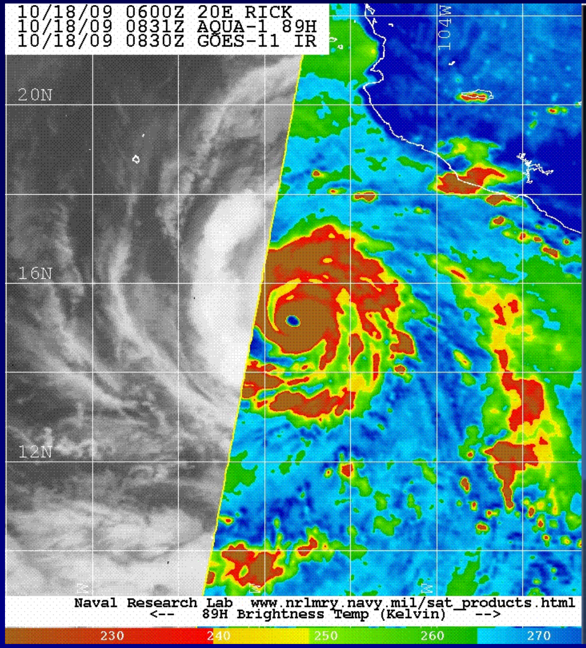
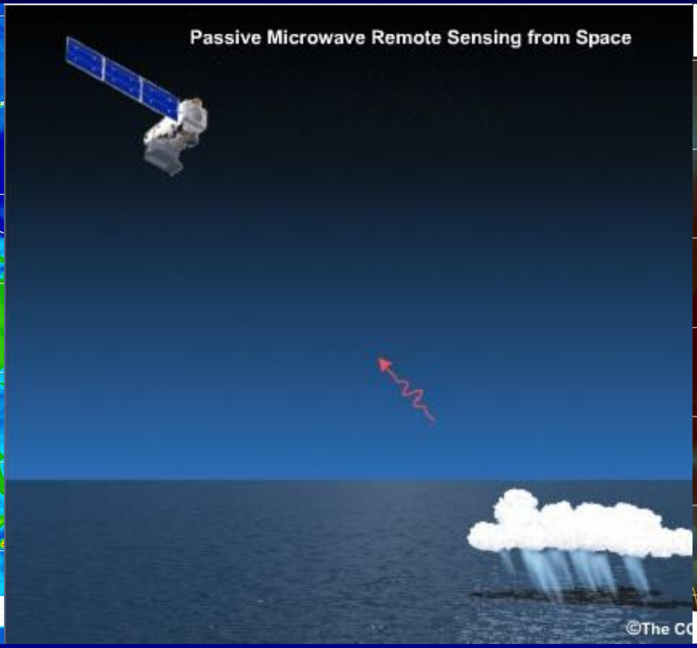
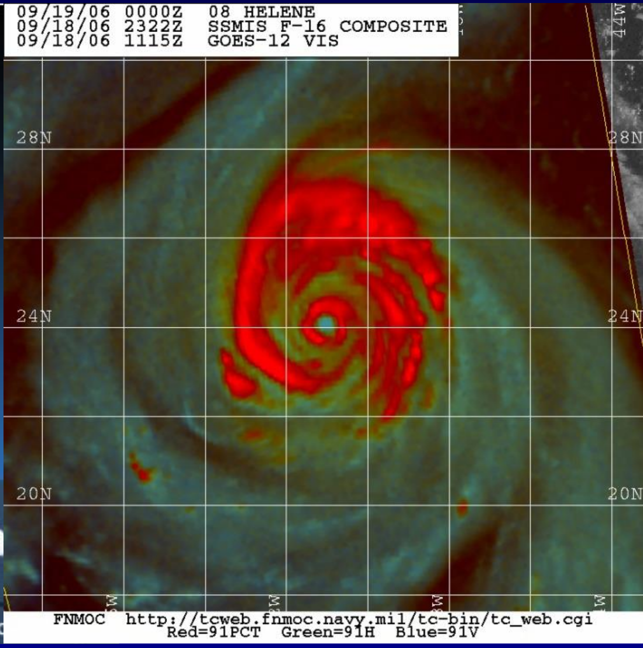
# Interpretation and Application of Microwave Imagery and Scatterometry




