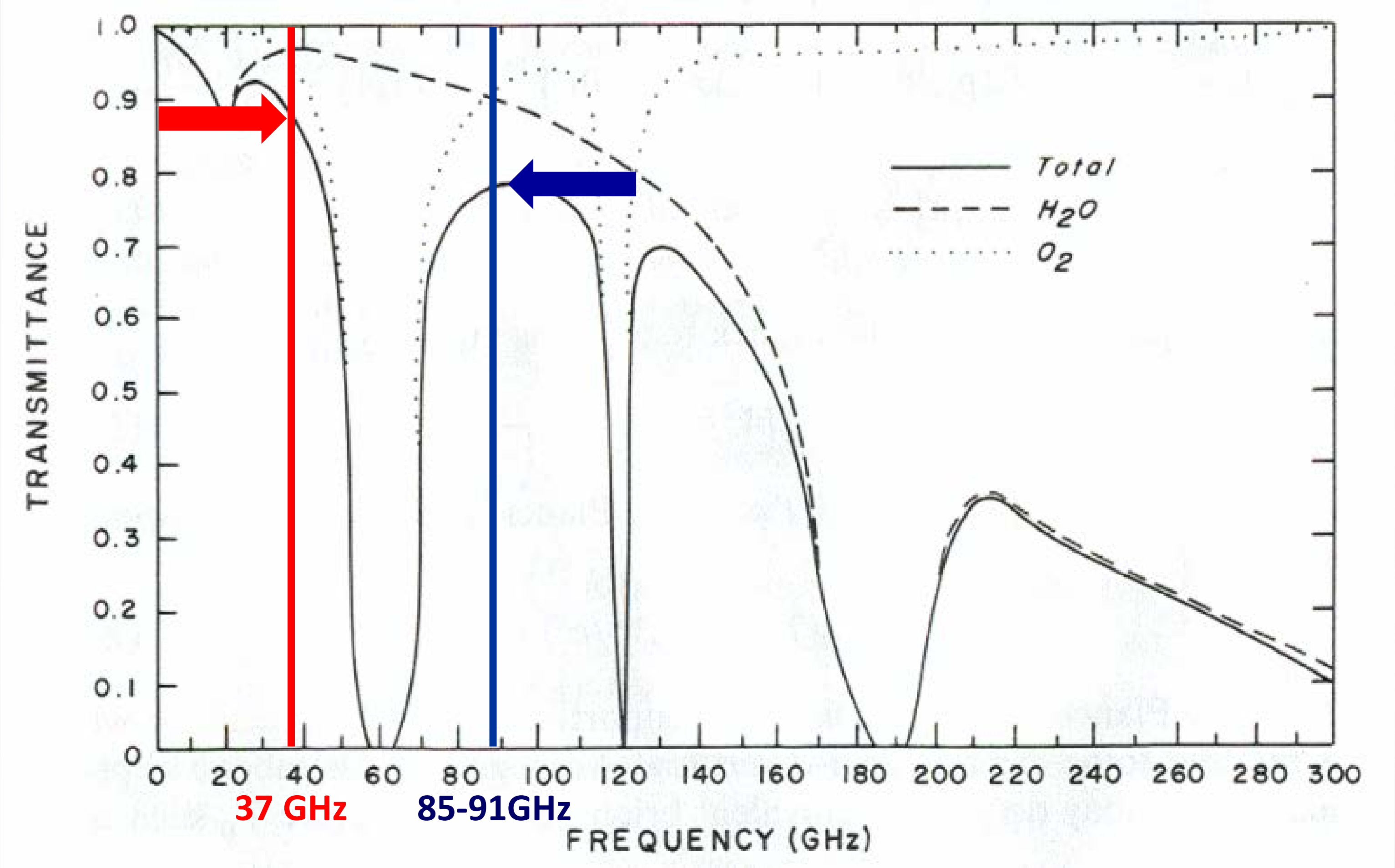
- Emissivity is directly related to brightness temperature (T_b)
  - scattering effects by ice
  - emission by light precipitation
  - emission/absorption by cloud liquid water and rain droplets





Images courtesy COMET

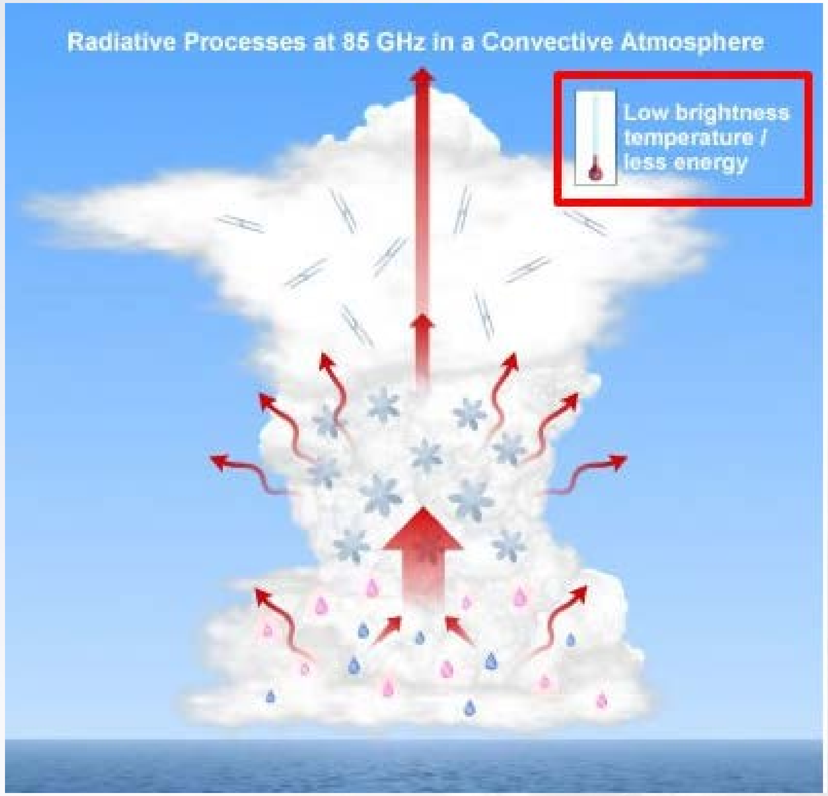
Microwave Remote Sensing Basics

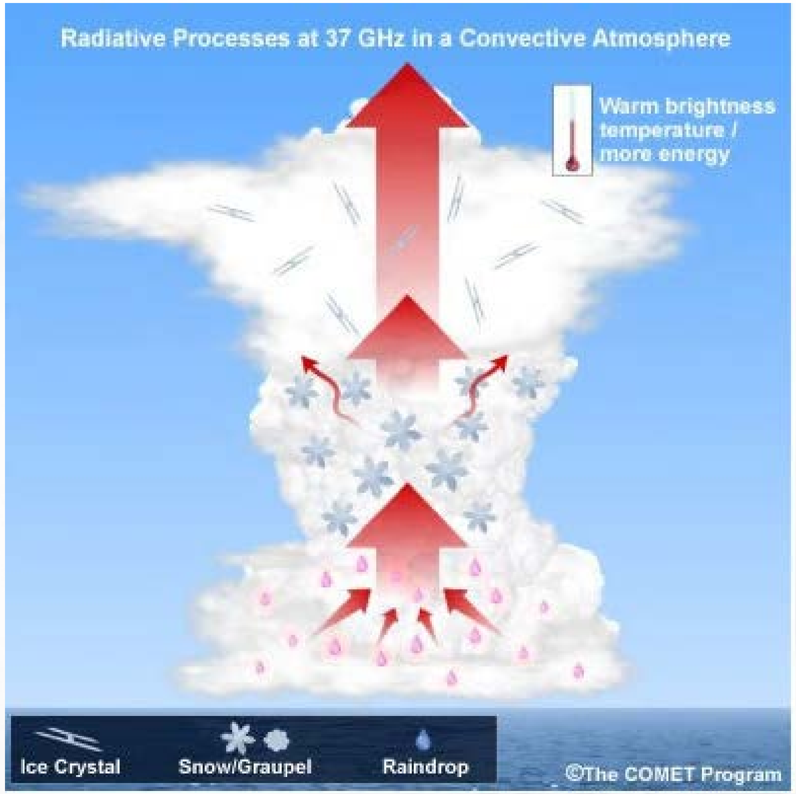


Why do we use the 85-91 & 37 GHz channels?

These are atmospheric "window" regions of high transmittance (low absorption by atmospheric gases at these frequencies).

Microwave Remote Sensing Basics





85 to 91-GHz: Primary signature is **lowered** T_b caused by scattering by ice, cloud, and rain droplets within deep convection and precipitating anvil clouds.

37-GHz: Primary signature is **enhanced** T_b because of minor emission from liquid hydrometeors near or below the freezing level.

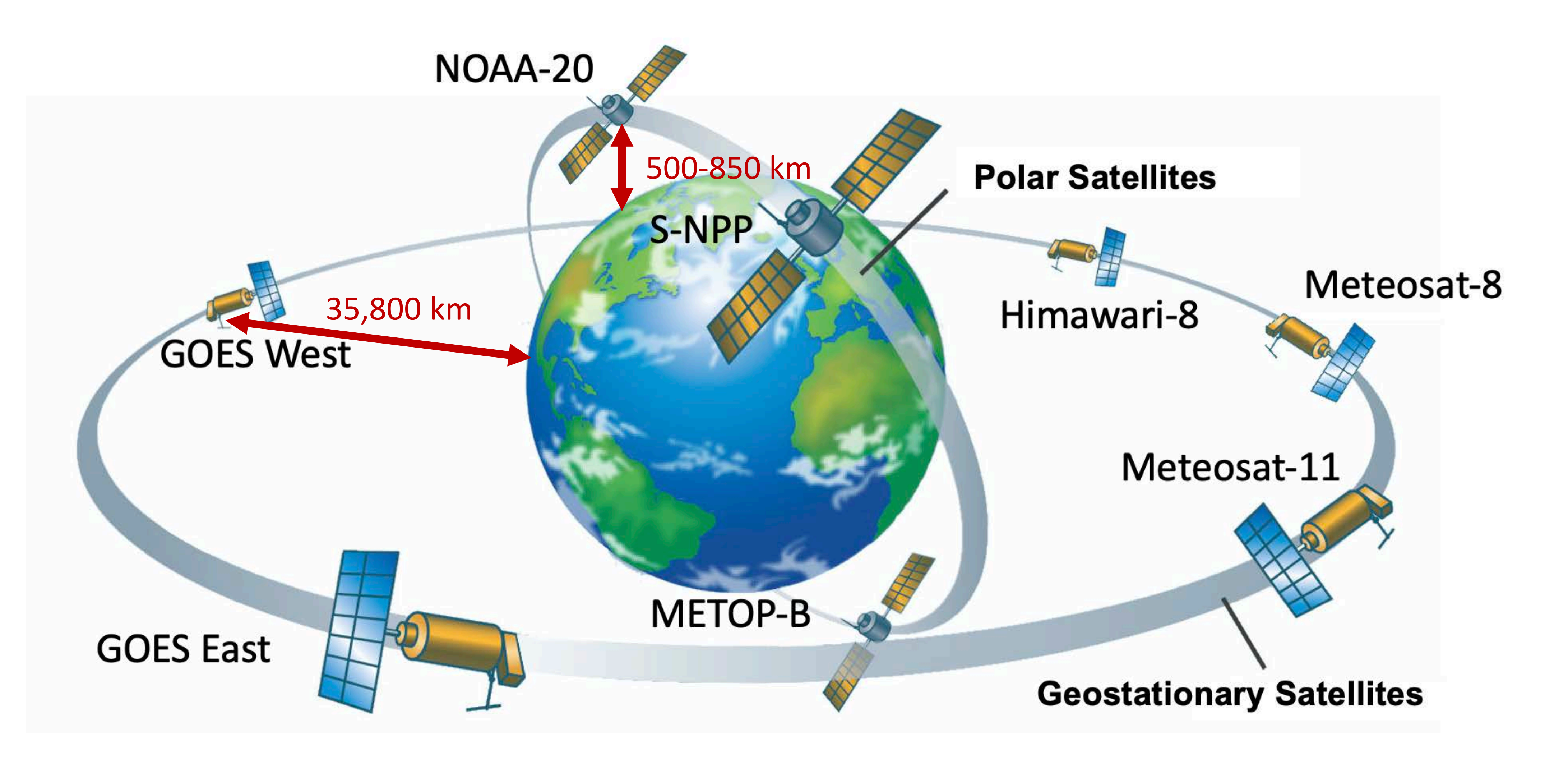
GEO vs. LEO Satellite Comparison

- **Geostationary (GEO) satellites**
  - ✓ Orbit at 35,800 km altitude over same spot on the equator
  - ✓ Good for continuous monitoring on a large scale
  - ✓ Good for visible and infrared, not good for microwave
  - ✓ Good for passive sensors, not good for active sensors

- **Low earth orbit (LEO) satellites**
  - ✓ Orbit at 500-850 km altitude, but not over same spot on earth
  - ✓ Limited spatial coverage (narrow data swaths, but can cover nearly entire globe daily depending on orbital configuration)
  - ✓ Views each area only twice per day (except near the poles)
  - ✓ Good for microwave, visible, and infrared
  - ✓ Good for active and passive sensors

Images courtesy NASA

GEO vs. LEO Satellite Comparison



LEO Satellites – Daily Orbital Path

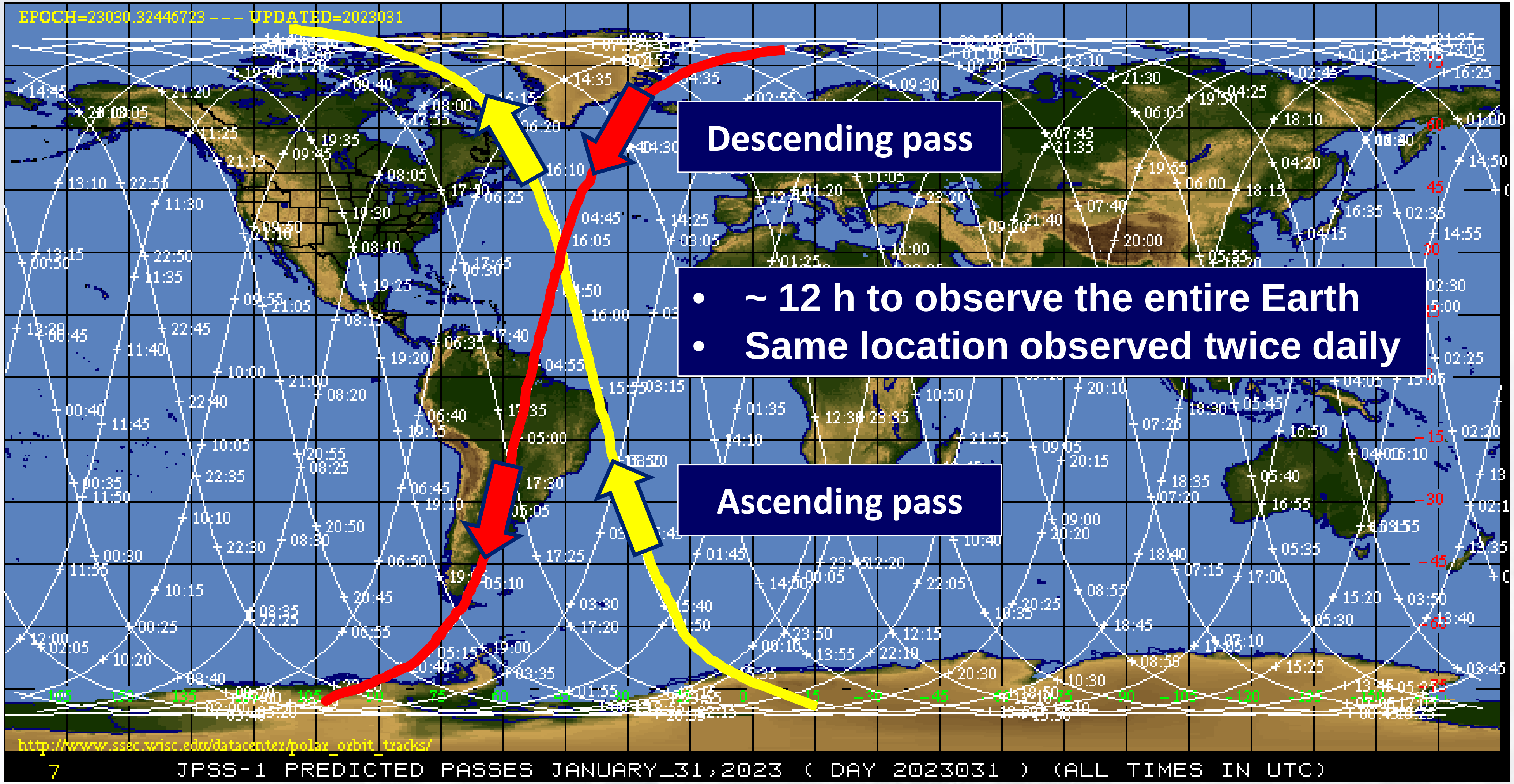


Image courtesy of Univ. of Wisconsin – SSEC

Passive Microwave Sensors

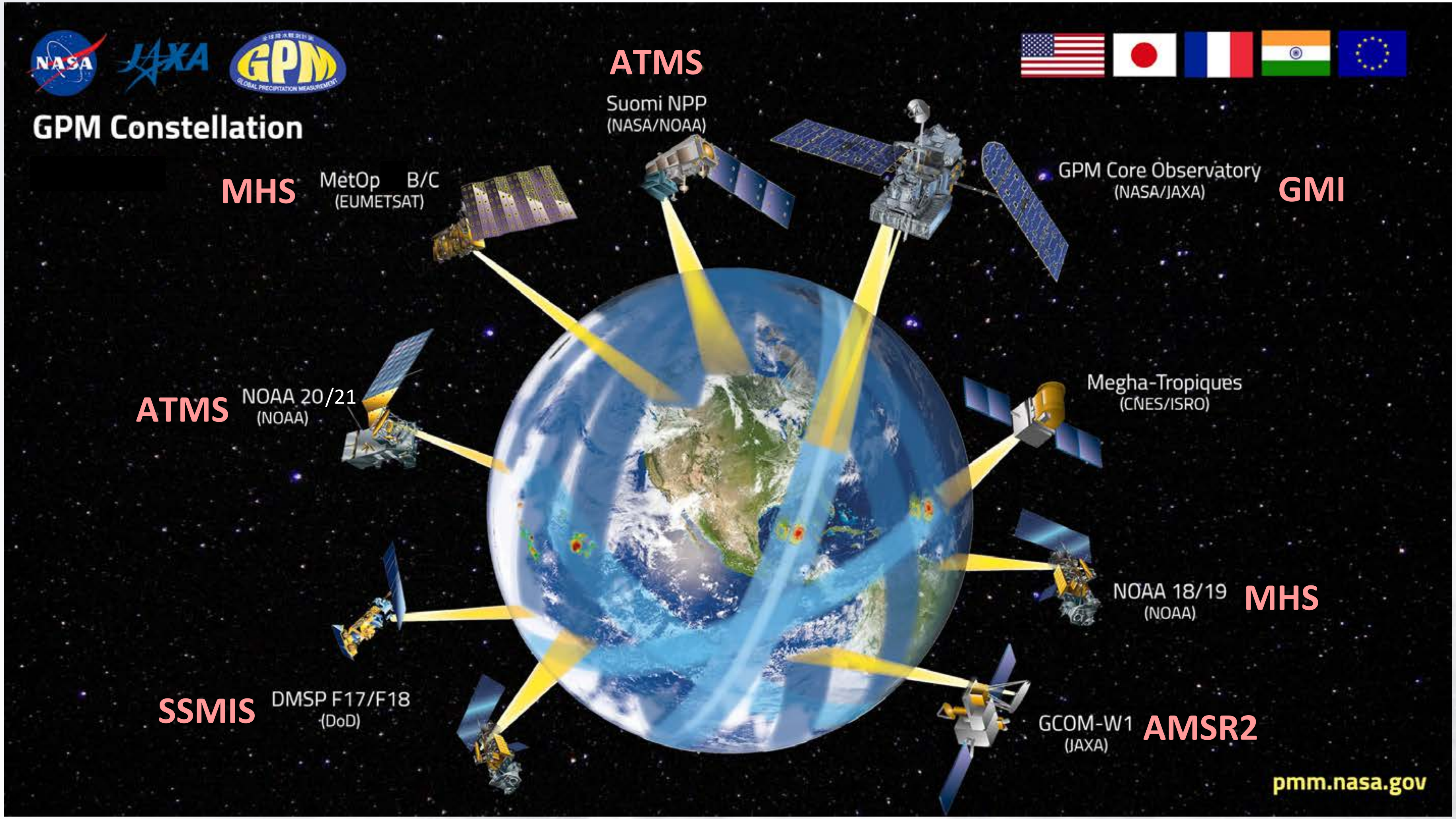
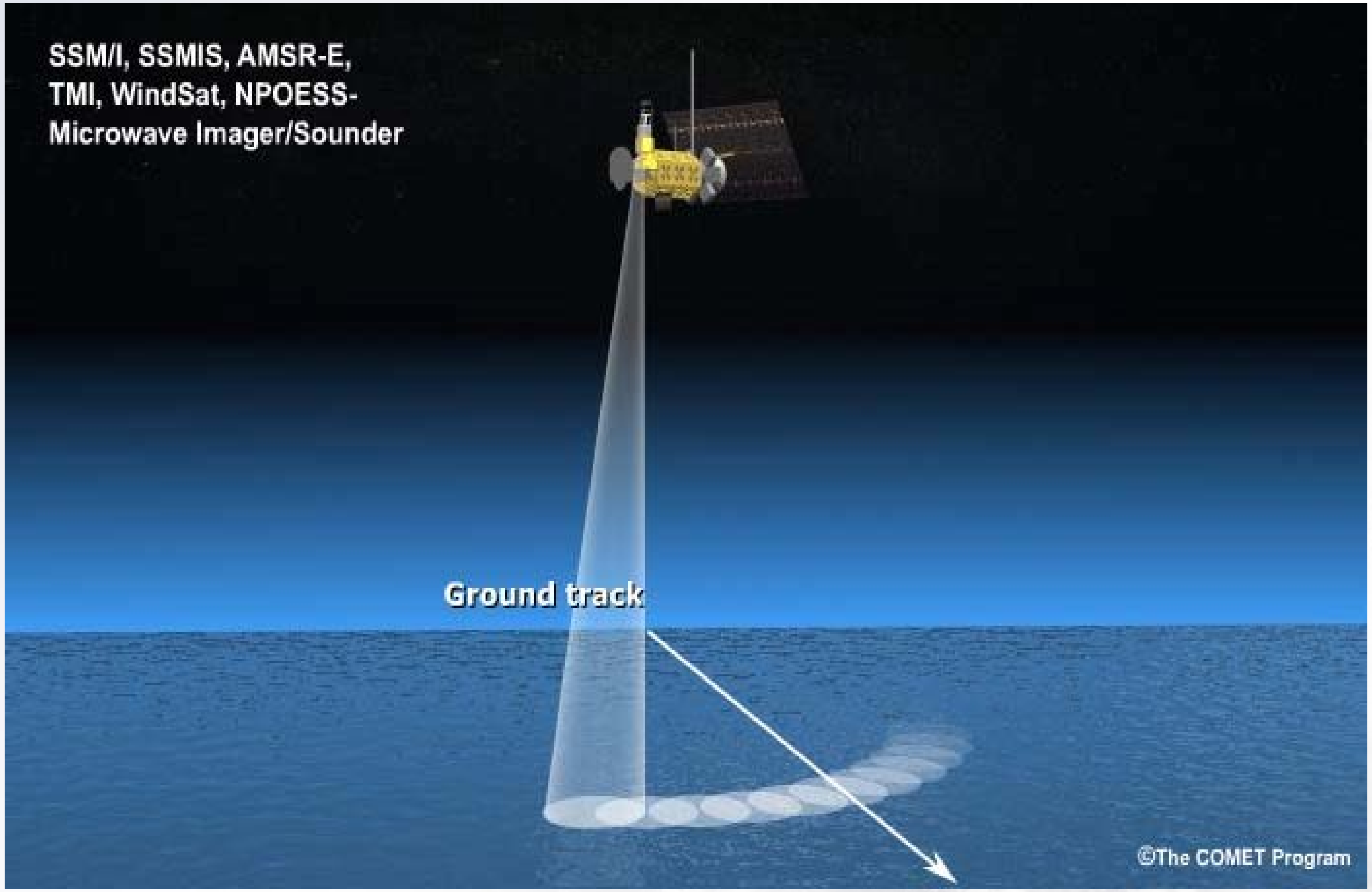