## 2019 RA-IV WMO Tropical Meteorology Course

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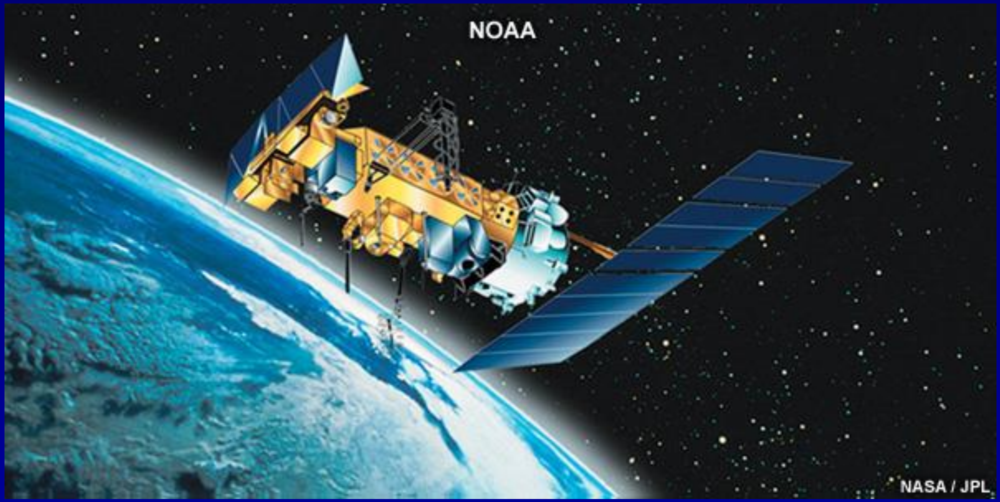
National Hurricane Center

# Outline

- Overview of basic principles/availability of Low Earth Orbit (LEO) microwave sensors
- Orbital characteristics
- Single frequency characteristics
- Color composite images
- Scatterometry
- Data availability
- Application/Exercises




* Acknowledgements to COMET, NRL, and FNMOC for many of the images shown here

# Overview of Remote Sensing Basics

- Passive sensors (SSM/I, SSMIS, TMI, AMSU, AMSR2, etc.) measure emitted microwave energy from 19 to 200 GHZ
- Emissivities are directly related to brightness temperatures ($T_b$)
  - scattering effects by ice
  - emission by light precipitation
  - emission/absorption by cloud liquid water and rain droplets
- Microwave window channel $T_b$ can be used to quantify these emissivities

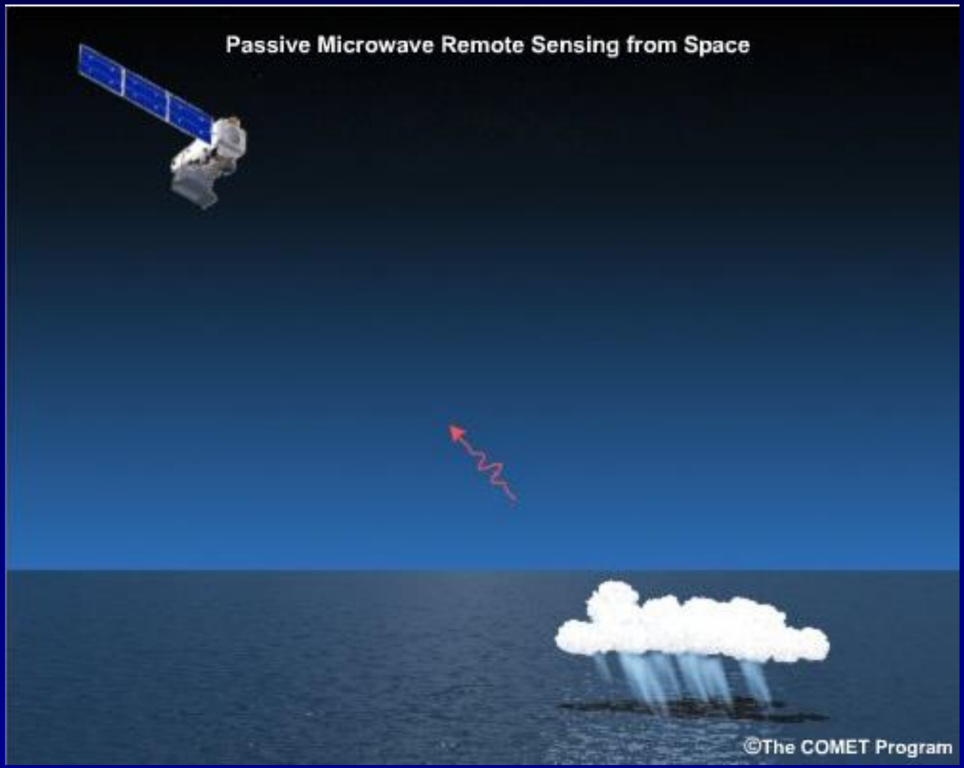
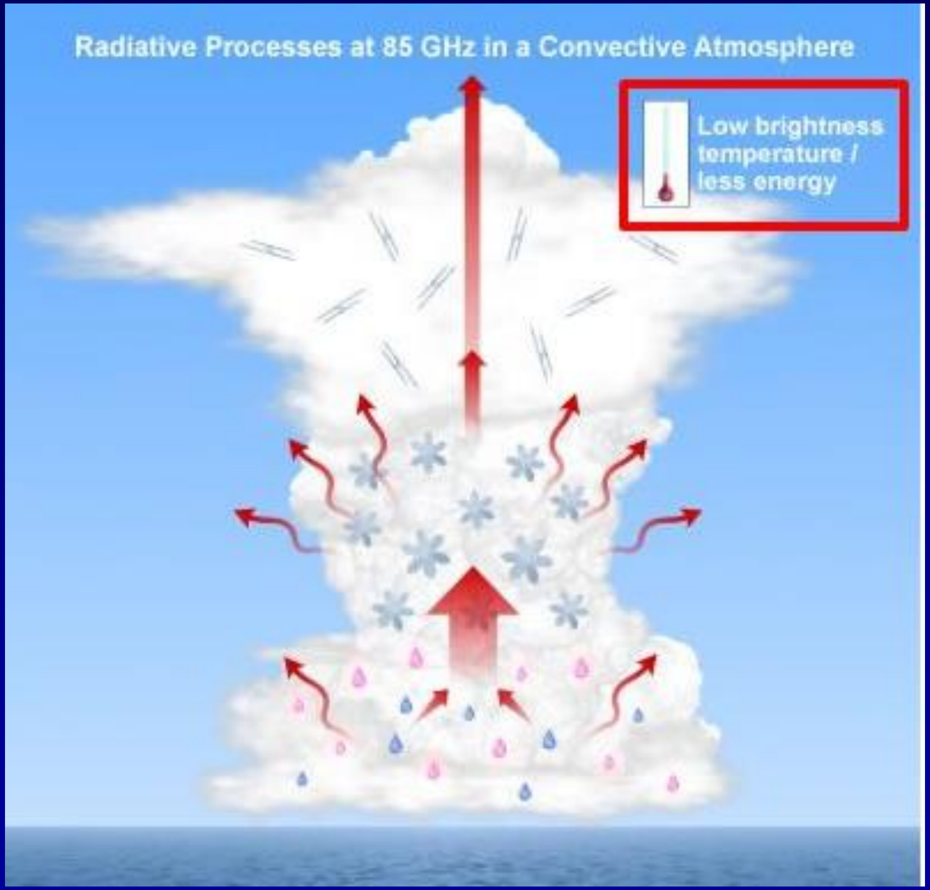



Image courtesy COMET

# Overview of Remote Sensing Basics

- 85-GHz images → primary signature is lowered $T_b$ caused by ice scattering and cloud and rain droplets within deep convection and precipitating anvil clouds

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# Overview of Remote Sensing Basics

- 37-GHz images → primary signature is elevated $T_b$ because of minor emission from liquid hydrometeors near or below the freezing level