Image courtesy NASA

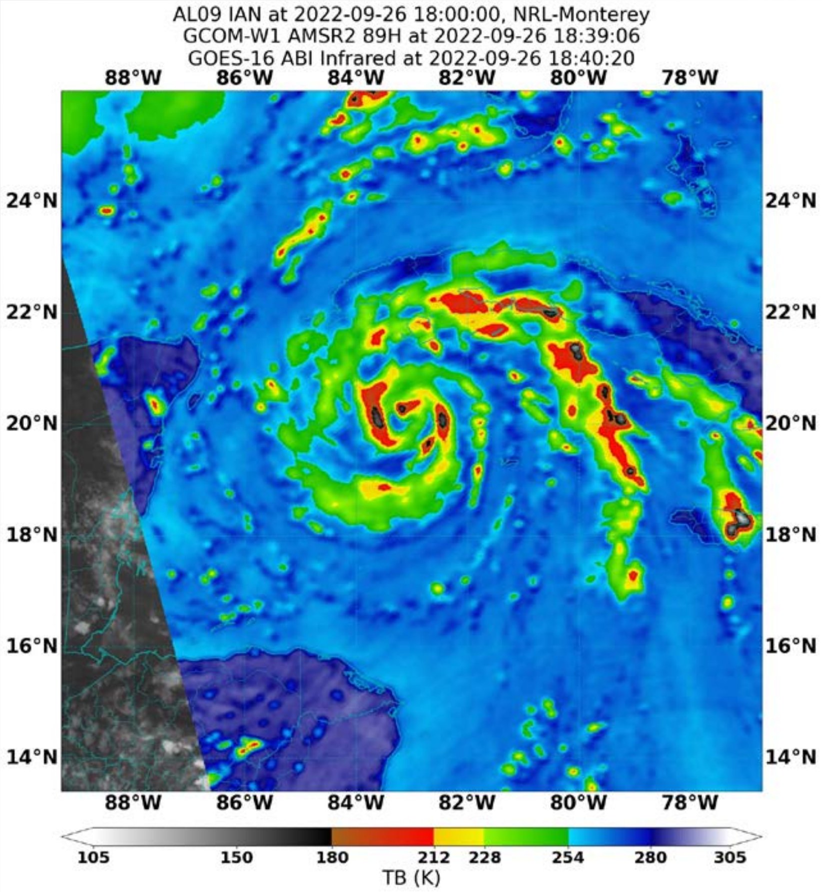
Conical Scan Strategy

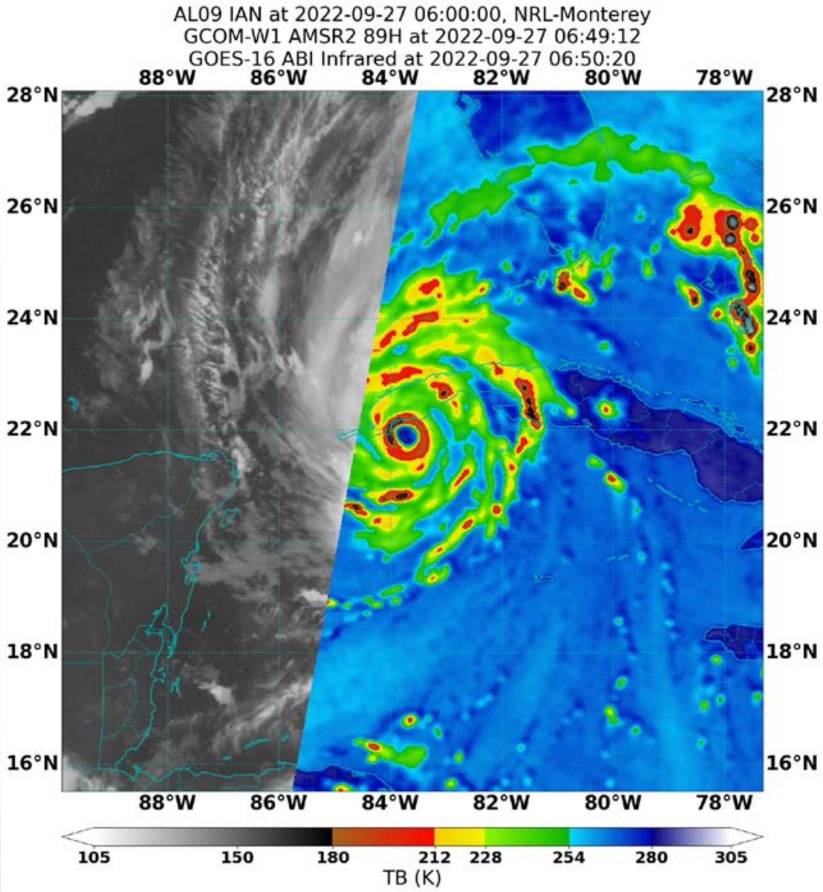


Most microwave sensors today use a conical scan strategy.

- **Advantage**: Resolution remains constant because scan footprints are the same size throughout the entire swath
- **Disadvantage**: Narrower coverage swath relative to cross-track scan

Conical Scan Strategy





Note that resolution remains constant across swath

Images courtesy Navy/NRL

Microwave Imagery Interpretation

85/89/91-GHz Imagery Interpretation

- Imagery can reveal internal storm structure
- Better for locating TC centers than conventional visible and infrared, but you cannot always see the low-level circulation
- Land appears warm relative to water surfaces
- Deep convection appears cold (due to scattering by large ice crystals)
- Offers higher spatial resolution than imagery at lower microwave frequencies

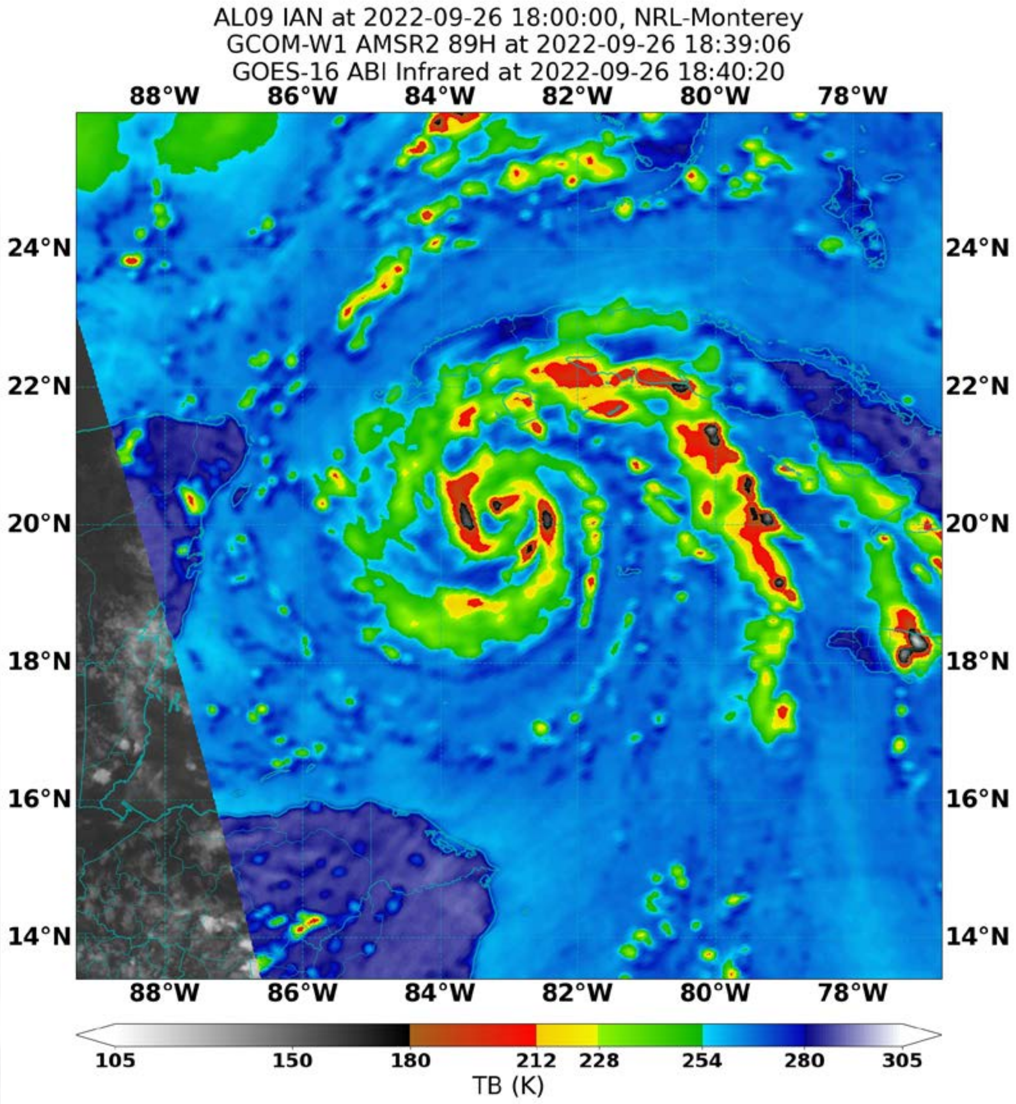
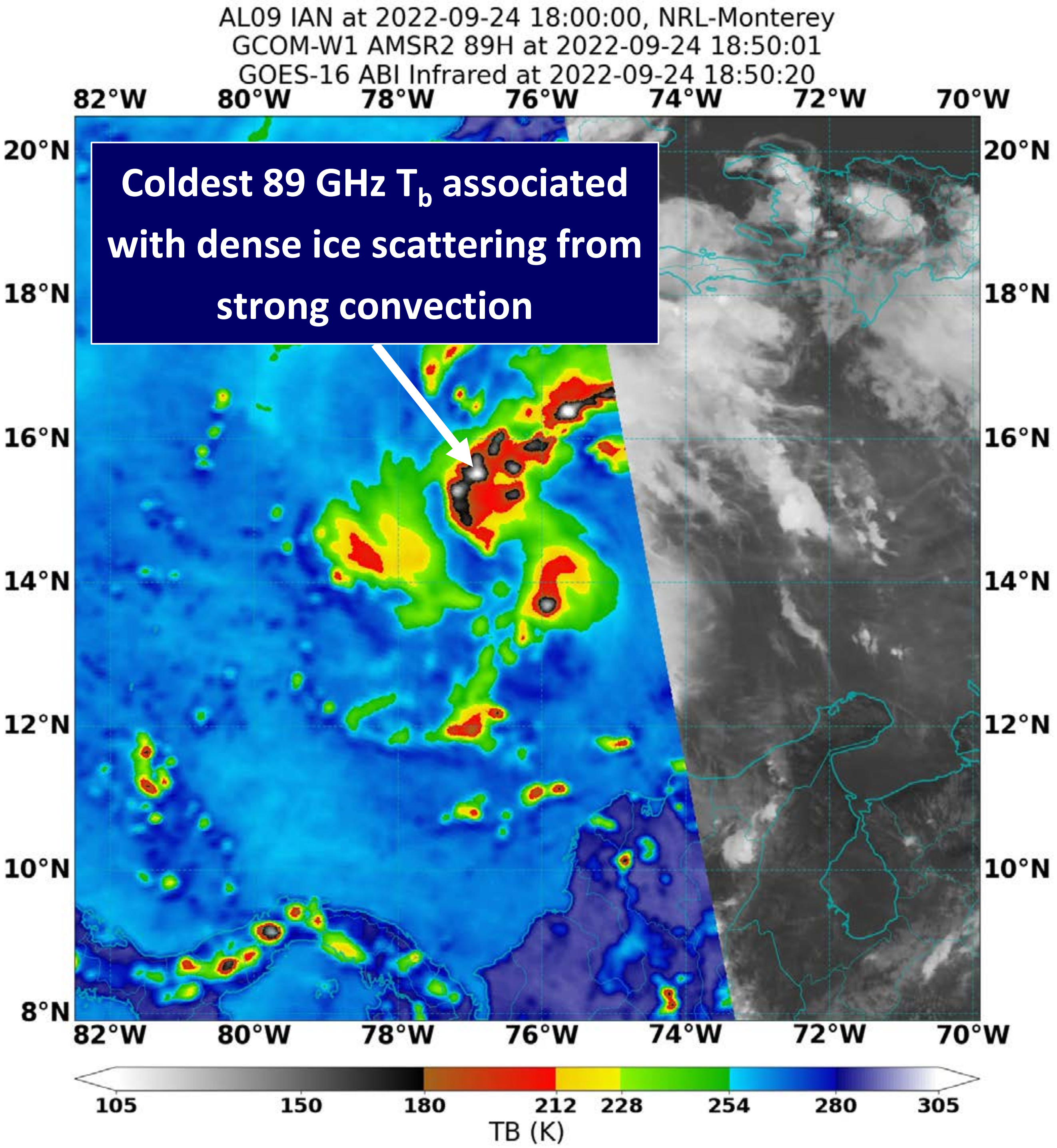


Image courtesy Navy/NRL



AL09 IAN at 2022-09-24 18:00:00, NRL-Monterey
GCOM-W1 AMSR2 89H at 2022-09-24 18:50:01
GOES-16 ABI Infrared at 2022-09-24 18:50:20
82°W
80°W
78°W
76°W
74°W
72°W
70°W
20°N
18°N
16°N
14°N
12°N
10°N
8°N
Coldest 89 GHz T_b associated with dense ice scattering from strong convection
105
150
180
212
228
254
280
305
TB (K)

37-GHz Imagery Interpretation

- Imagery reveals the low-level cloud features and storm structure
- Can help identify cirrus-covered eyes and give a ‘true’ low-level center (instead of a mid- to upper-level center as in 85-91 GHz imagery)
- Precipitating clouds and land appear warm
- Sea surface appears cold

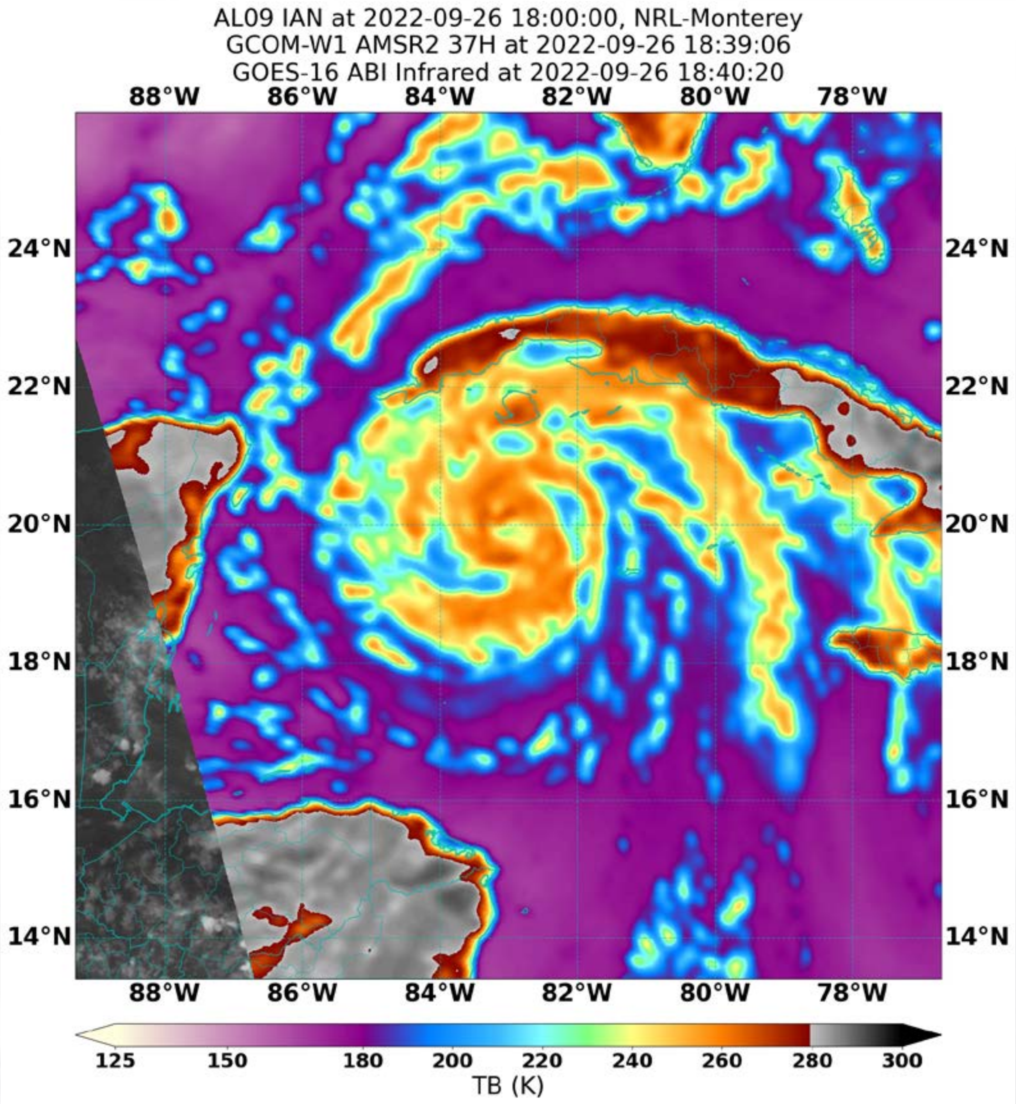
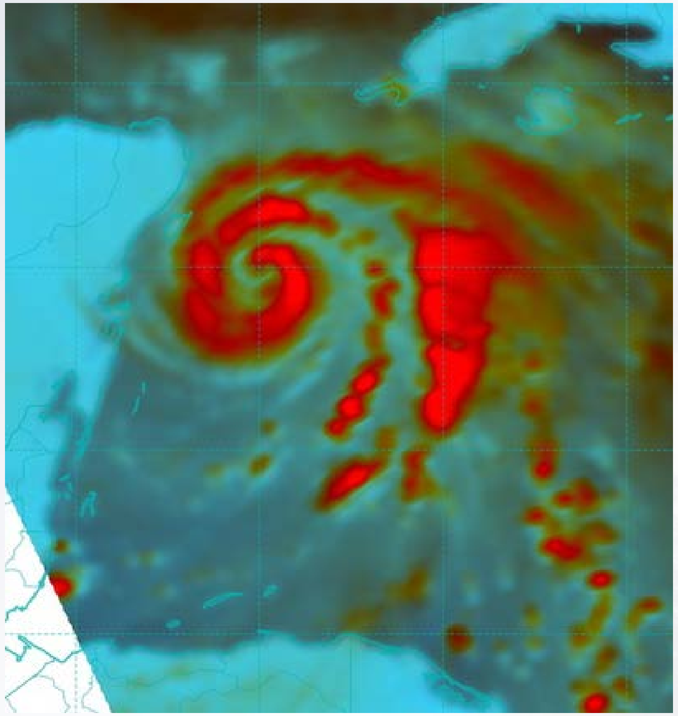


Image courtesy Navy/NRL

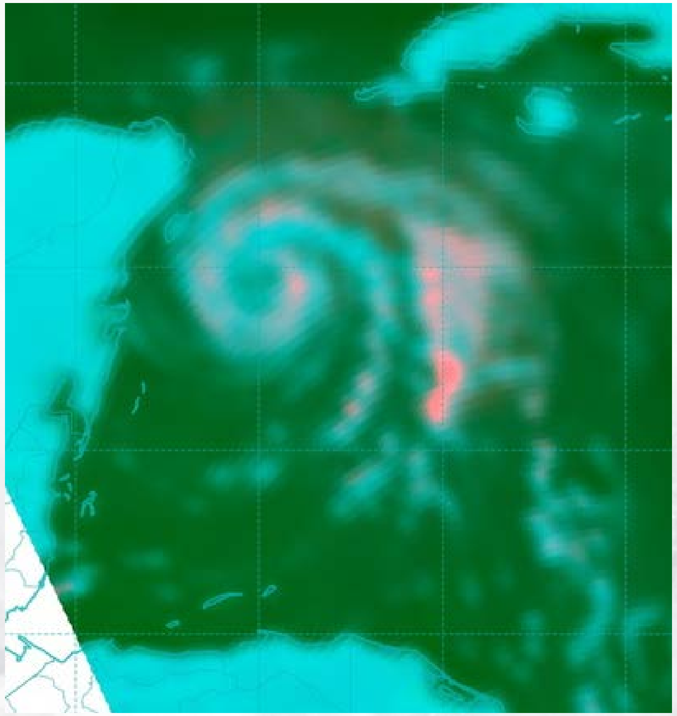
Color Composite Imagery Interpretation

- Color composite images combine Polarization Corrected Temperature (PCT) with horizontal (H) and vertical (V) polarizations to remove ambiguities between convection and the sea surface and highlight the deep convection.