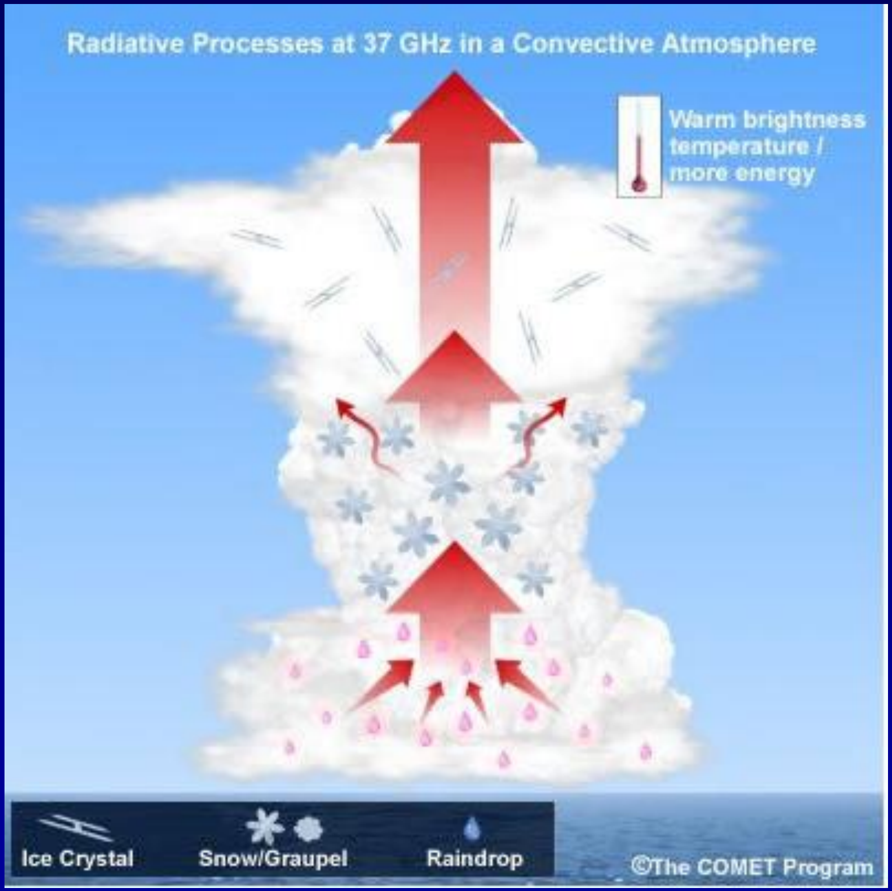



Image courtesy COMET

# Remote Sensing Satellites - Orbits

- Geostationary (GEO) satellites
  - Orbit at 35,800 km altitude over same spot on the equator
  - Good for continuous monitoring, not good for high resolution
  - Good for visible and infrared, not good for microwave
  - Good for passive, not good for active
  - Good for middle latitudes and tropics, not good for polar regions


- Low earth orbit (LEO) satellites
  - Good for microwave (active and passive), visible, and infrared
  - Lower altitude orbit, but not over same spot on earth
  - Finer spatial resolution
  - Limited spatial coverage (narrow swaths of data)
  - Views each area only twice per day (except near poles)
  - Depending on orbital configuration, can cover nearly entire globe each day

# Data Timeliness

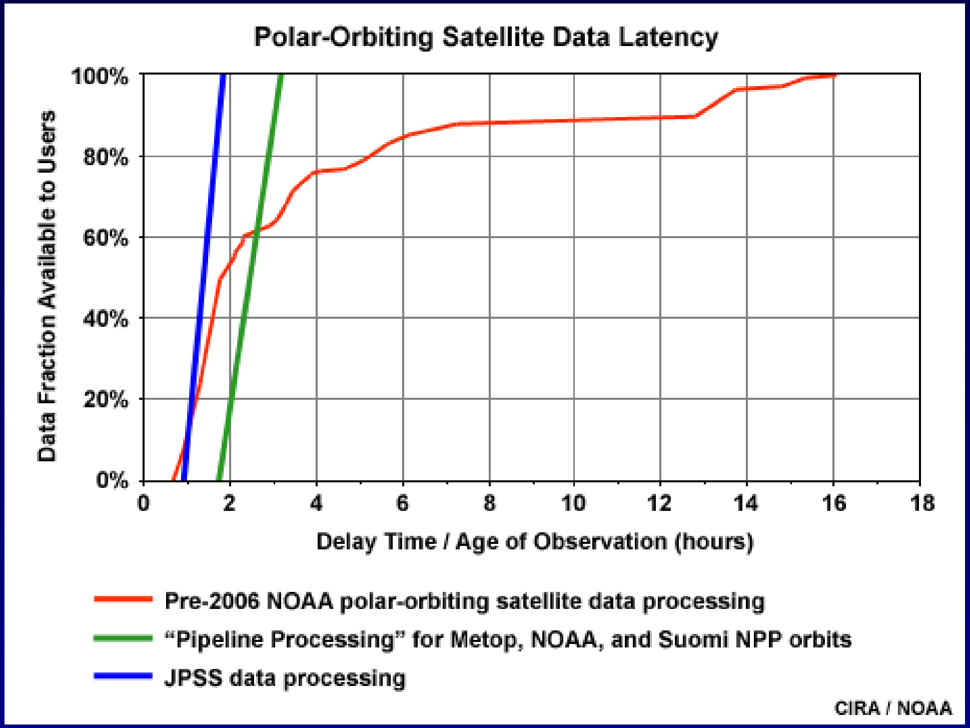
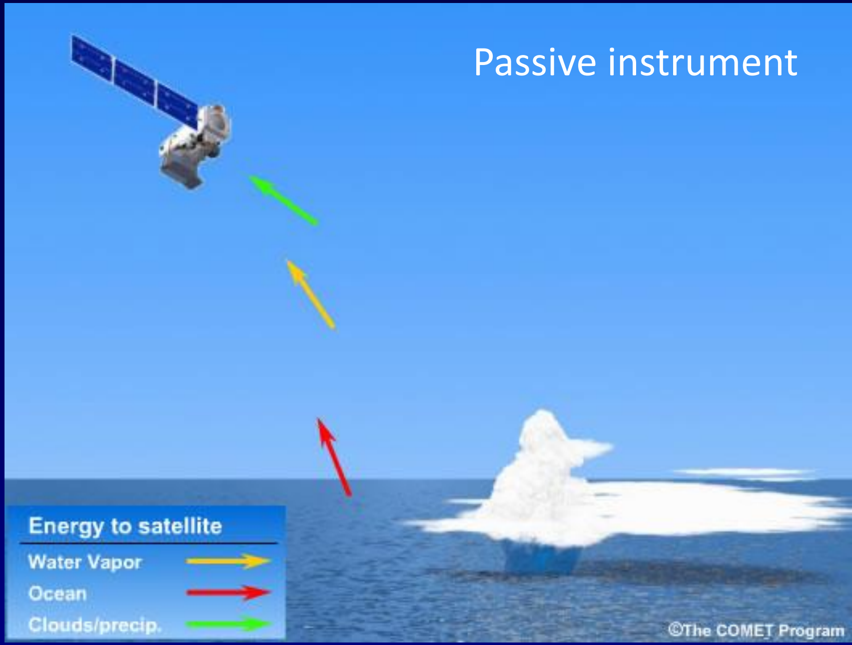