85-91 GHz composite

- Deep convection (red)
- Low-level clouds, water vapor, and warm precipitation (blue-green)
- Relatively cloud-free (gray or black)



37 GHz composite

- Deep convection & intense ice scattering (pink)
- Rain and clouds (blue-green)
- Sea surface (green)

Images courtesy Navy/NRL

Advantages of Microwave Imagery for TC Analysis

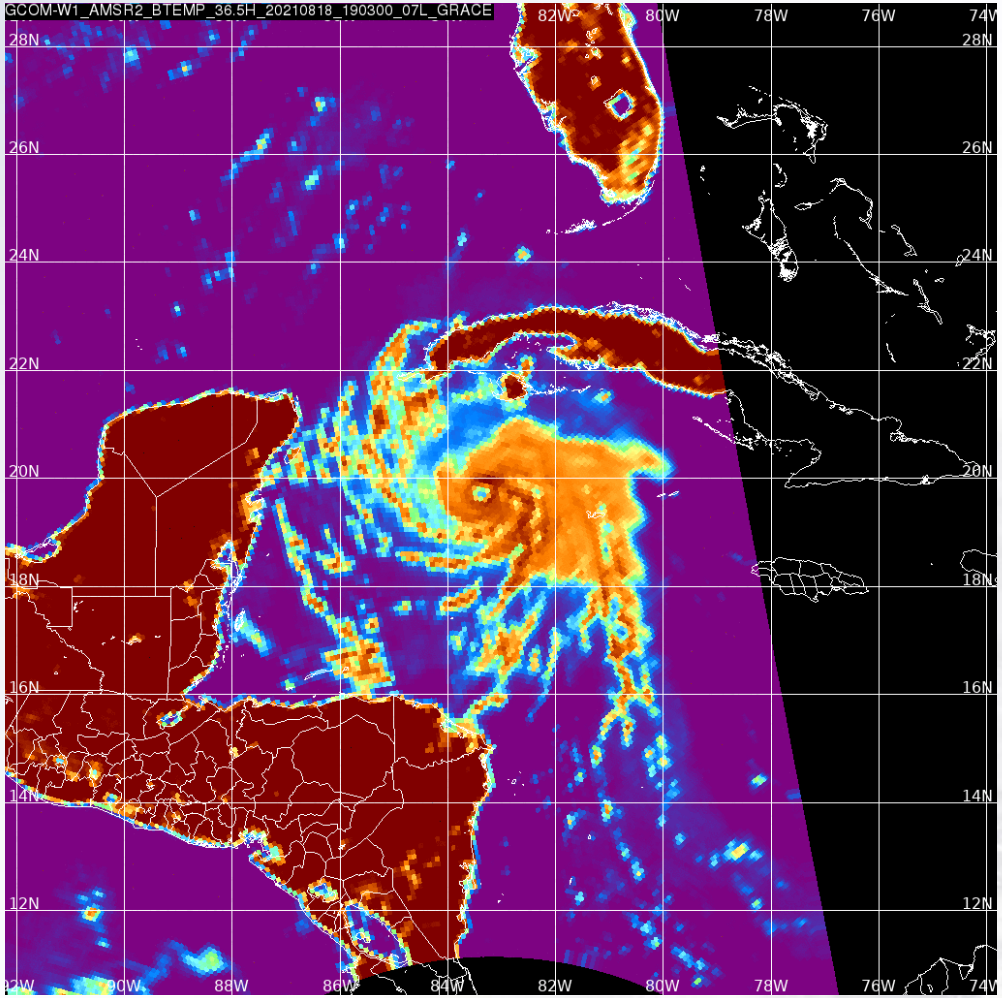
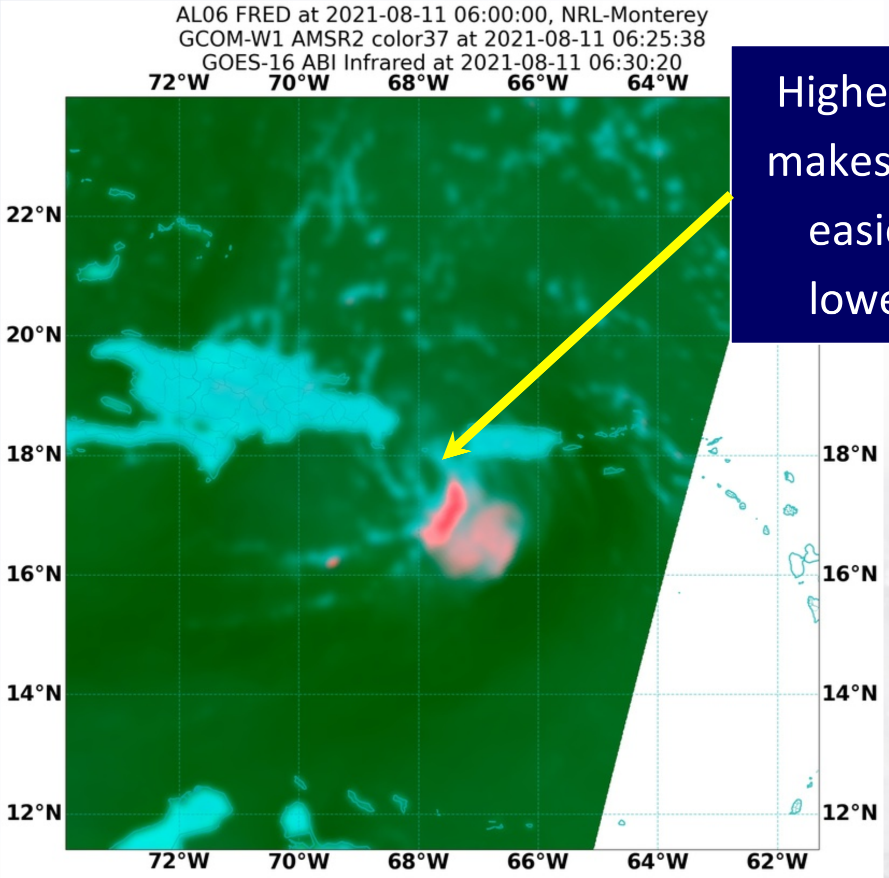


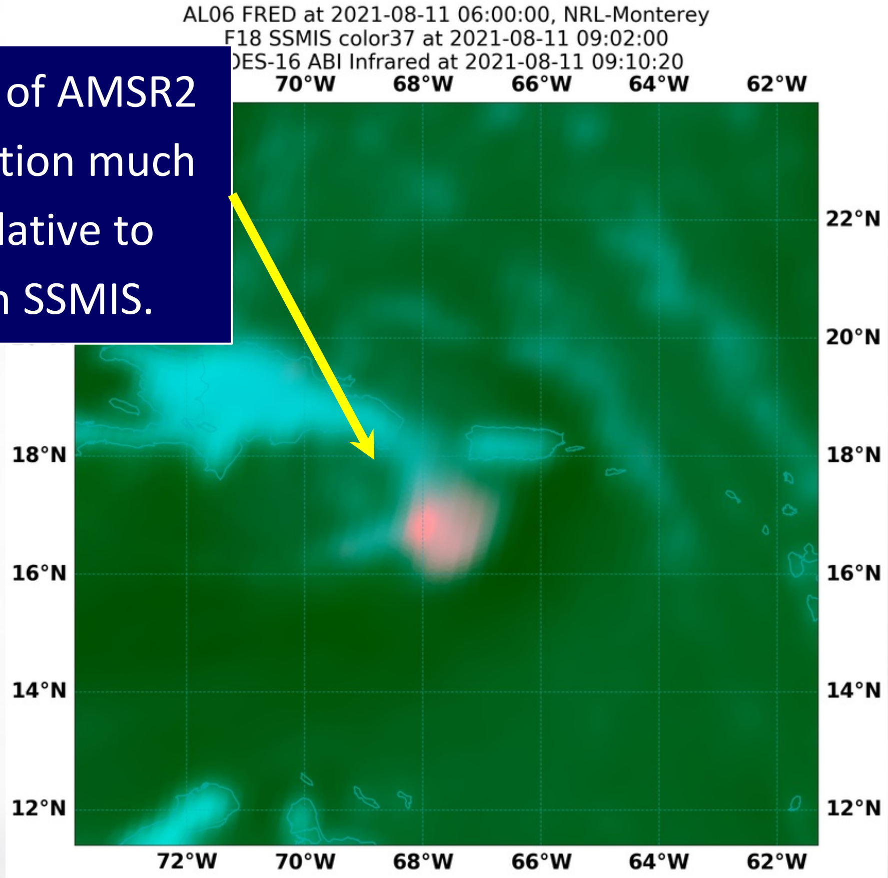
Image courtesy CIMSS Satellite Blog

- Identification of circulation center (critical step in initiating TC advisories)
- Assess the position of TCs in difficult situations (especially in early stages of development and at night)
- View convective rain bands that are directly related to TC intensification
- Monitoring structural changes such as eyewall replacement cycles

Resolution Limitations



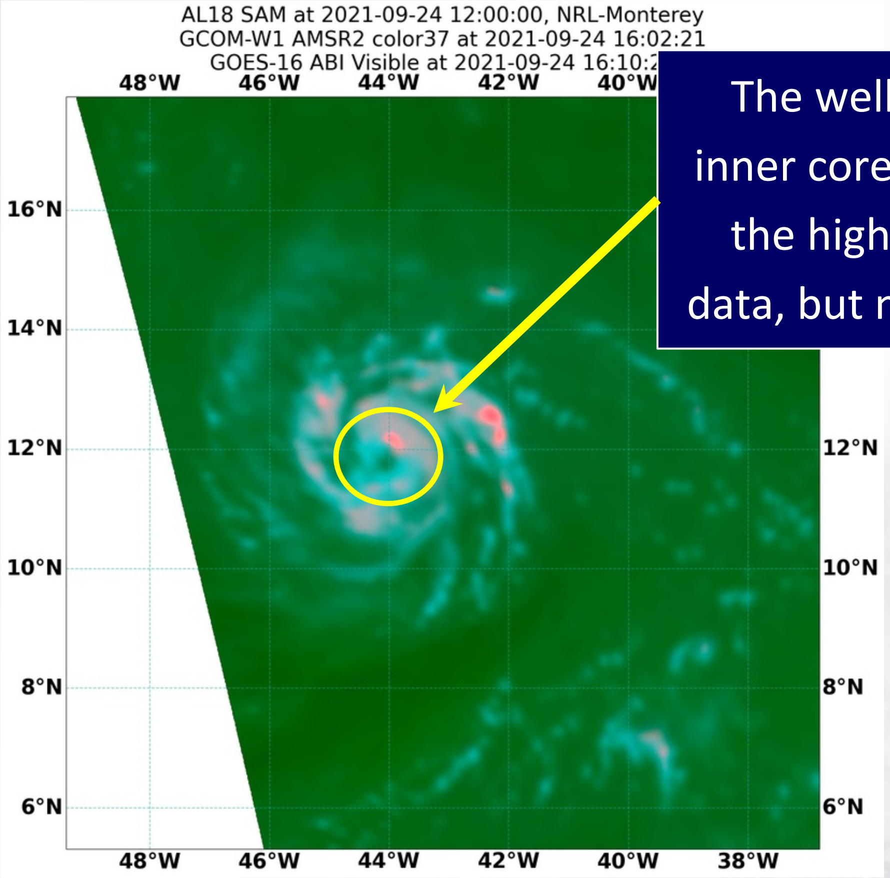
Higher resolution of AMSR2 makes center location much easier to find relative to lower-resolution SSMIS.



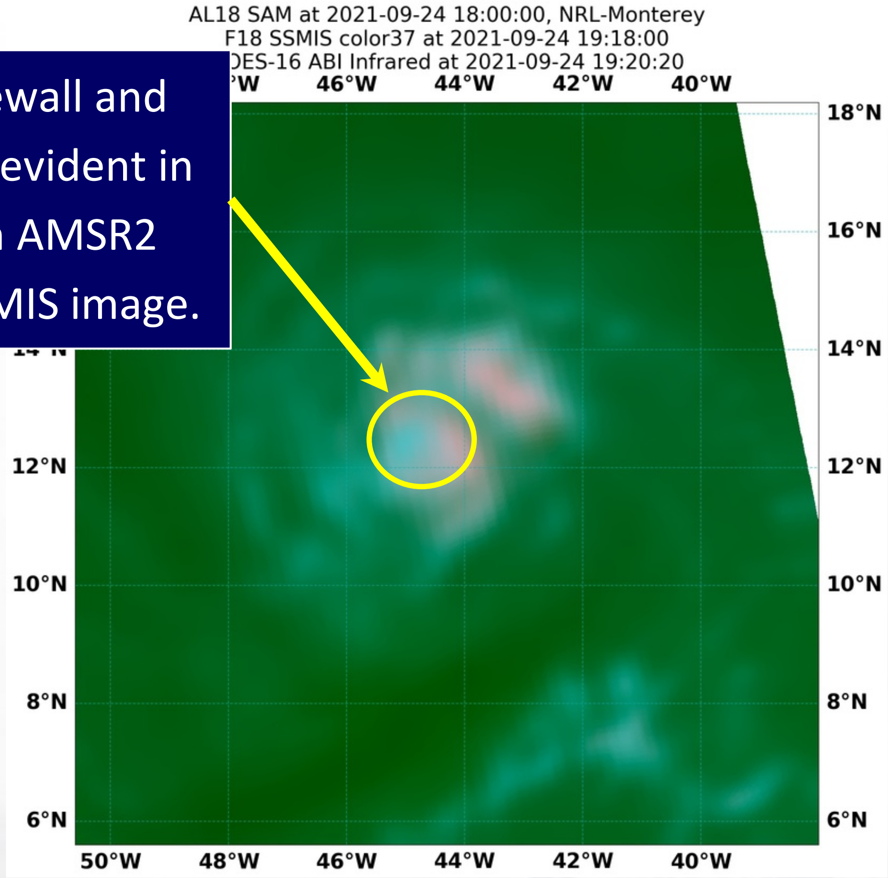
Comparison of 37-GHz color composite imagery over Tropical Storm Fred from AMSR2 (left) and SSMIS (right) at 0625 UTC and 0902 UTC 11 August 2021, respectively.

Images courtesy Navy/NRL

Resolution Limitations



The well-defined eyewall and inner core structure is evident in the higher resolution AMSR2 data, but not in the SSMIS image.



Comparison of 37-GHz color composite imagery over Hurricane Sam from AMSR2 (left) and SSMIS (right) at 1602 UTC and 1918 UTC 24 September 2021, respectively.

Images courtesy Navy/NRL

TC Applications of Microwave Imagery

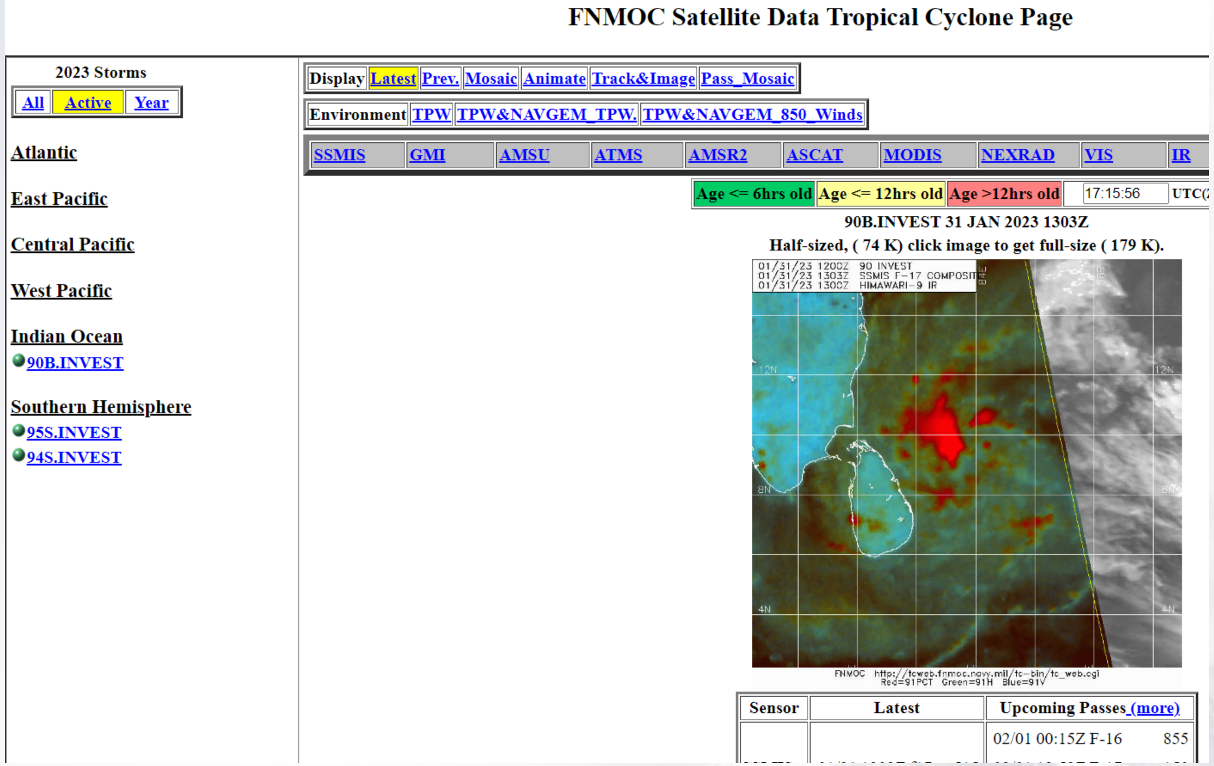
Accessing Microwave Imagery

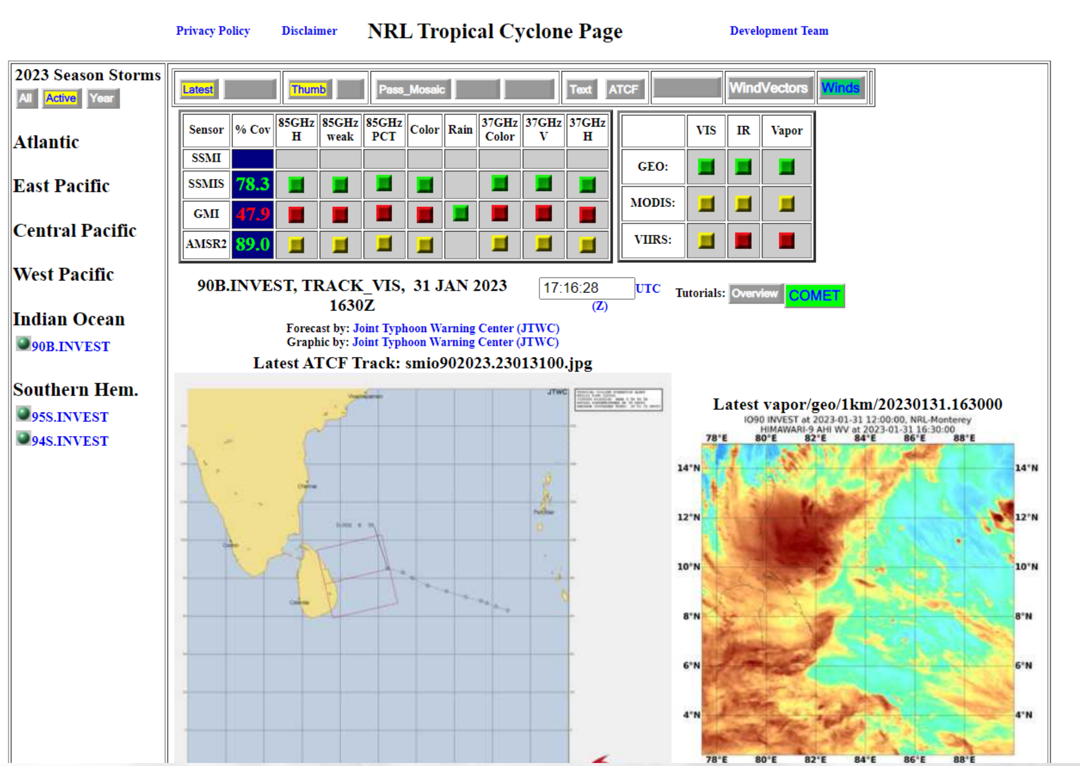
FNMOC Tropical Cyclone Webpage

https://www.fnmoc.navy.mil/tcweb/cgi-bin/tc_home.cgi

NRL Tropical Cyclone Webpage

https://www.nrlmry.navy.mil/TC.html





Data Latency and Timeliness

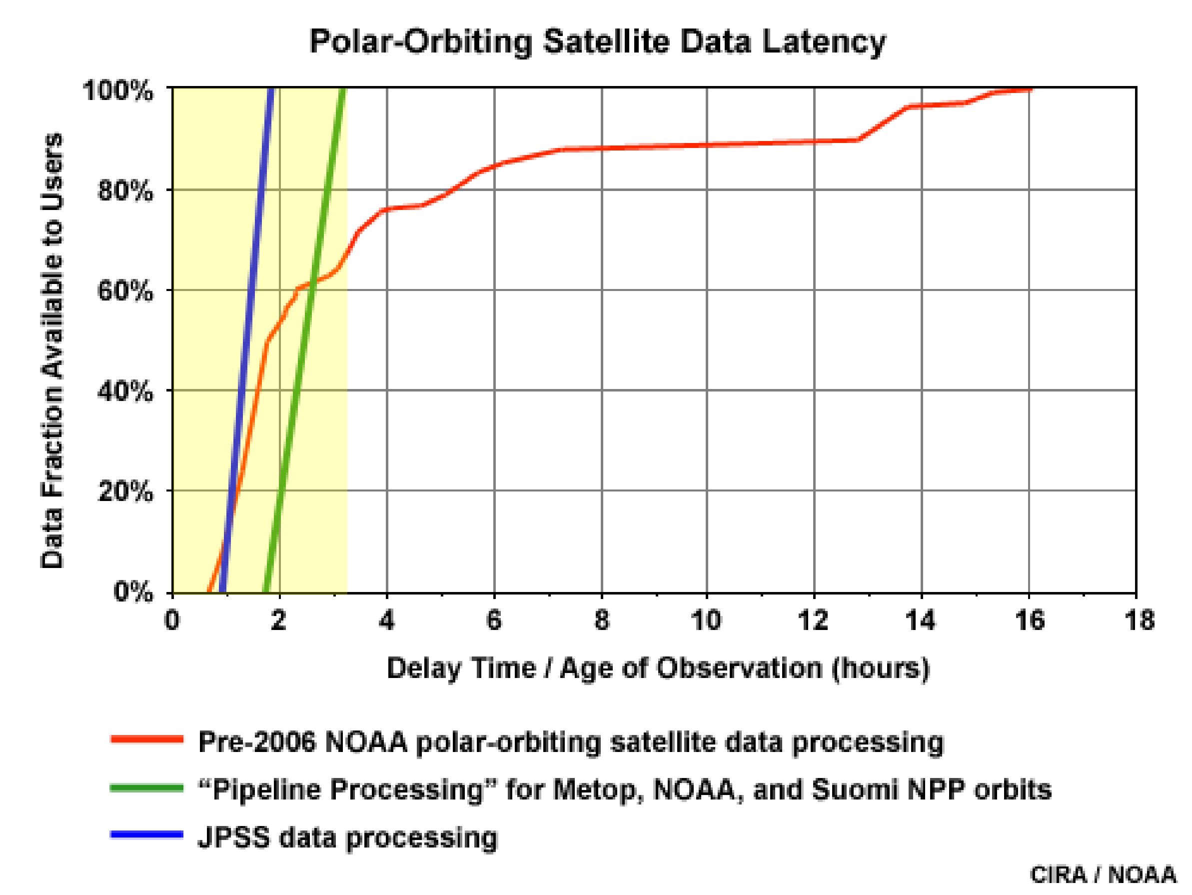


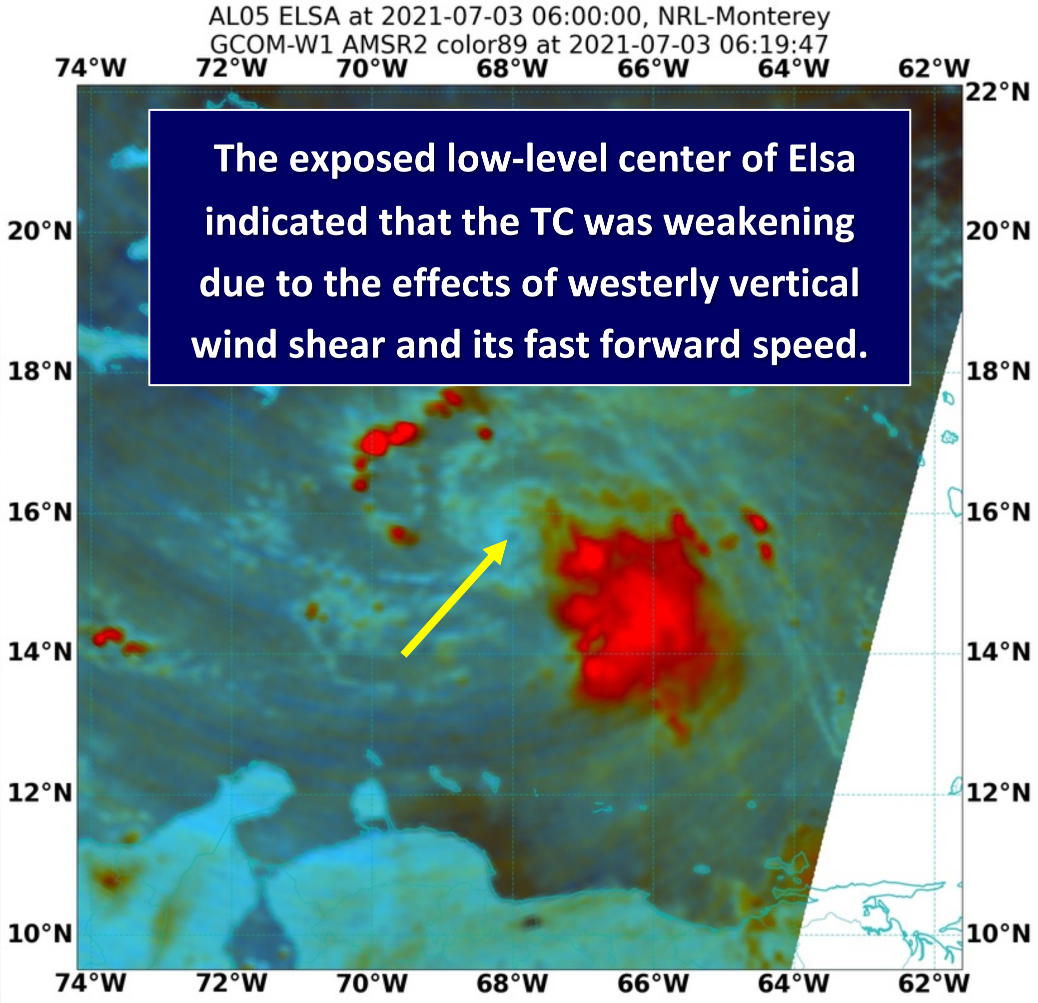
Image courtesy COMET

Why is there a delay in receiving the data?