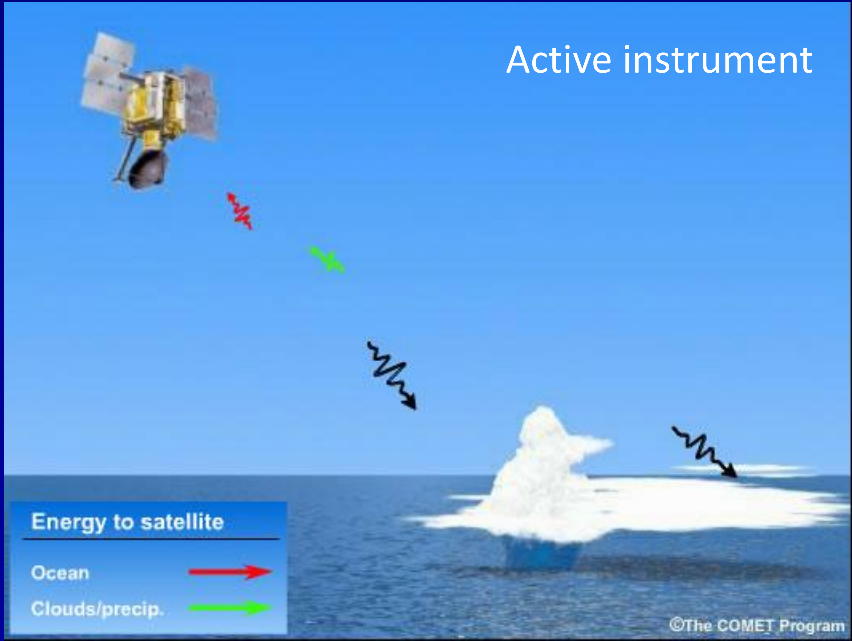

Image courtesy COMET

- LEO satellites are not continuously in view of data receiving stations
- They can only download data when they are in range of those stations, which leads to delays in data transmission and processing

# Measuring Electromagnetic Energy

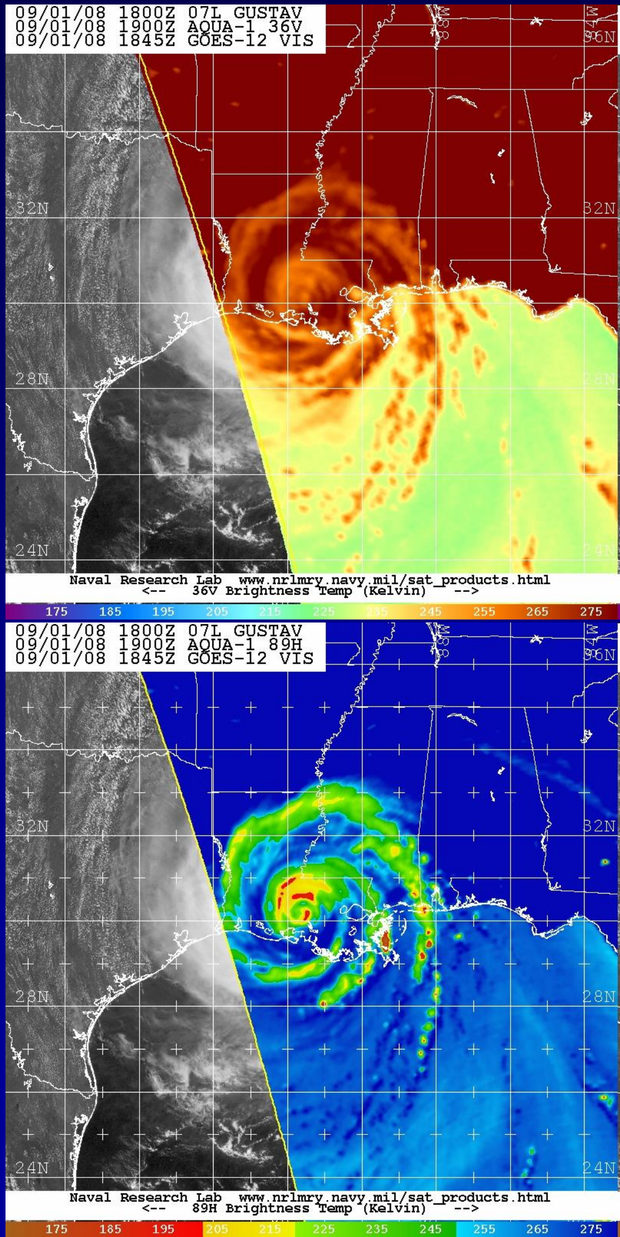
- **Passive Instruments:**
  - Receive radiation leaving the earth-atmosphere system
  - Measure solar radiation reflected by earth/atmosphere targets (visible light)
  - Measure emitted and scattered infrared radiation
  - Measure microwave radiation resulting from emission and scattering
- **Active Instruments:**
  - Send out pulses of radiation, usually at microwave frequencies
  - Measure radiation returned to the sensor
  - Examples
    - Surface-based and airborne radars
    - Satellite scatterometers