- LEO satellites are not continuously in view of data receiving stations.
- They can only download data when in range of those stations.
- This leads to a delay in data transmission and processing up to a couple of hours.

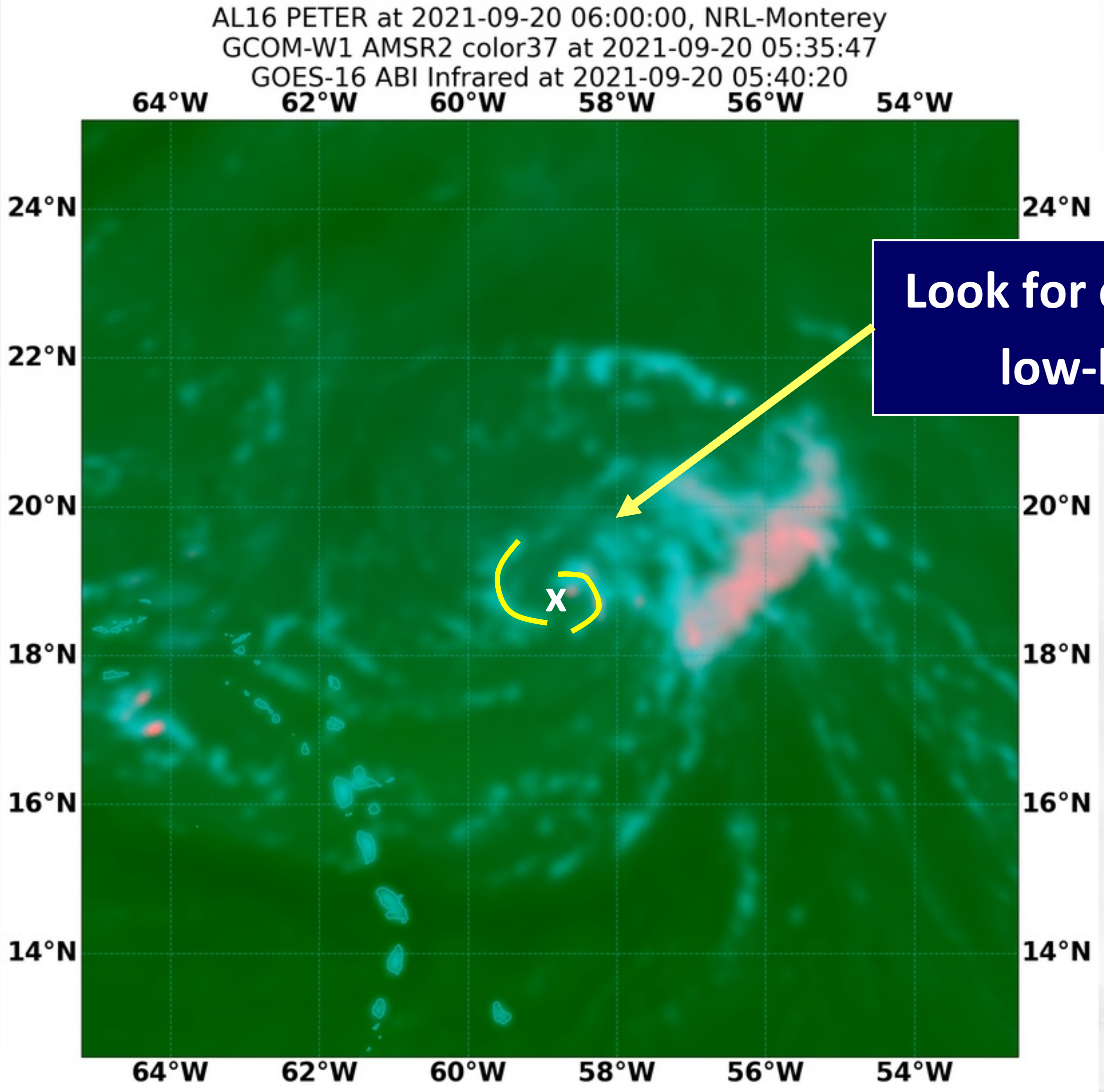
Locating the TC Center

- **Why is correctly locating the TC center so important?**
  - Determining initial motion
  - Initializing model guidance
  - Forecasting the track
  - Assessing the organization and intensity of the TC (Dvorak intensity estimates are very sensitive to the center position)

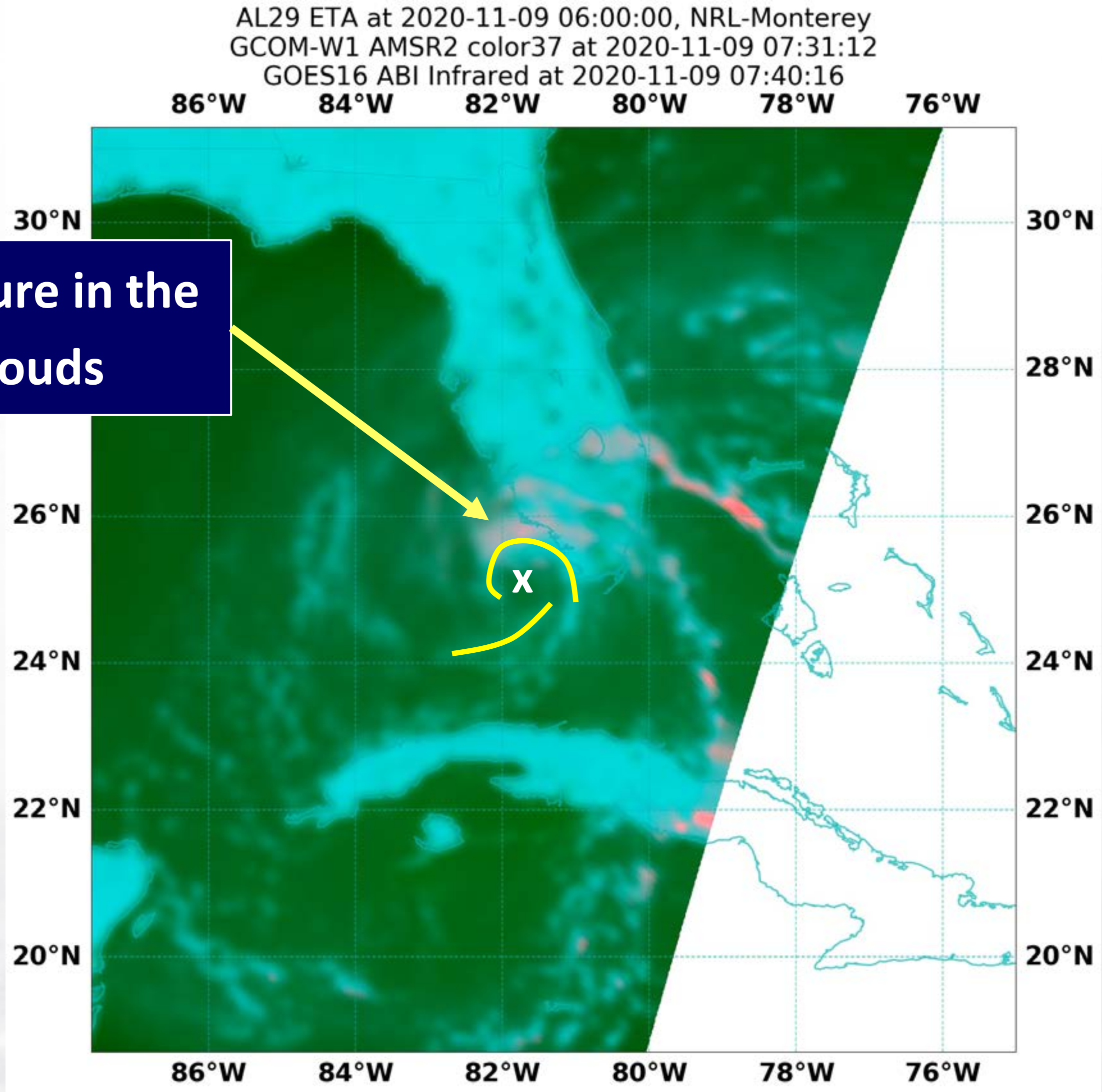


Hurricane Elsa – 3 July 2021 0620 UTC
Image courtesy Navy/NRL

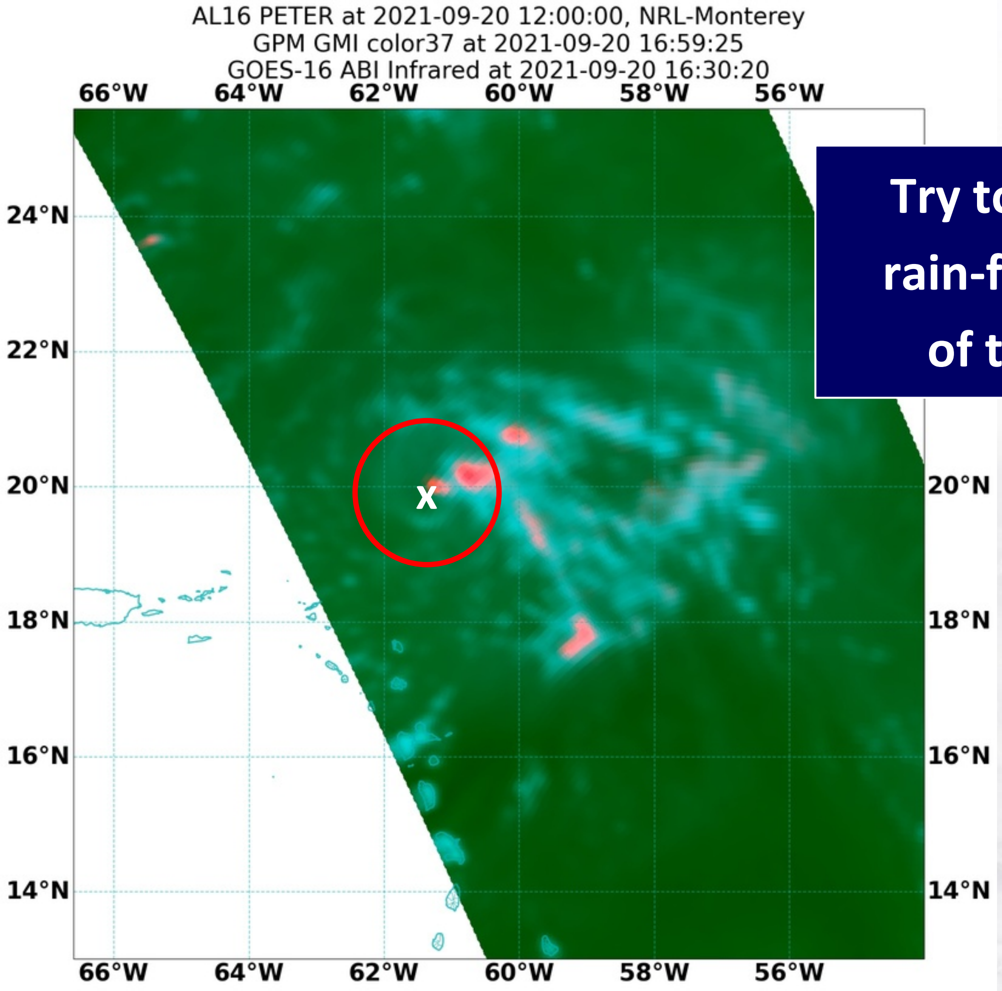
Locating the TC Center



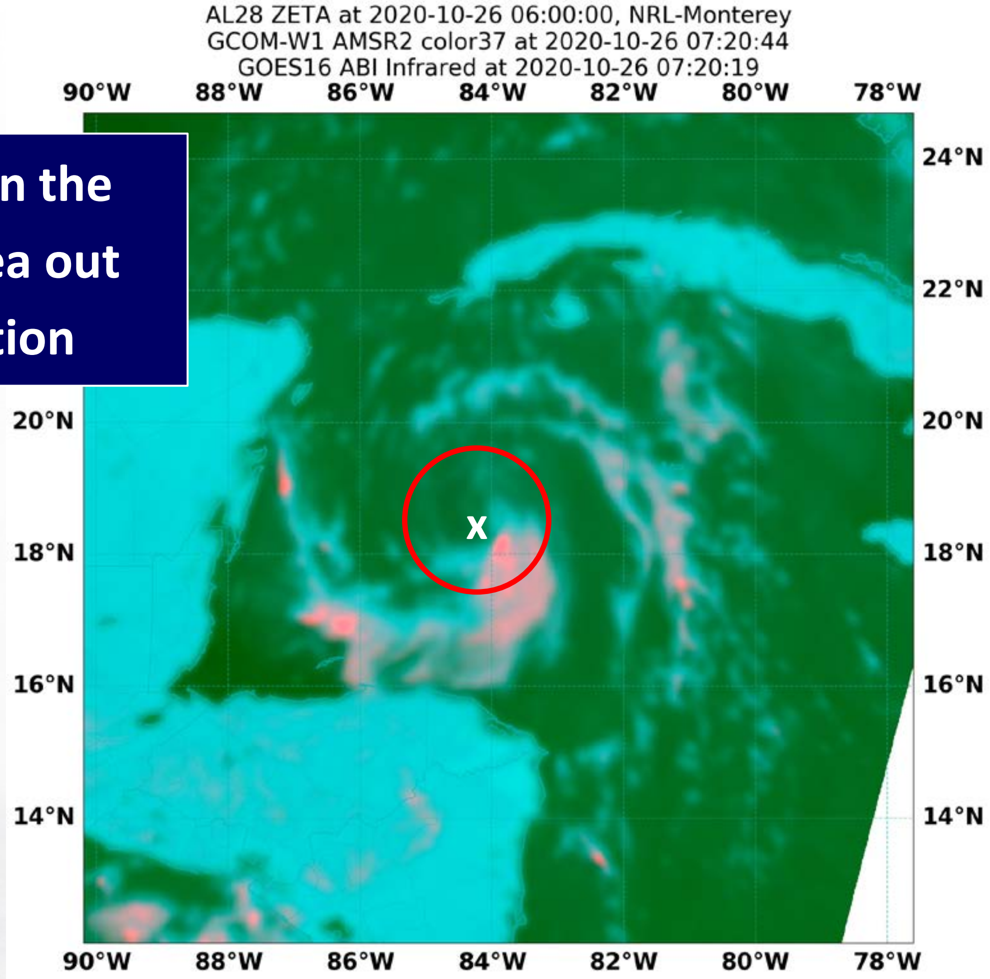
Look for curvature in the low-level clouds



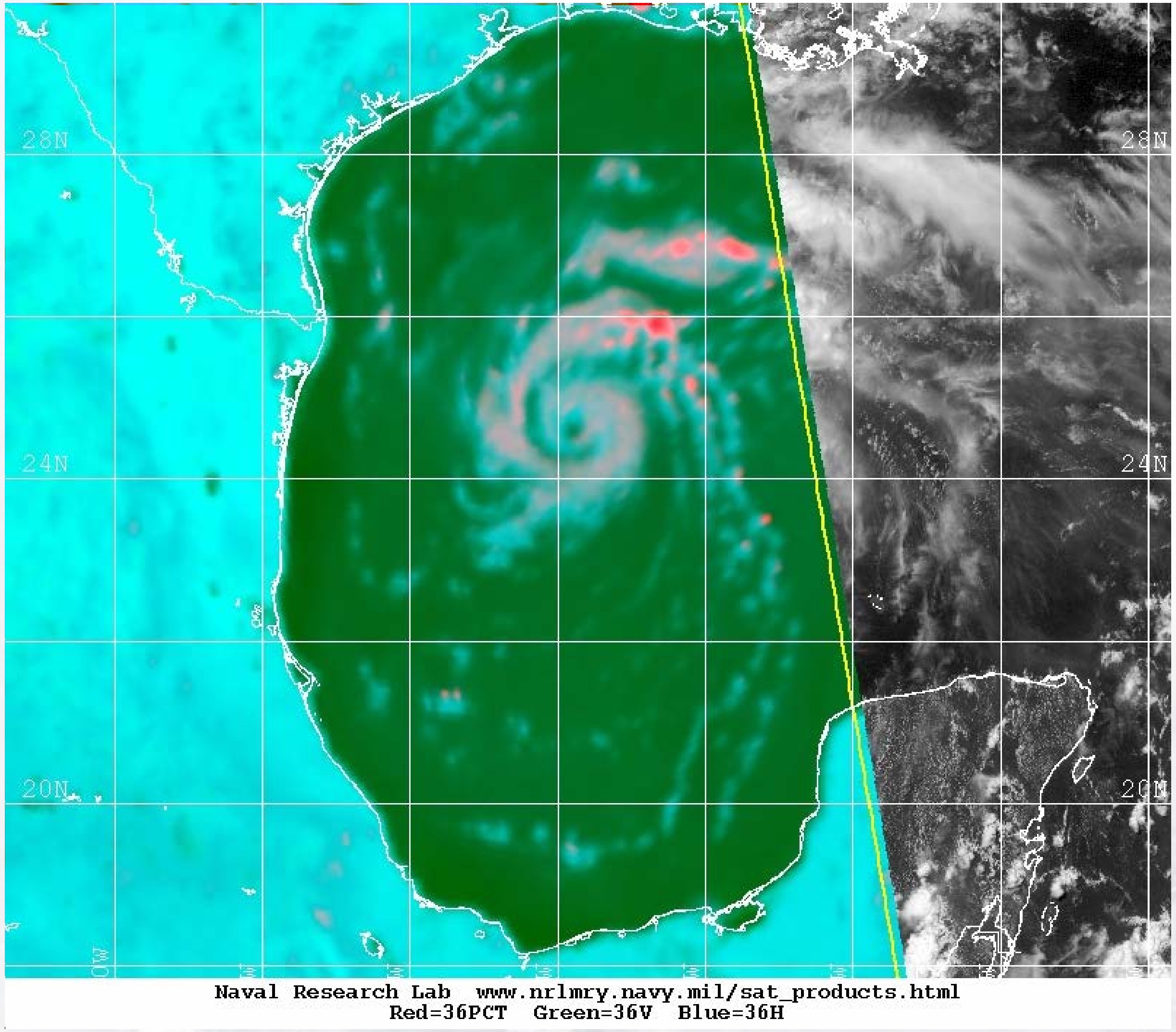
Locating the TC Center



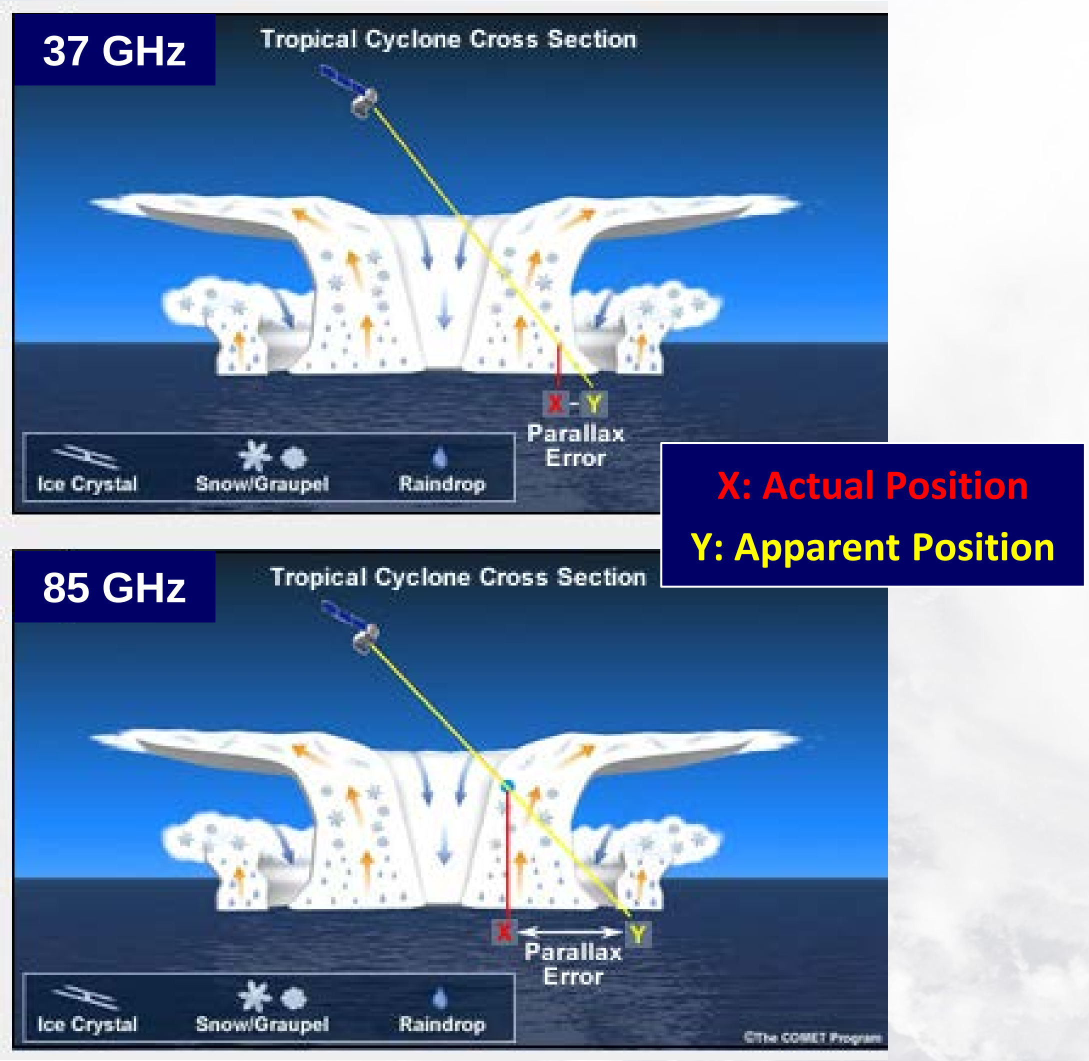
Try to position in the rain-free dry area out of the convection



Locating the TC Center



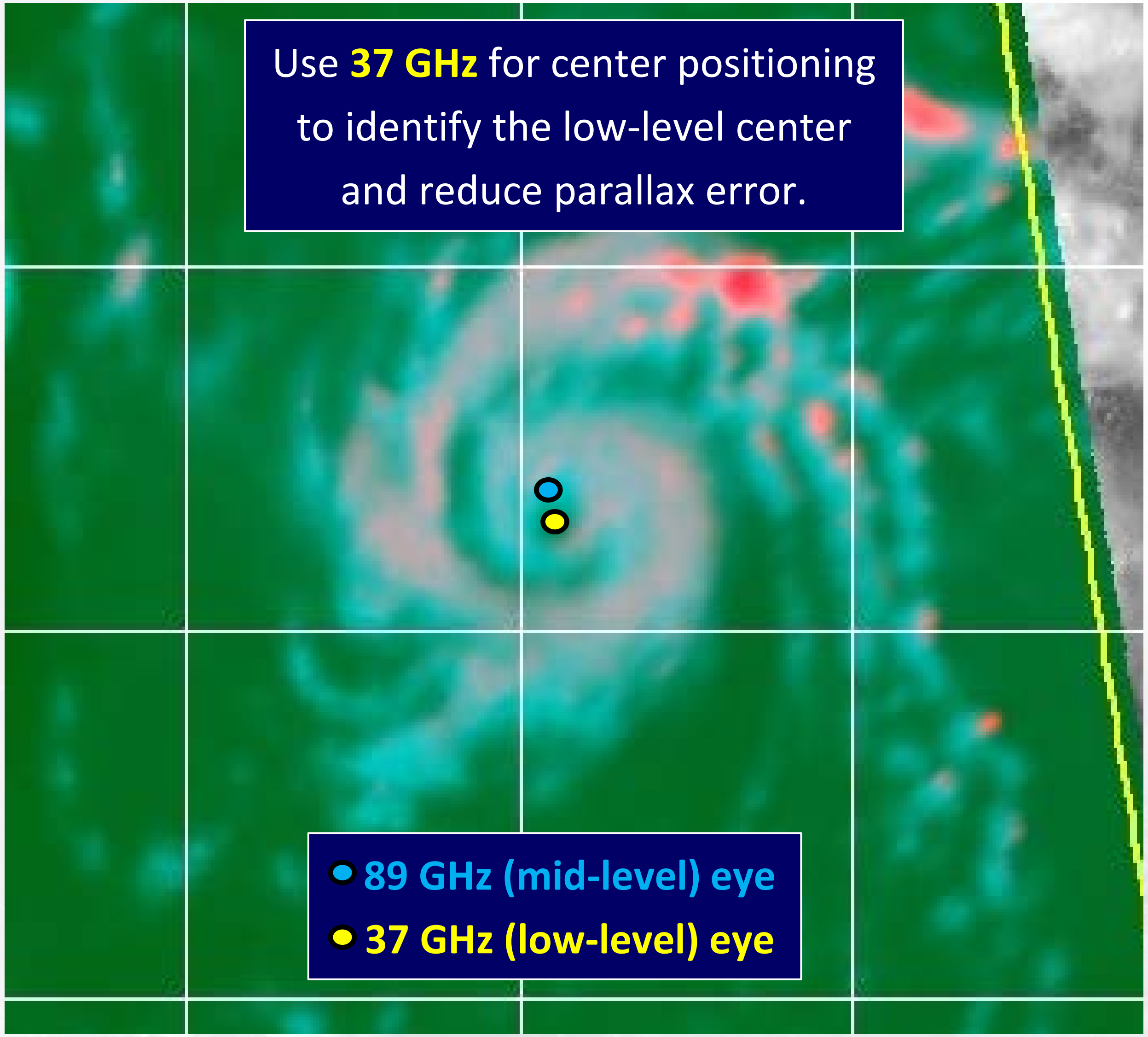
Parallax Error in Center Fixing



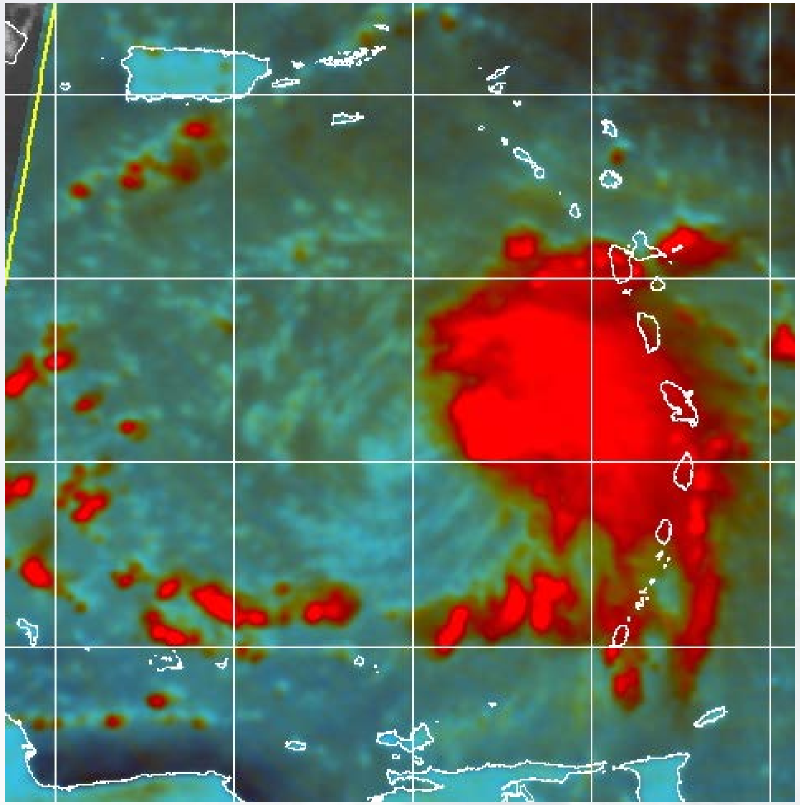
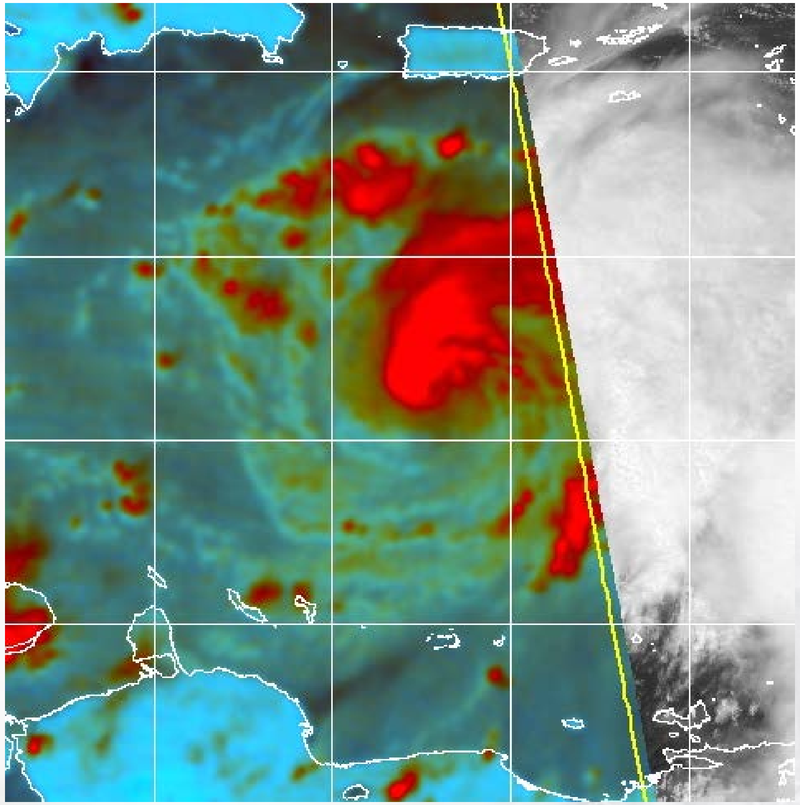
- **Parallax** is the apparent shift in a feature's position due to the viewing angle of the satellite
- Satellite-derived position error exists, potentially up to 20 km (~ 10.8 n mi) from the actual position
- Larger parallax error in 85–91-GHz images since scattering hydrometeors produce a signature much higher in the eyewall at 85–91 GHz than at 37 GHz

Images courtesy COMET

Locating the TC Center



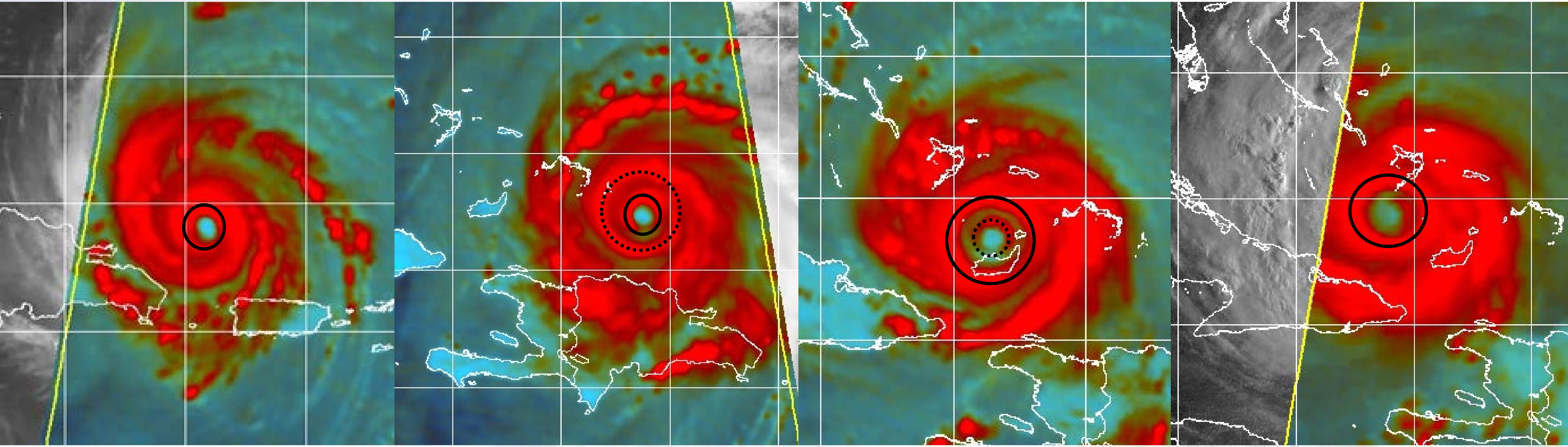
Assessing Structural Changes

Note the sheared appearance of Matthew on the morning of 29 September 2016 (left), followed by an increase in convection over the center later that day (right).

Images courtesy Navy/NRL

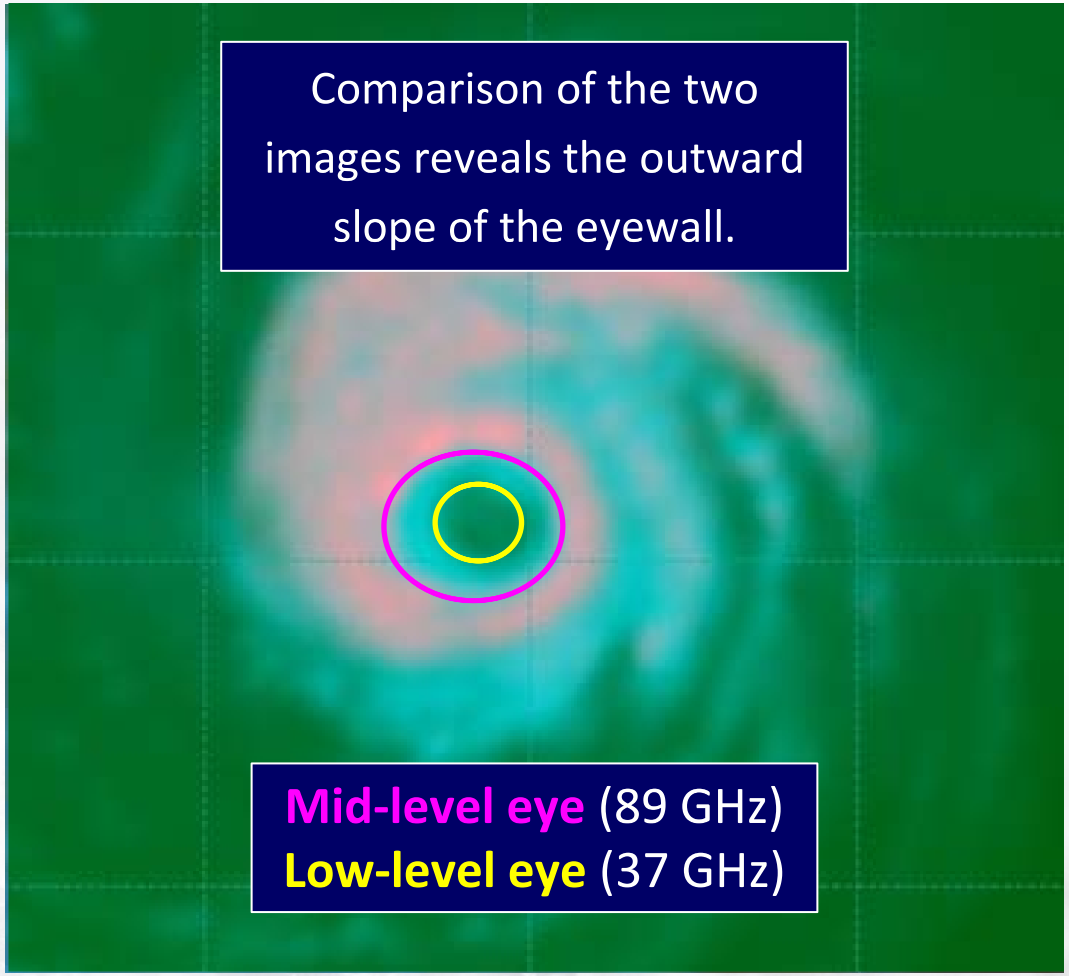
Assessing Structural Changes



Comparison of 89-GHz color composite imagery over Hurricane Irma during an eyewall replacement cycle on 7 – 8 September 2017.

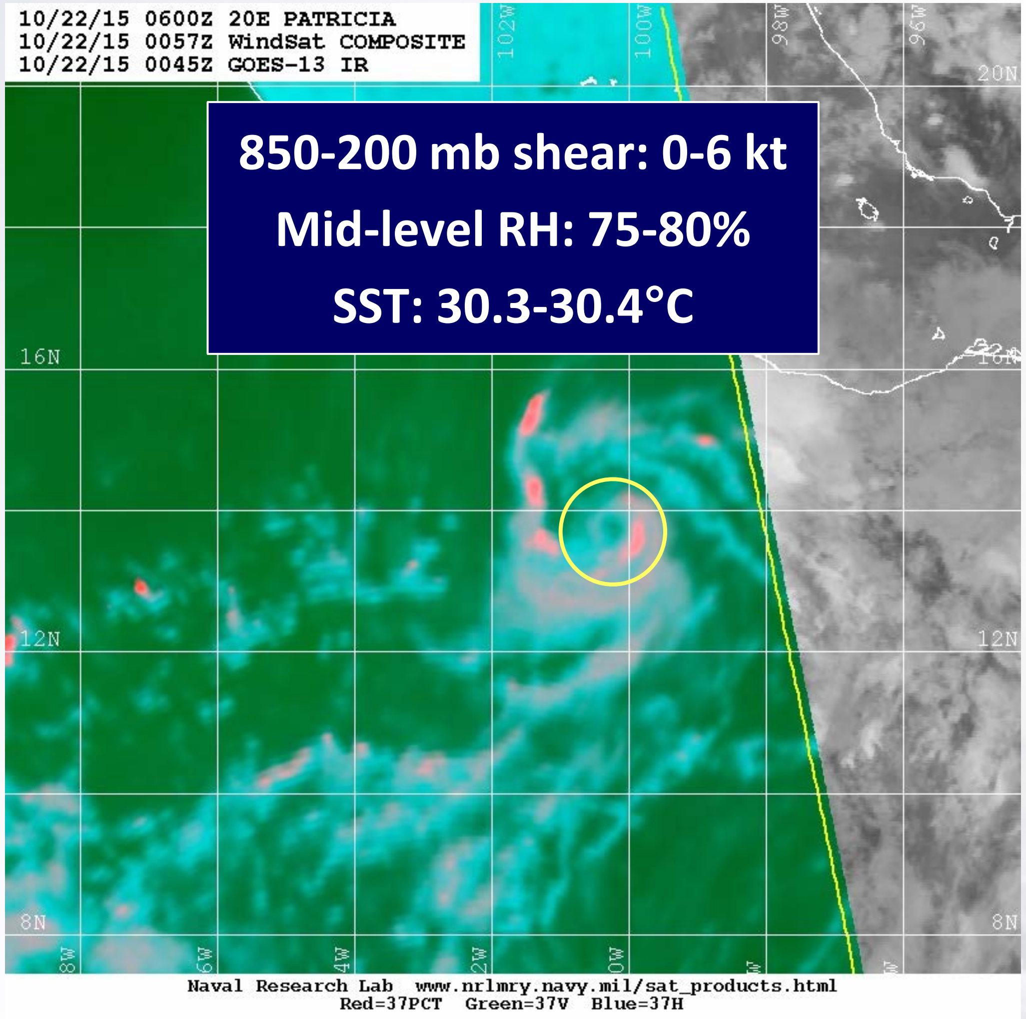
Images courtesy Navy/NRL

Determining Eye Size



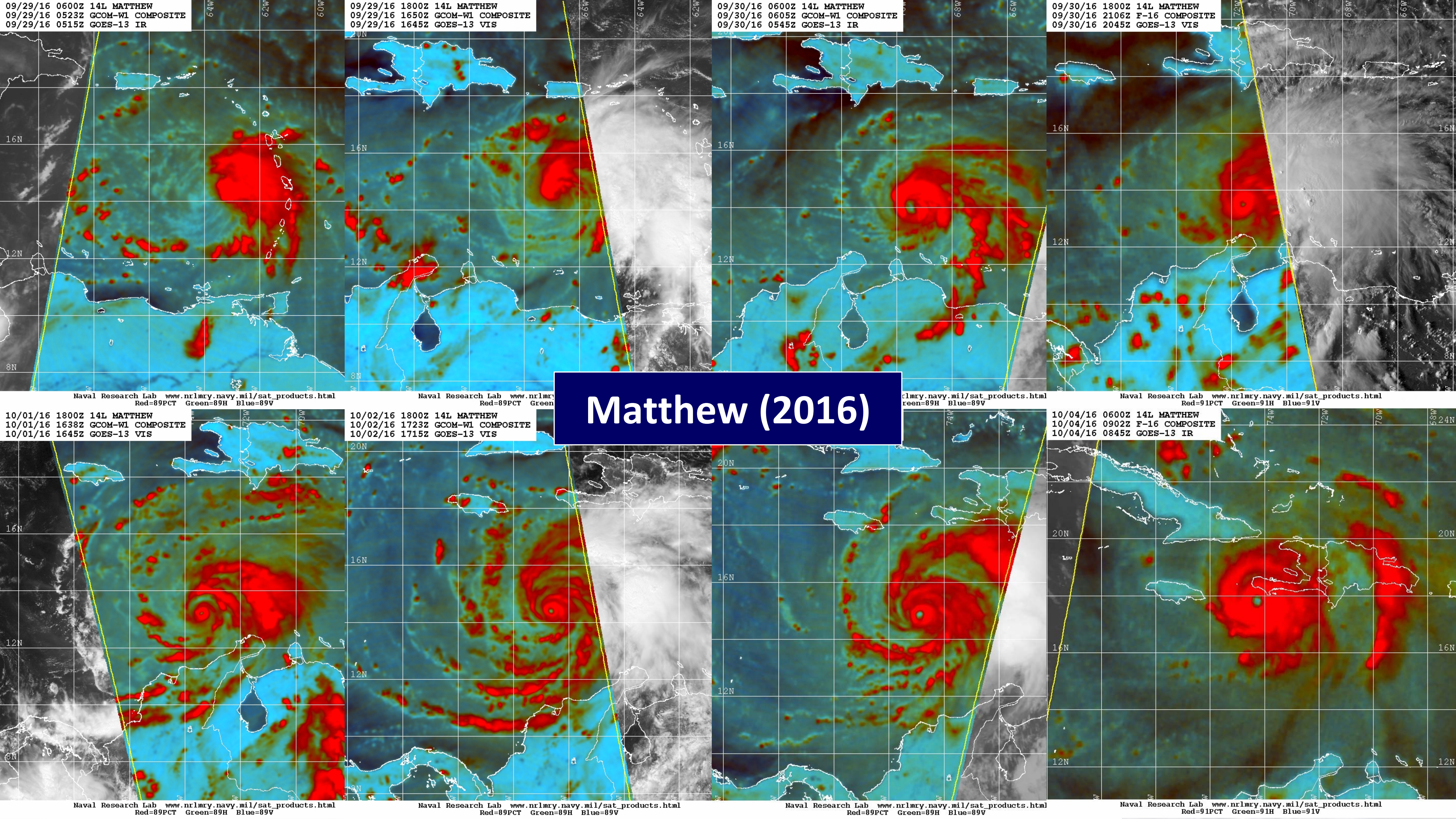
Hurricane Larry – 0440 UTC 5 September 2021
Image courtesy Navy/NRL

Precursor Structure to Rapid Intensification

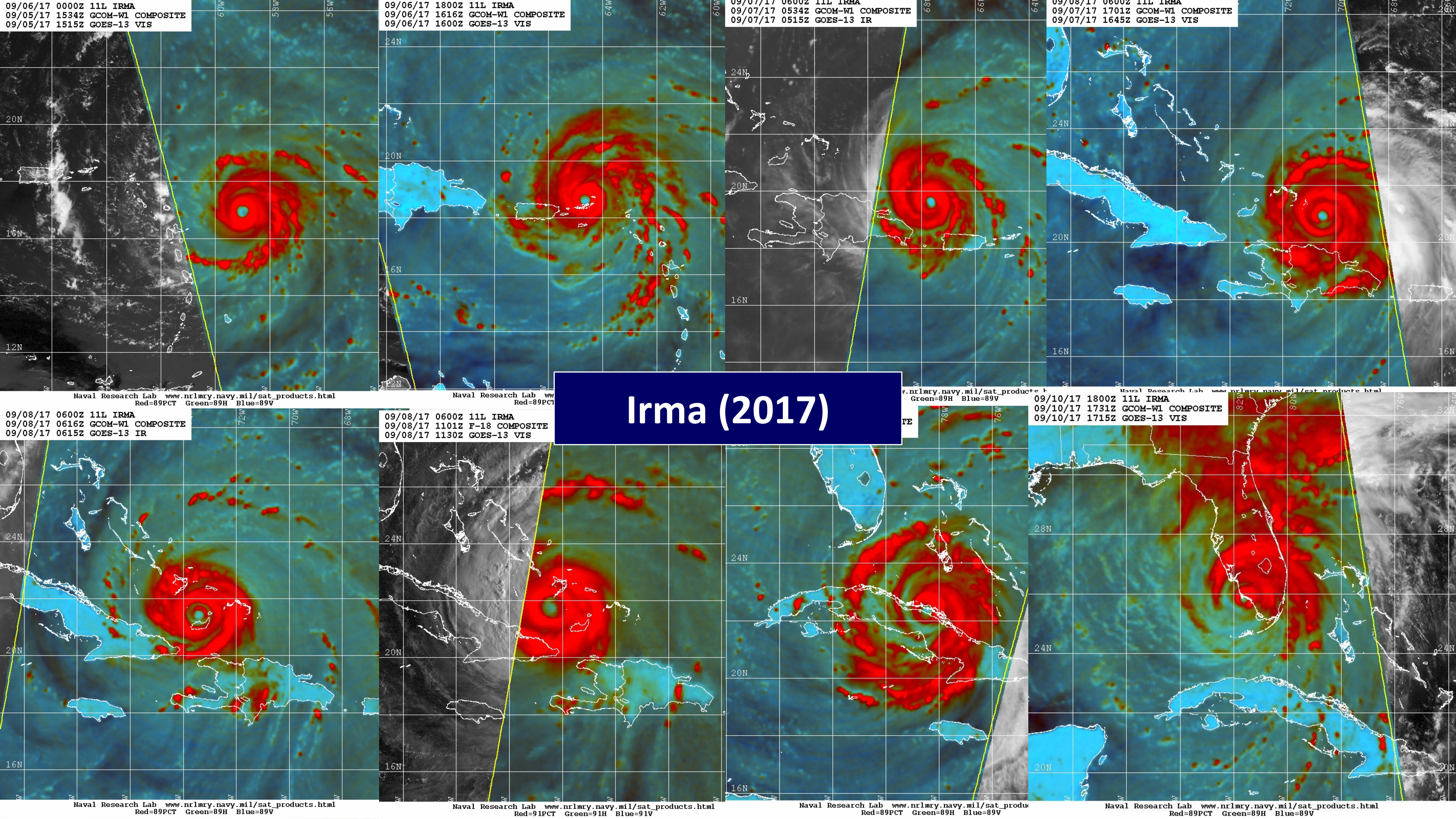


- A closed low-level ring of convection in 37-GHz imagery can be a precursor signal to rapid intensification.
- In this case, Patricia (2015) strengthened an incredible 90 kt (60 to 150 kt) in only 24 hours!

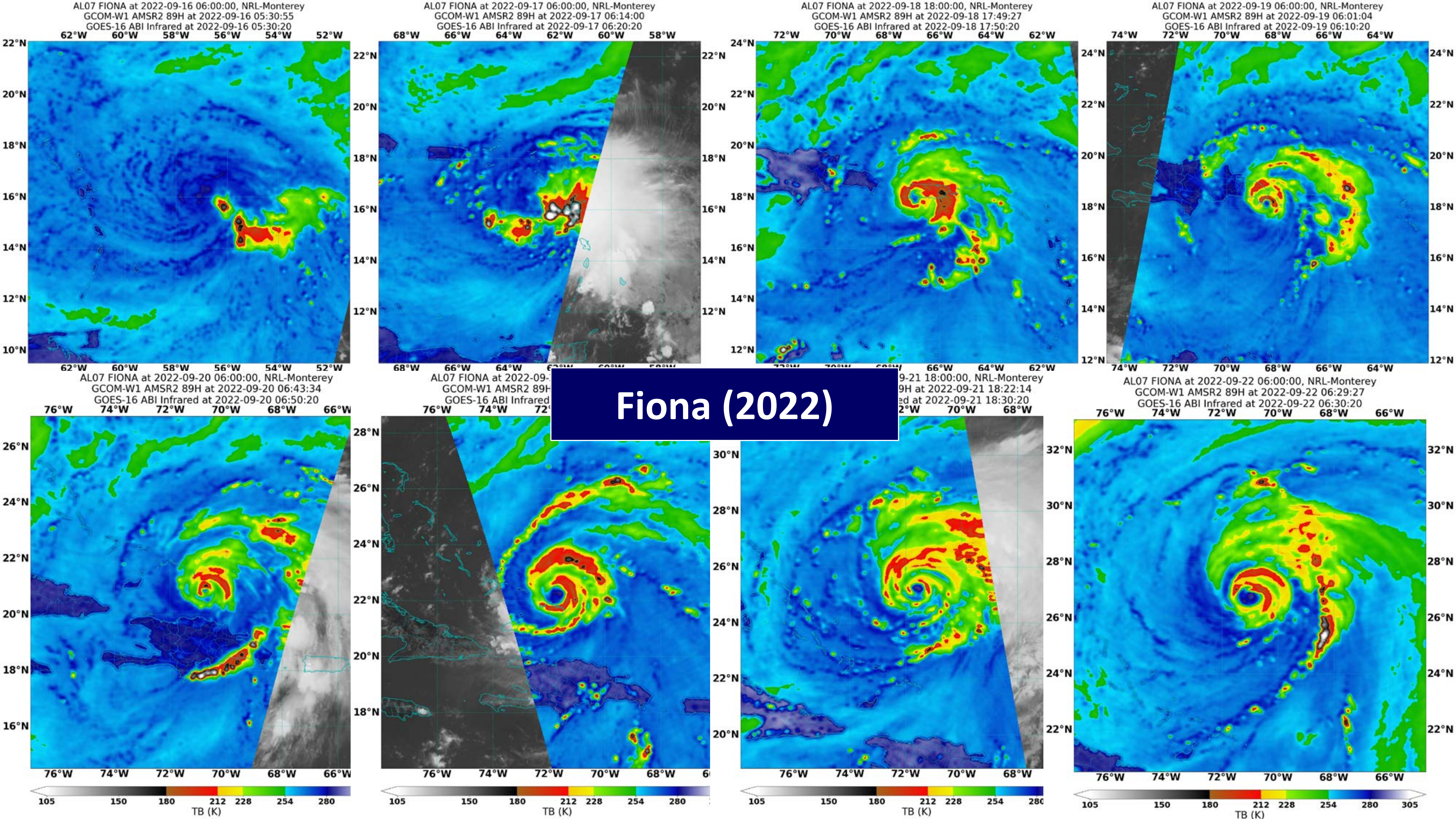
Matthew (2016)



Irma (2017)


09/06/17 0000Z 11L IRMA
09/05/17 1534Z GCOM-W1 COMPOSITE
09/05/17 1515Z GOES-13 VIS
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
Red=89PCT Green=89H Blue=89V
09/06/17 1800Z 11L IRMA
09/06/17 1616Z GCOM-W1 COMPOSITE
09/06/17 1600Z GOES-13 VIS
09/07/17 0534Z GCOM-W1 COMPOSITE
09/07/17 0515Z GOES-13 IR
09/07/17 1701Z GCOM-W1 COMPOSITE
09/07/17 1645Z GOES-13 VIS
09/08/17 0600Z 11L IRMA
09/08/17 0616Z GCOM-W1 COMPOSITE
09/08/17 0615Z GOES-13 IR
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
Red=89PCT Green=89H Blue=89V
09/08/17 0600Z 11L IRMA
09/08/17 1101Z F-18 COMPOSITE
09/08/17 1130Z GOES-13 VIS
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
Red=91PCT Green=91H Blue=91V
Naval Research Lab www.nrlmry.navy.mil/sat_produ
Red=89PCT Green=89H Blue=89V
09/10/17 1800Z 11L IRMA
09/10/17 1731Z GCOM-W1 COMPOSITE
09/10/17 1715Z GOES-13 VIS
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
Red=89PCT Green=89H Blue=89V

Fiona (2022)



AL07 FIONA at 2022-09-16 06:00:00, NRL-Monterey
GCOM-W1 AMSR2 89H at 2022-09-16 05:30:55
GOES-16 ABI Infrared at 2022-09-16 05:30:20
AL07 FIONA at 2022-09-17 06:00:00, NRL-Monterey
GCOM-W1 AMSR2 89H at 2022-09-17 06:14:00
GOES-16 ABI Infrared at 2022-09-17 06:20:20
AL07 FIONA at 2022-09-18 18:00:00, NRL-Monterey
GCOM-W1 AMSR2 89H at 2022-09-18 17:49:27
GOES-16 ABI Infrared at 2022-09-18 17:50:20
AL07 FIONA at 2022-09-19 06:00:00, NRL-Monterey
GCOM-W1 AMSR2 89H at 2022-09-19 06:01:04
GOES-16 ABI Infrared at 2022-09-19 06:10:20
AL07 FIONA at 2022-09-20 06:00:00, NRL-Monterey
GCOM-W1 AMSR2 89H at 2022-09-20 06:43:34
GOES-16 ABI Infrared at 2022-09-20 06:50:20
AL07 FIONA at 2022-09-22 06:00:00, NRL-Monterey
GCOM-W1 AMSR2 89H at 2022-09-22 06:29:27
GOES-16 ABI Infrared at 2022-09-22 06:30:20
TB (K)

Scatterometry & Tropical Cyclone Applications

Scatterometry Basics

What is a scatterometer?

- Microwave radar located aboard polar-orbiting (LEO) satellites
- The instrument actively transmits energy toward the Earth's surface and measures the energy reflected back to it.
- How does this information help us as tropical cyclone forecasters?

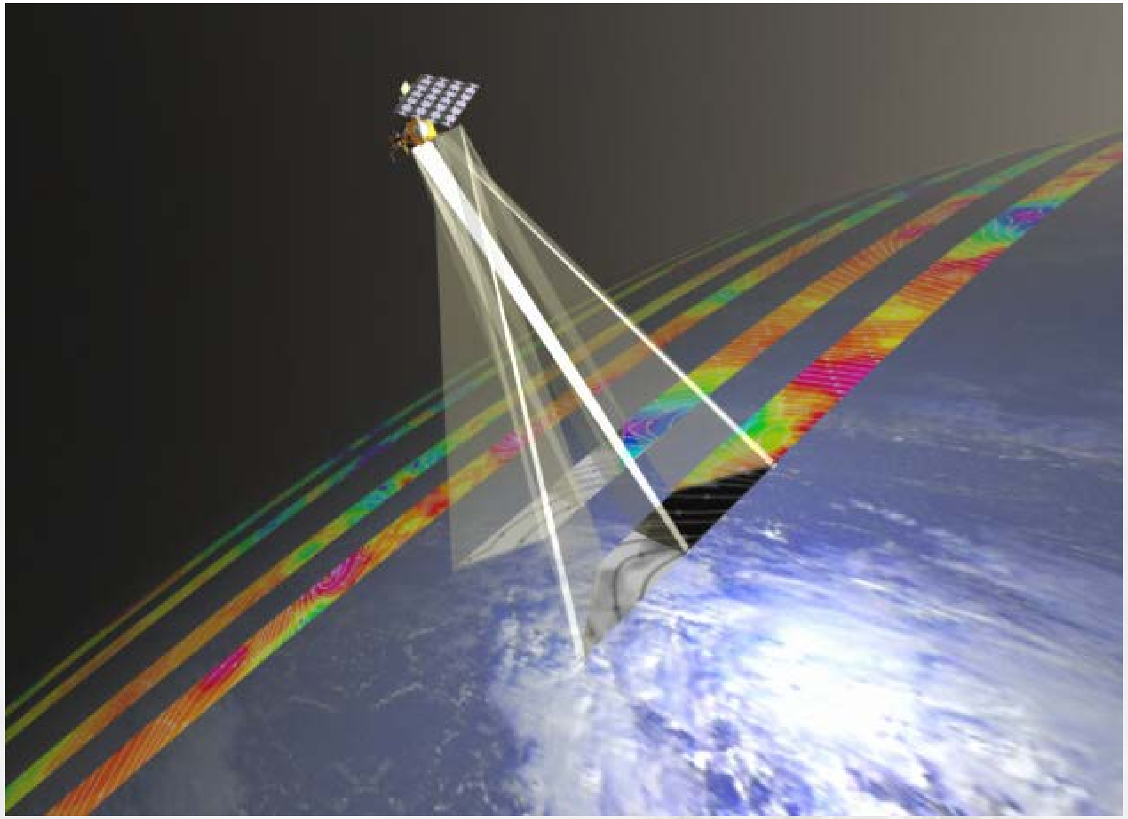


Image courtesy EUMETSAT

Scatterometry Basics

- Microwave energy is sensitive to small-scale roughness of the ocean surface that is generated by surface winds.
- By viewing the same patch of ocean from several angles, it is possible to derive wind speed and direction.

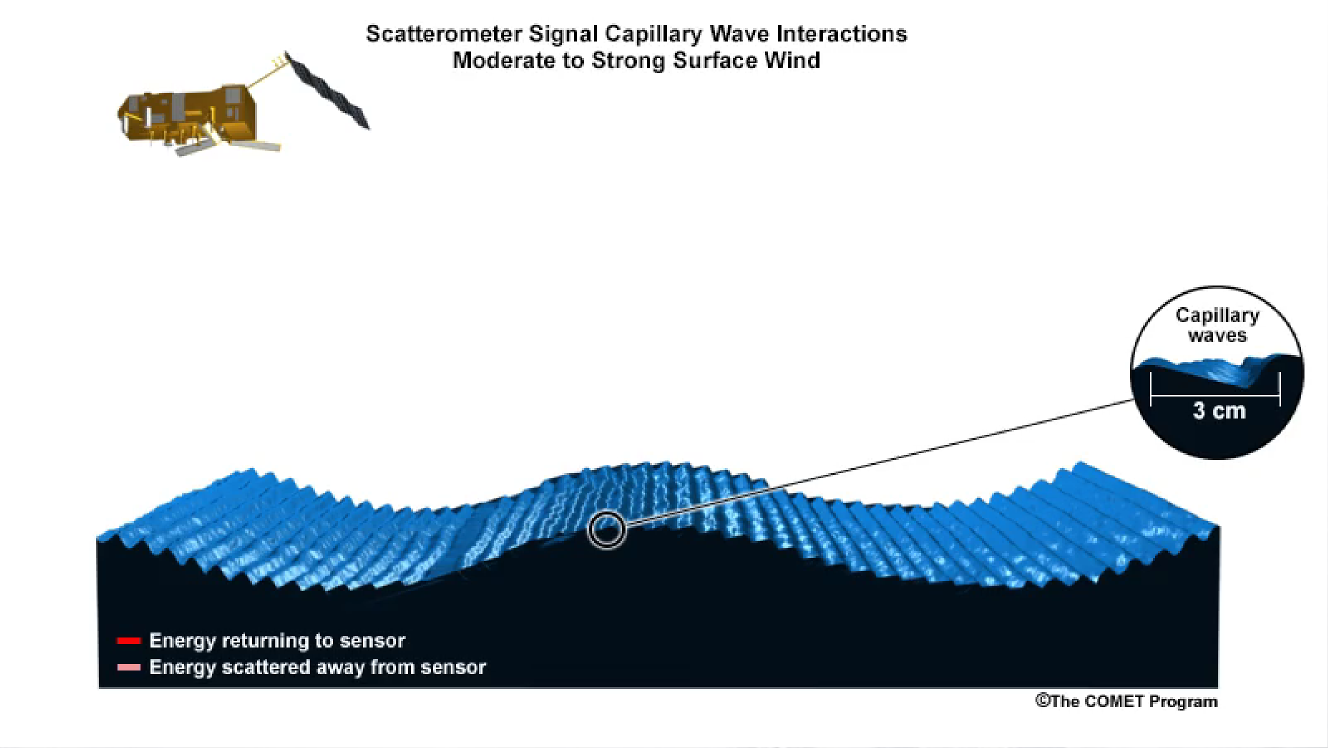


Image courtesy COMET

Advanced Scatterometer (ASCAT)

Satellites: Metop-B, -C
Launched: 2012, 2018
Operator: EUMETSAT

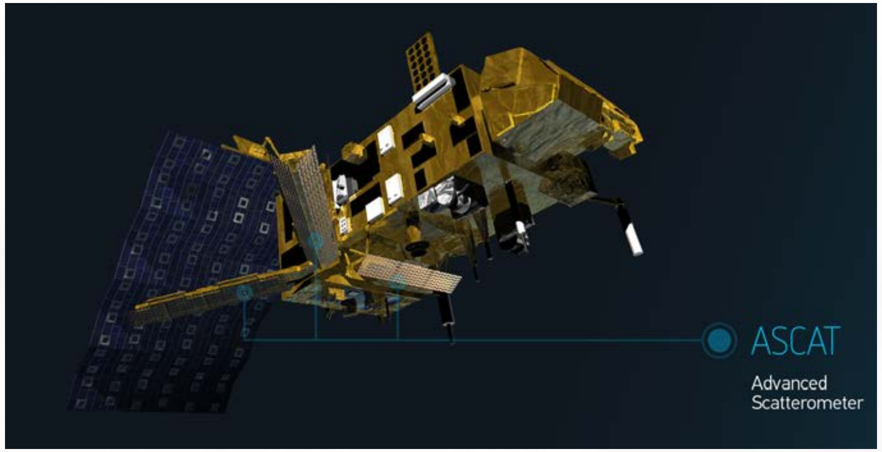


Image courtesy EUMETSAT

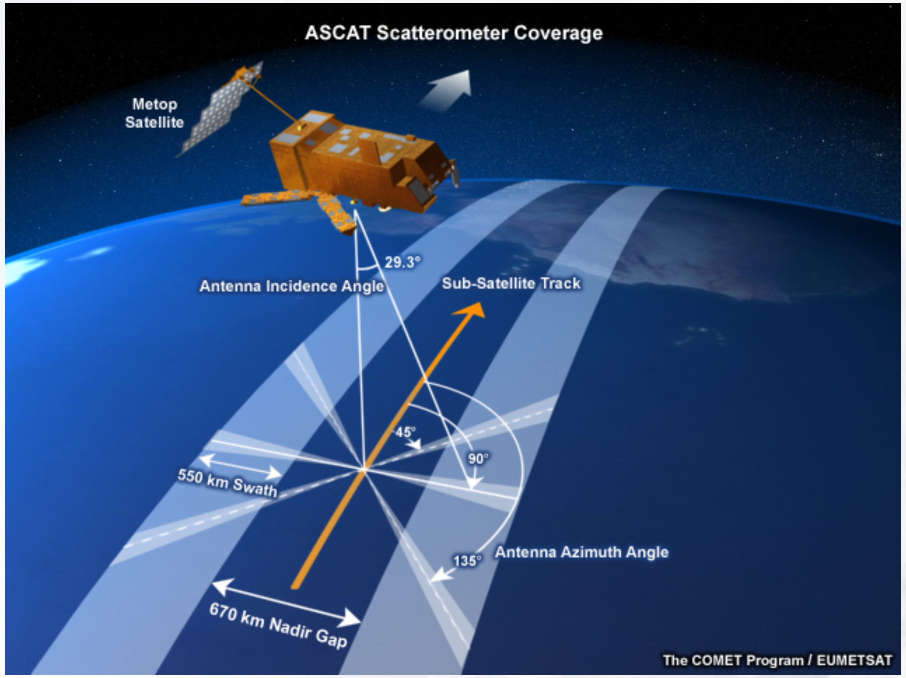
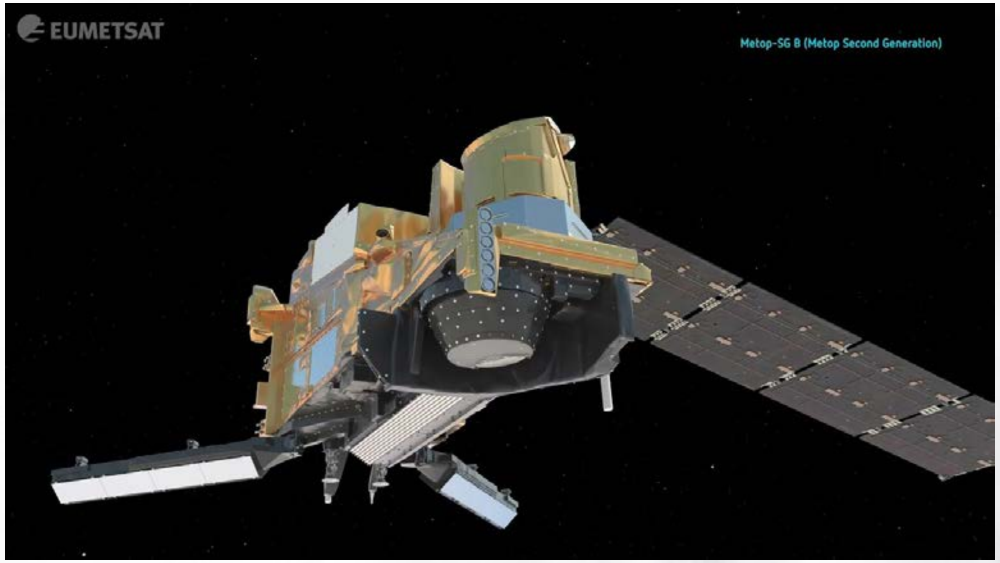


Image courtesy COMET

Sensor: Microwave radar
Channel: 5.25 GHz (C-band)
Swath: Two 550-km swaths;
670 km nadir gap
Resolution: 25 km
(resampled at 12.5 km)

ASCAT (2023 Update)

- Metop-SG (Second Generation) A1 satellite launch is planned for early 2025.
- Metop-B and -C satellites follow a similar orbital path, so for now the data gaps over the tropics remain large.

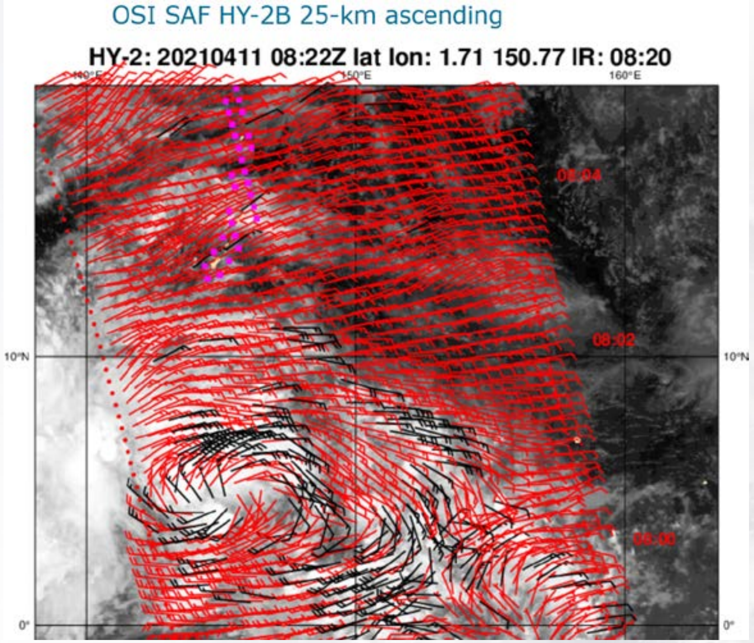


Metop-SG Satellite

Image courtesy EUMETSAT

Other Scatterometer Data

Satellites: HY-2B, -2C, -2D
Launched: 2018, 2020, 2021
Operator: Chinese National Satellite Ocean Application Service (NSOAS)



Black wind barbs = QC flagged data

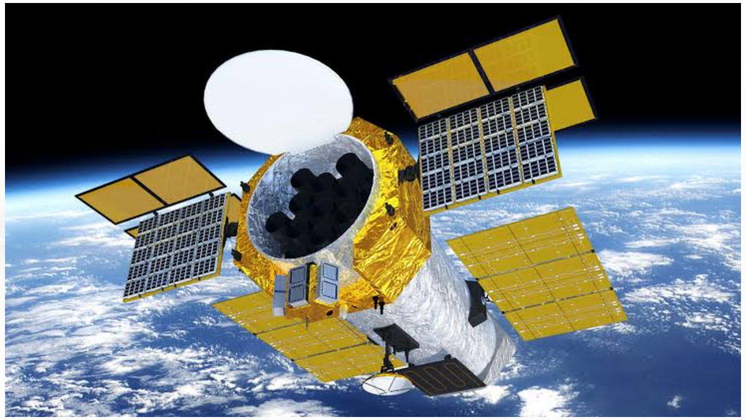


Image courtesy NSOAS

Sensor: Microwave radar
Channel: 13.3 GHz (Ku-band)
Swath: 1300 km
Resolution: 25 km

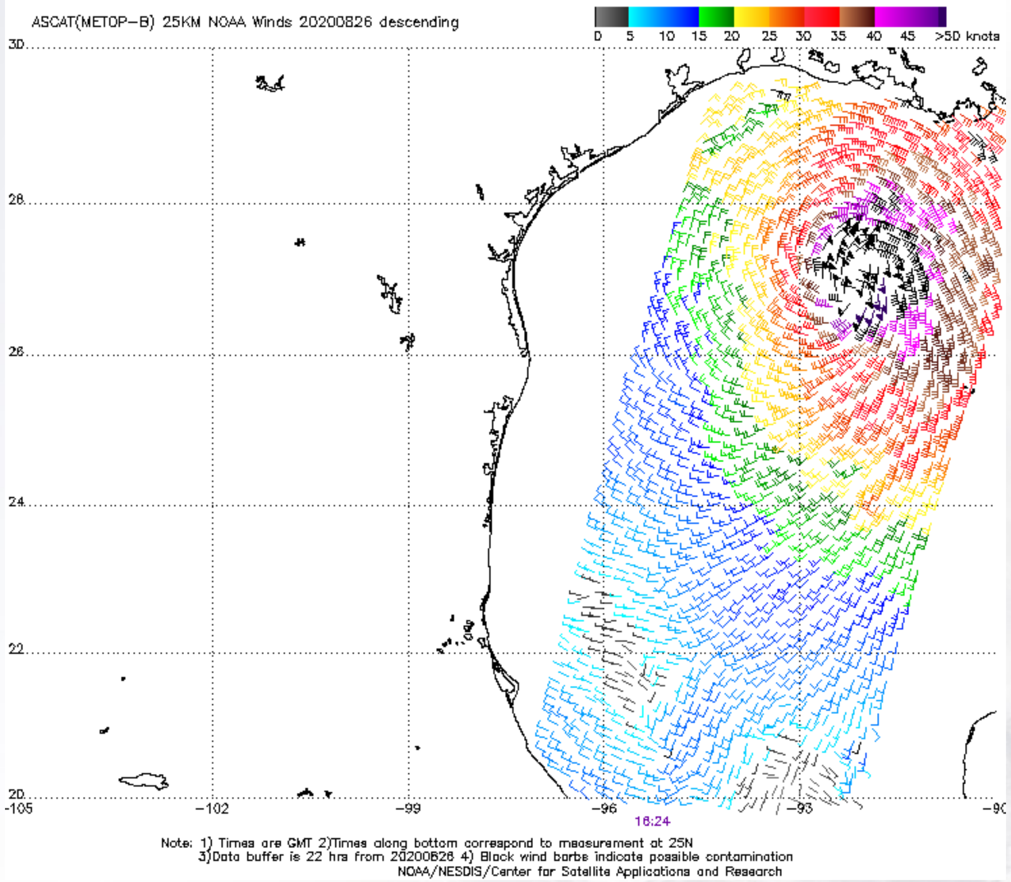
Note: Ku-band is more sensitive to rain contamination, which can lead to overestimated winds.

Accessing Scatterometer Data

NOAA/NESDIS

https://manati.star.nesdis.noaa.gov/

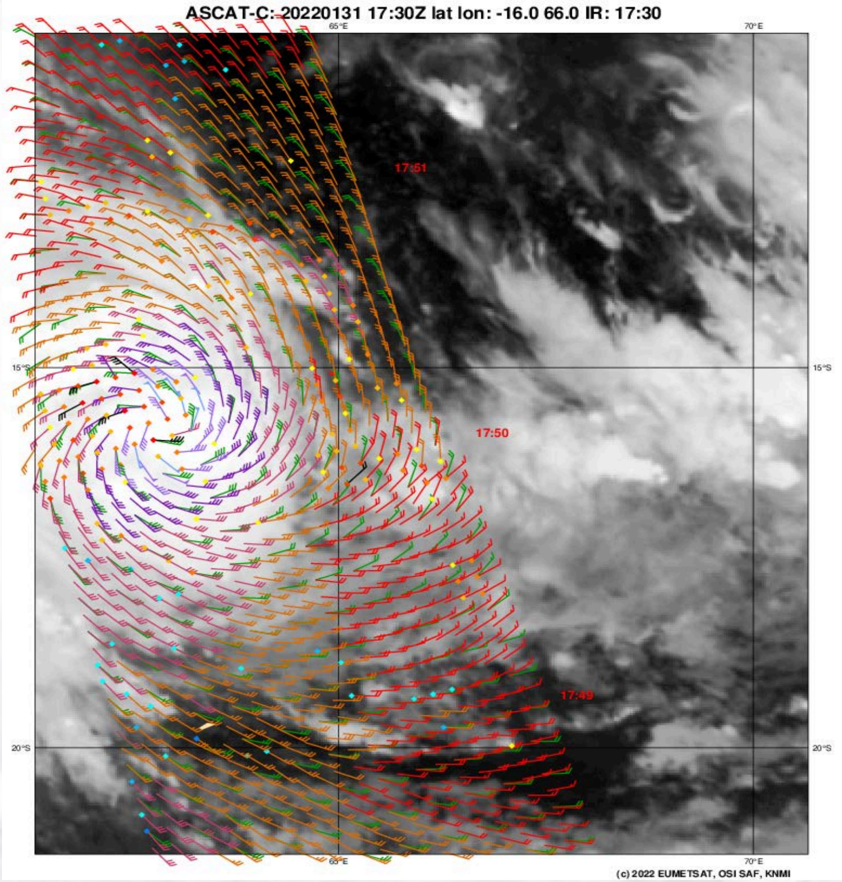
(25- and 50-km ASCAT wind vector products)



KNMI/EUMETSAT

https://scatterometer.knmi.nl/tile_prod

(Public, operational HY-2B, -2C winds)



Scatterometer Limitations

- Gaps over the tropics reduce spatial data coverage, and data swaths may completely miss TCs

- Spatial sampling/resolution does not allow for detection of peak winds in hurricanes or strong tropical storms

- Uncertainties in derived wind direction (directional ambiguity)

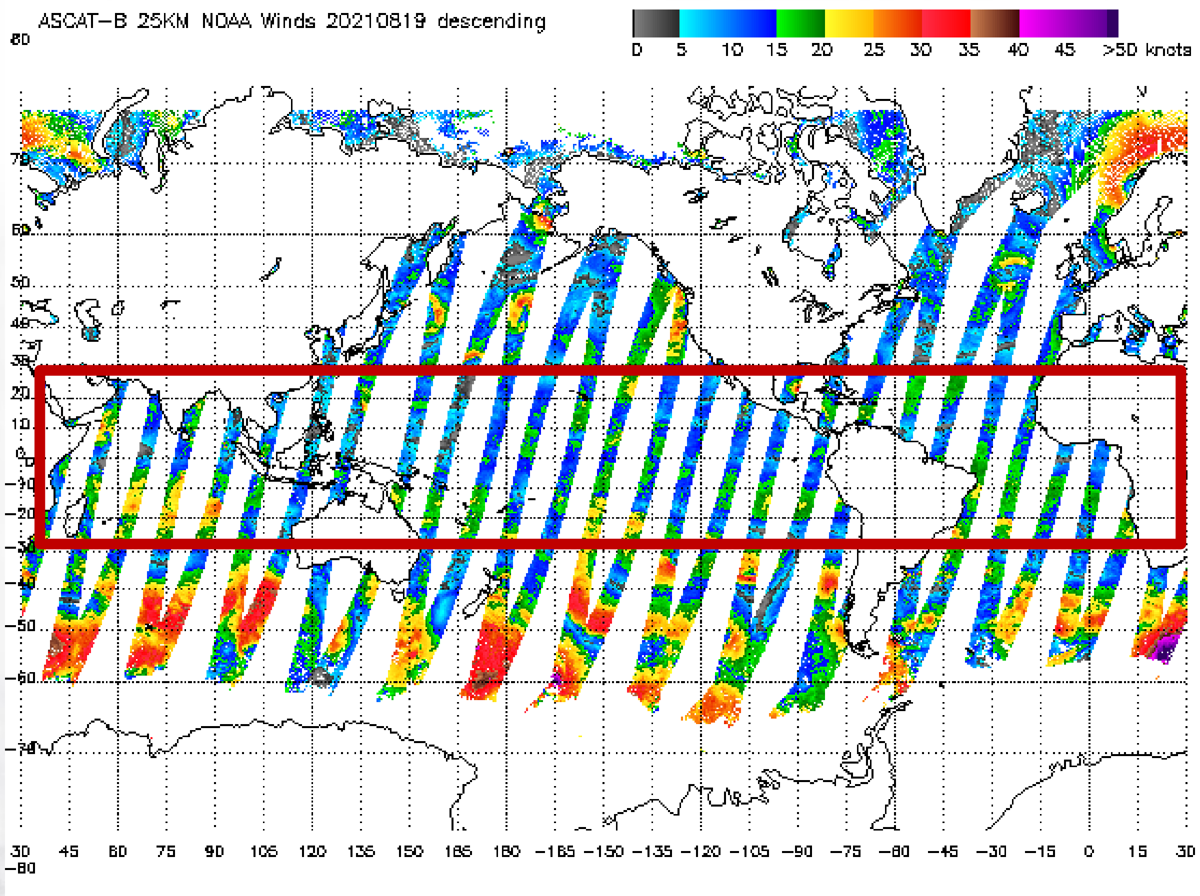


Image courtesy NOAA/NESDIS

Directional Ambiguity

- Wind direction is derived by determining the angle that is most likely consistent with the backscattered energy.
  - The best fit *usually* matches the true wind direction
  - But what if it doesn't?
    - Look at ambiguities to view other possible directions and identify the most likely solution

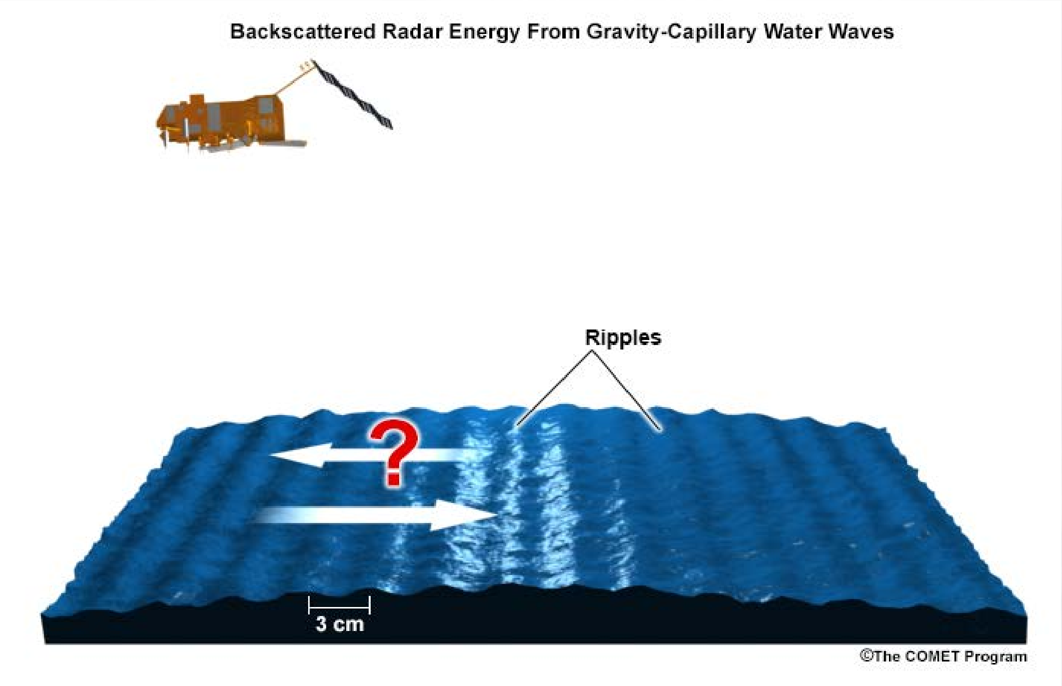
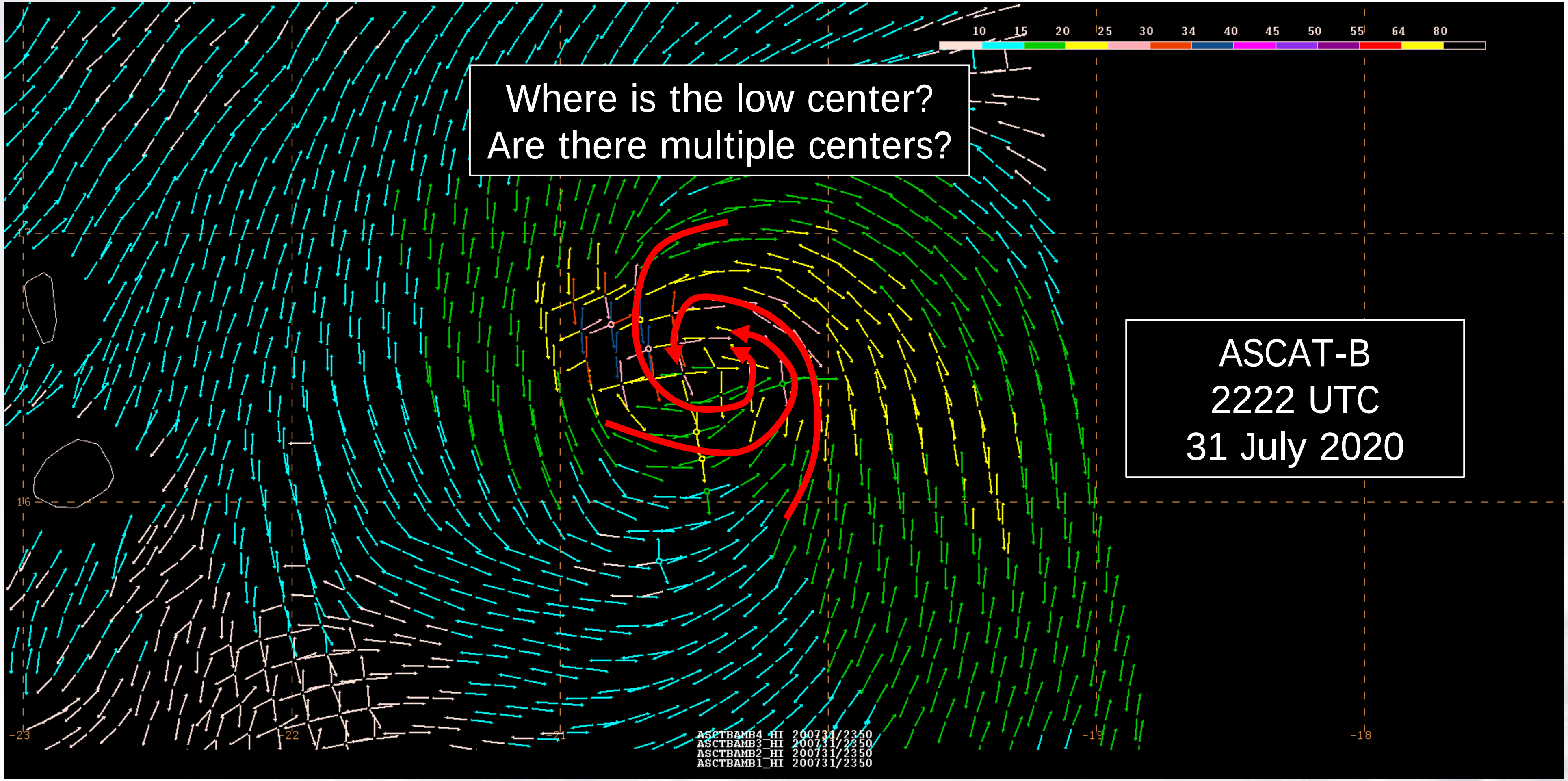


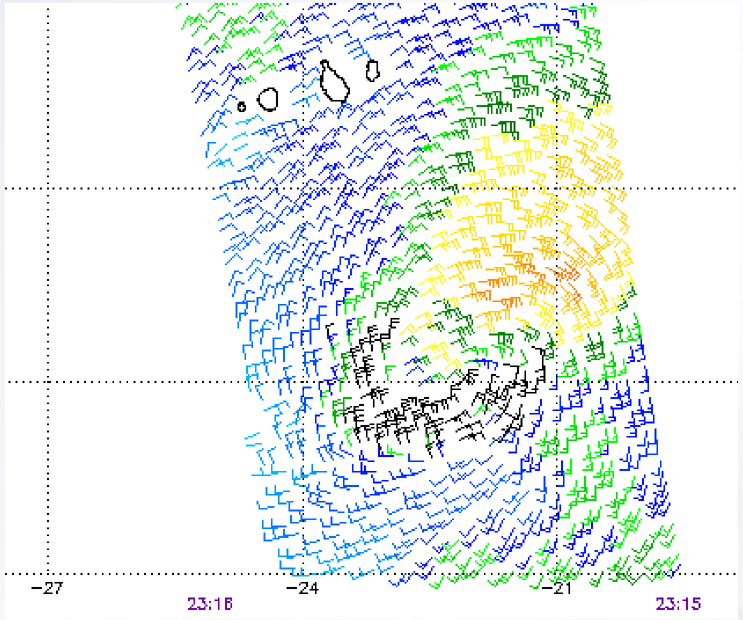
Image courtesy COMET

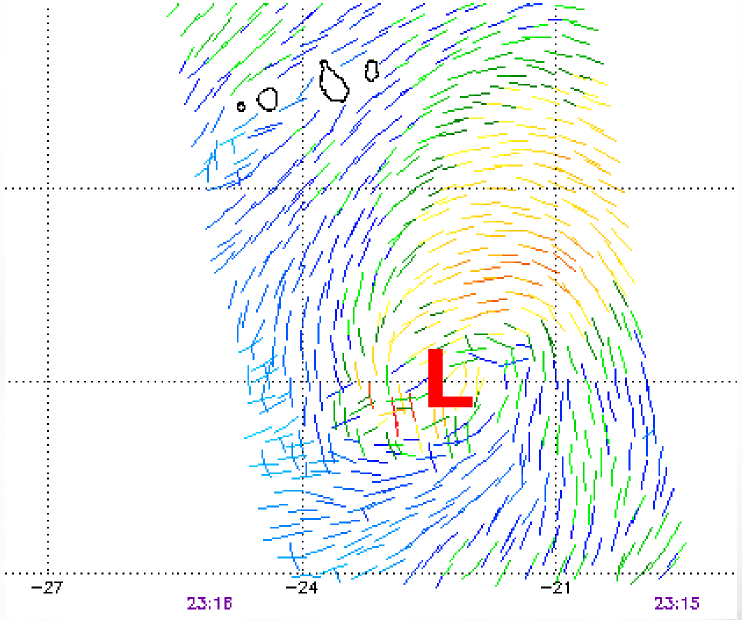
Directional Ambiguity



- ASCAT ambiguities can be used to help assess appropriate wind directions and improve the center fix for developing TCs

TC Applications: Genesis

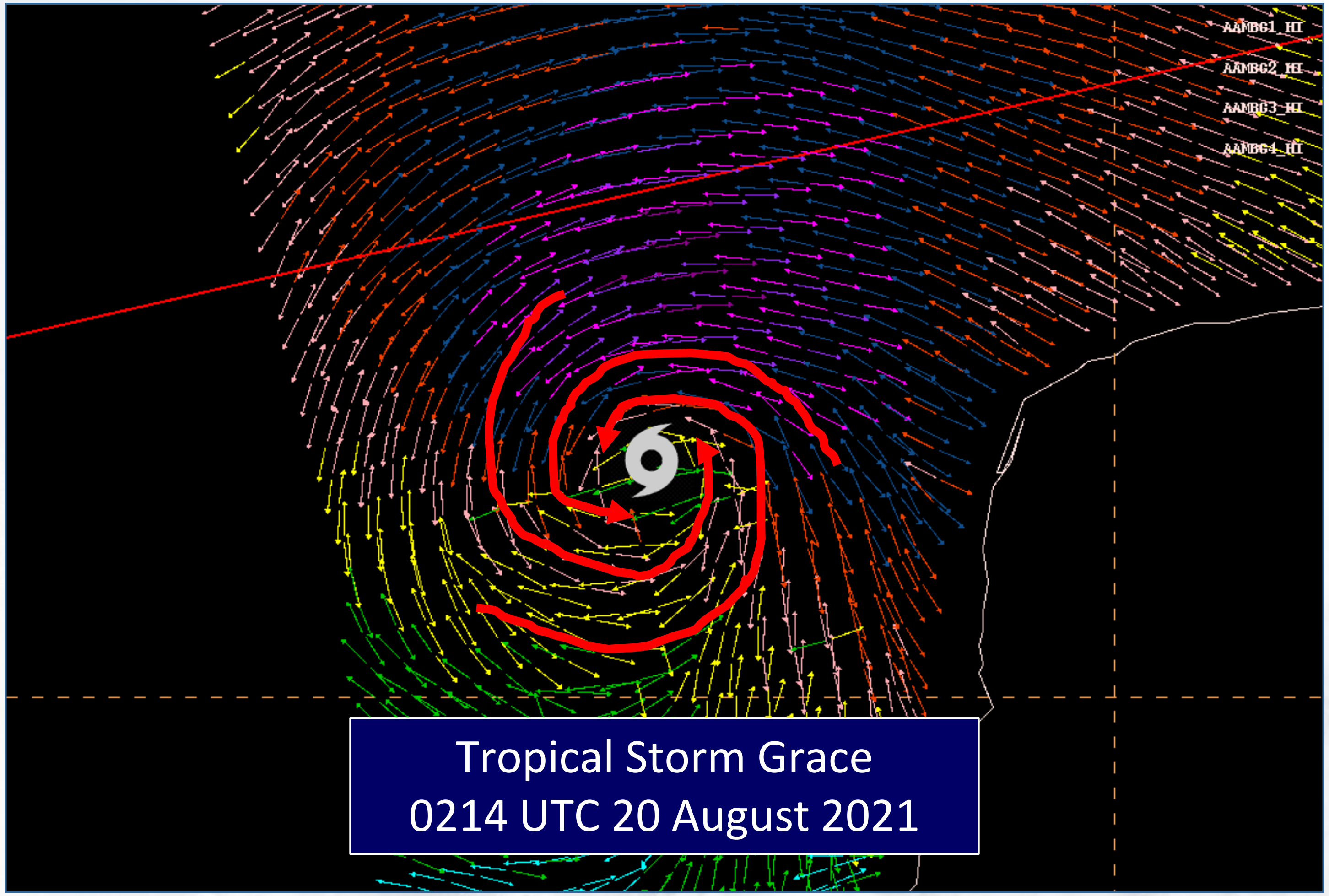




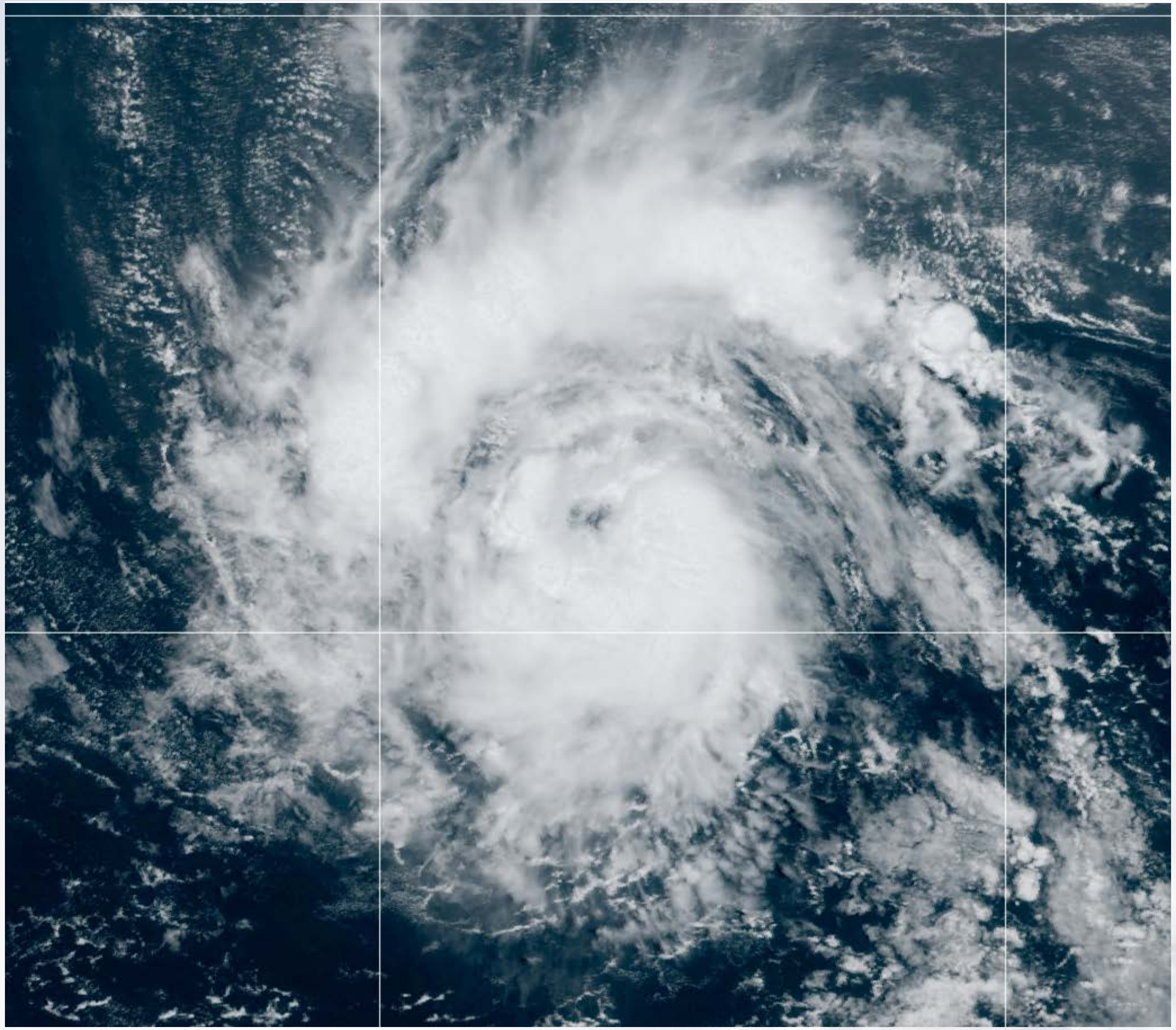
Tropical Depression Twelve Discussion Number 1
NWS National Hurricane Center Miami FL AL122021
800 PM CVT Tue Aug 31 2021

Satellite imagery, along with **earlier scatterometer data**, indicates that the low pressure area over the eastern tropical Atlantic has a well-defined circulation and sufficient organized convection to be considered a tropical depression. Thus, **advisories are being initiated on Tropical Depression Twelve**. The **initial intensity is set at 30 kt** based on satellite intensity estimates from TAFB and SAB as well as the **scatterometer data**.

TC Applications: Center Fix



TC Applications: Intensity Analysis



Tropical Storm Sam Discussion Number 4
NWS National Hurricane Center Miami FL AL182021
1100 AM AST Thu Sep 23 2021

"Subjective Dvorak satellite intensity estimates are now **T3.5/55-kt** from SAB and **T2.5/35-kt** from TAFB..."

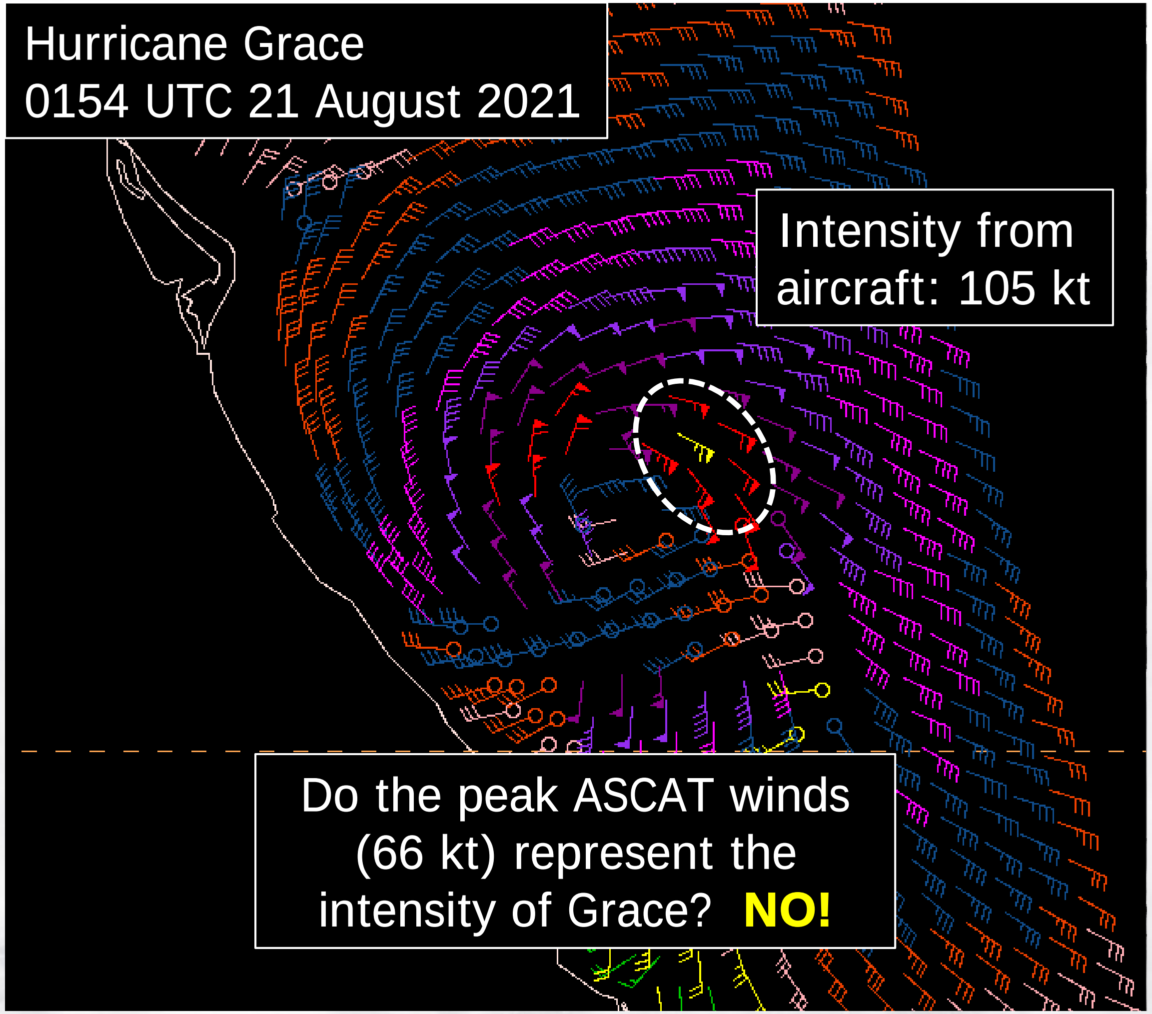
"**ASCAT-B wind retrievals** at 1234 UTC also indicated a tight, well-defined circulation had formed, with **peak winds of 44 kt** on the north side of the vortex..."

Given the recent scatterometer data, the intensity has been set to 45-kt for this advisory. Thus, Tropical Depression 18 has been upgraded to Tropical Storm Sam.

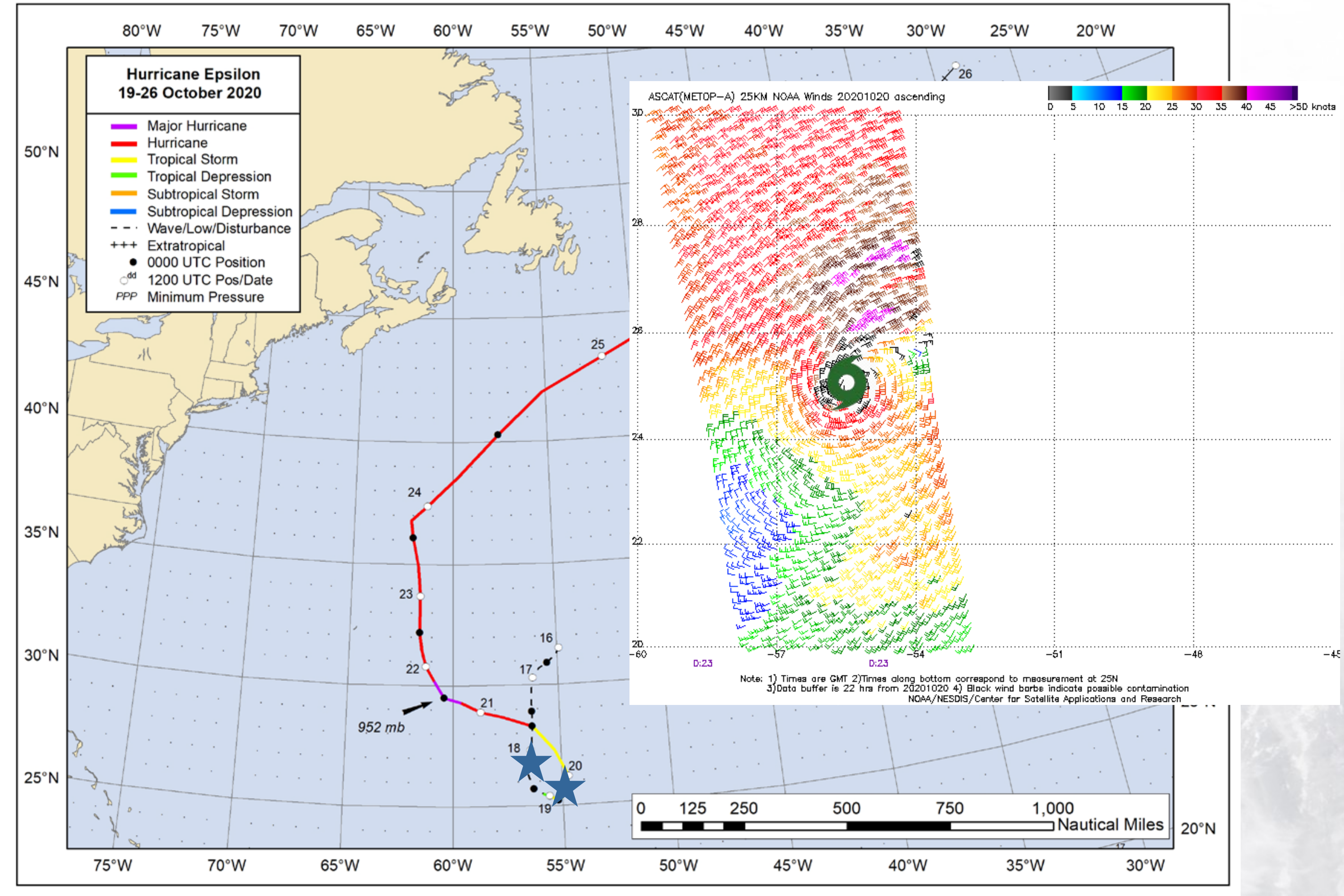
TC Applications: Intensity Analysis

- Remember: Scatterometer winds **cannot** be used to determine the peak intensity of hurricanes or stronger tropical storms.

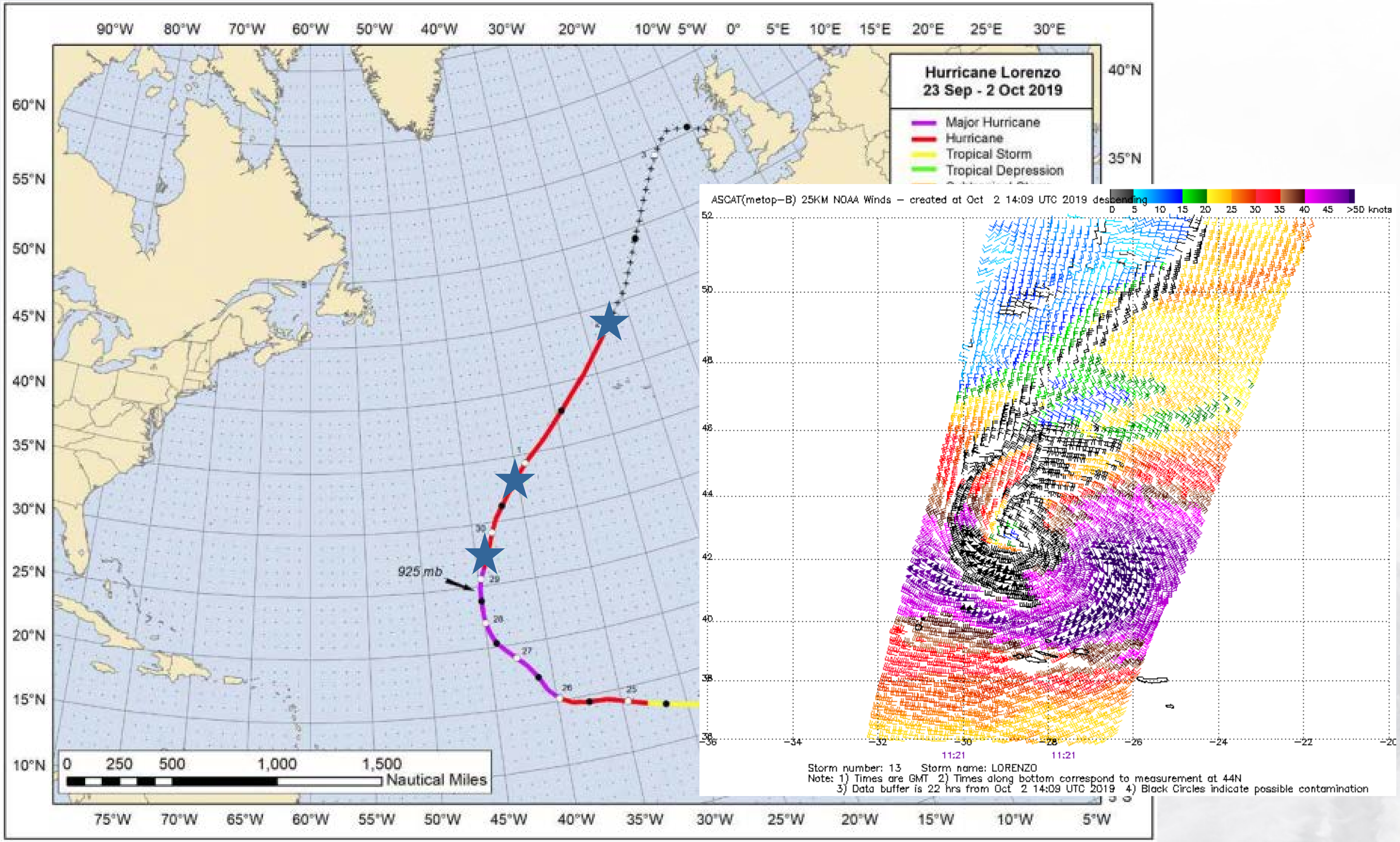
- But, the data can still provide us with valuable information.
  - Center fix (w/ambiguities)
  - Radius of maximum wind
  - 34, 50-kt wind radii



TC Applications: Cyclone Phase Transition



TC Applications: Extratropical Transition

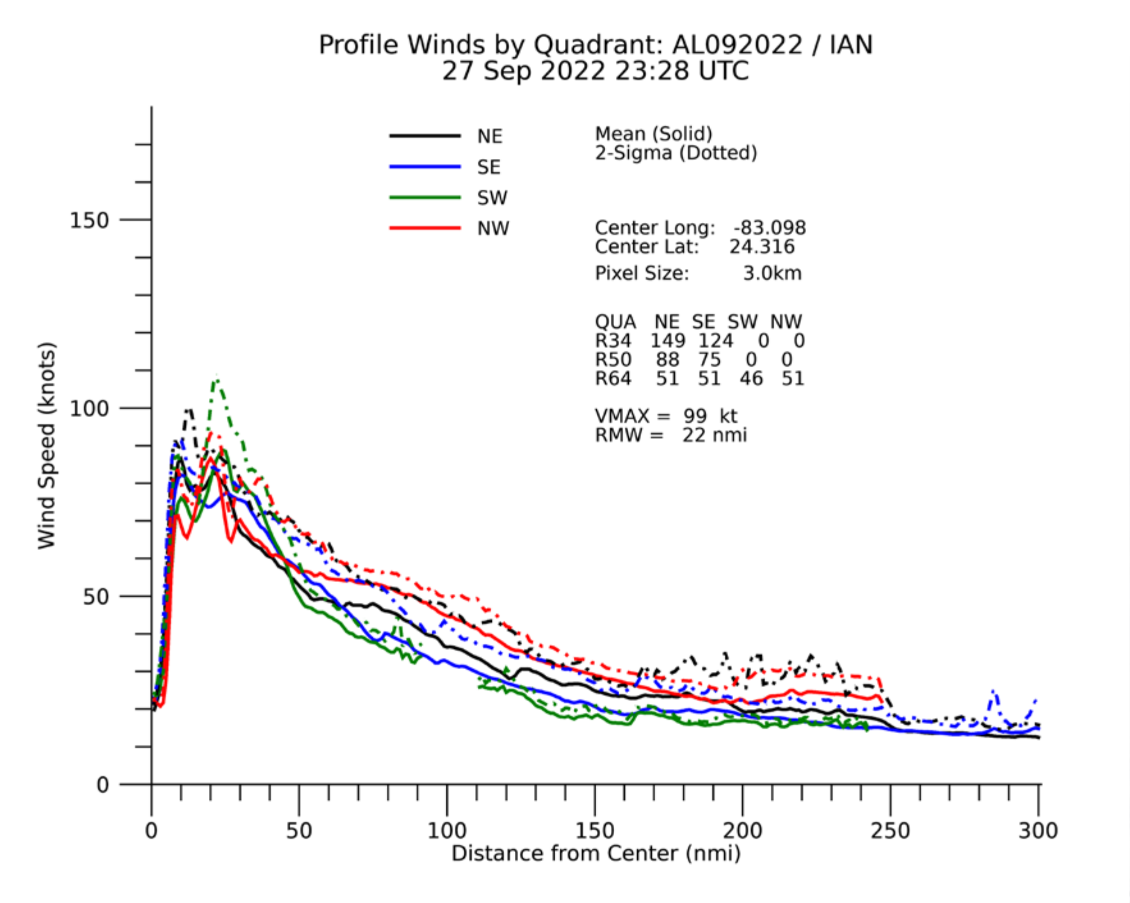


Synthetic Aperture Radar (SAR) Data

- Microwave (C-band) radar aboard polar-orbiting satellites
- Provides very high-resolution ocean surface wind speed data
- Data collections must be programmed 2-5 days in advance
  - Requires storm forecast track
  - Location/timing of SAR footprint must align with the storm
  - Only a few collection opportunities may be possible for a given storm

Synthetic Aperture Radar (SAR) Data

Hurricane Ian
2328 UTC 27 Sep 2022



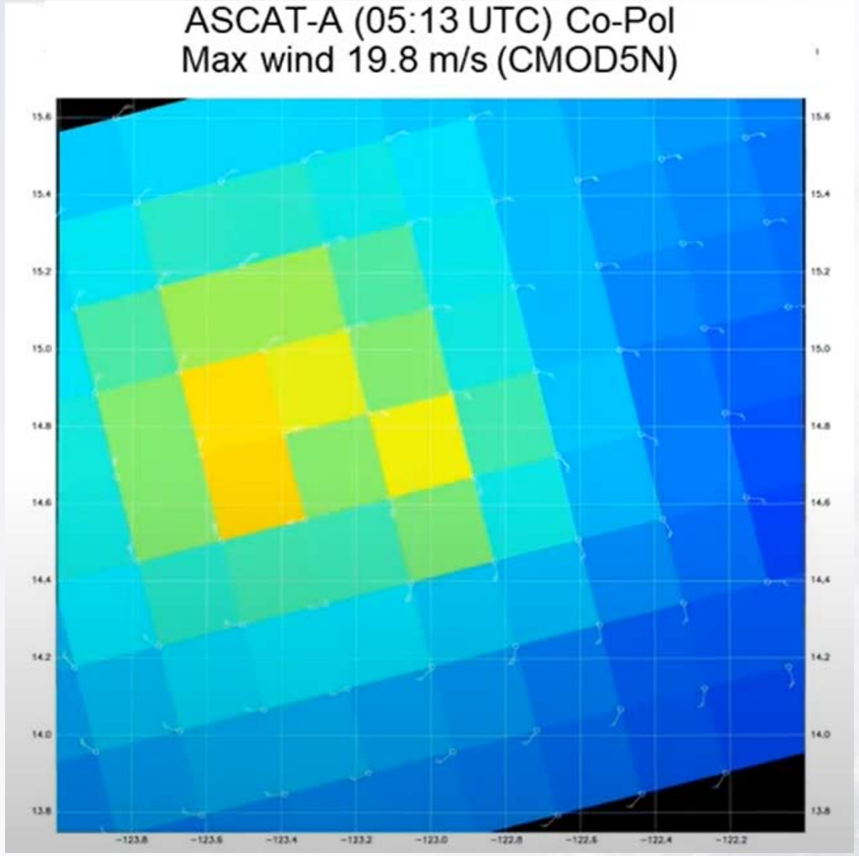
NOAA STAR TC products:

- 500 m and 3 km wind speed images
- Radial wind profiles (maximum wind speed and radius of maximum winds)
- 34-, 50-, and 64-kt wind radii
- Center/eye location

https://www.star.nesdis.noaa.gov/socd/mecb/sar/AKDEMO_products/APL_winds/tropical/index.html

Images courtesy NOAA/NESDIS/STAR

SAR vs. ASCAT Comparison



Major Hurricane Felicia

17 July 2021 - 120 kt

SAR V_{max} = 122 kt (0.5 km resolution)

ASCAT V_{max} = 38 kt (25 km resolution)

Eye diameter = 10 km
RMW = 9.25 km

Reminder: Scatterometer data cannot provide the peak hurricane winds due to its coarse resolution.

Adapted from NOAA Satellite Book Club Session 60 – Christopher R. Jackson et al. (July 2021)

Microwave Imagery Exercise

PollEv.com/nhcpoll903