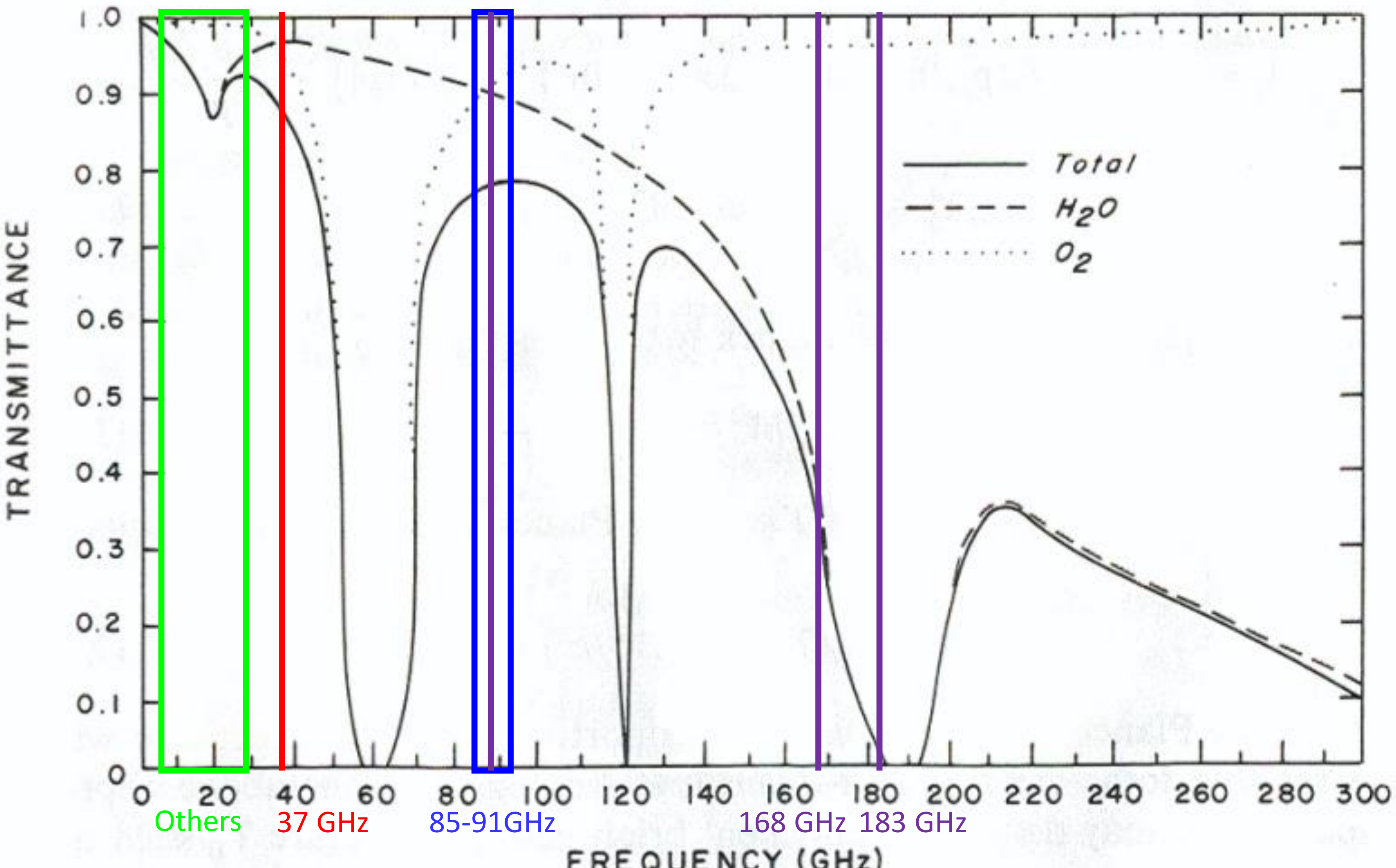



# Key Characteristics of Microwave Radiation

- Water surfaces (e.g., oceans) have low emissivity (~0.4-0.5) and appear "cold" at microwave frequencies
- Land surfaces have a much greater emissivity (~0.9)
- Raindrops have high emissivity and are "warmer"; they contrast against a "colder" ocean background
- Higher frequency (shorter wavelength) microwaves (~85 GHz) are scattered by ice particles in precipitating clouds, reducing radiation reaching the satellite (these regions also look "cold")

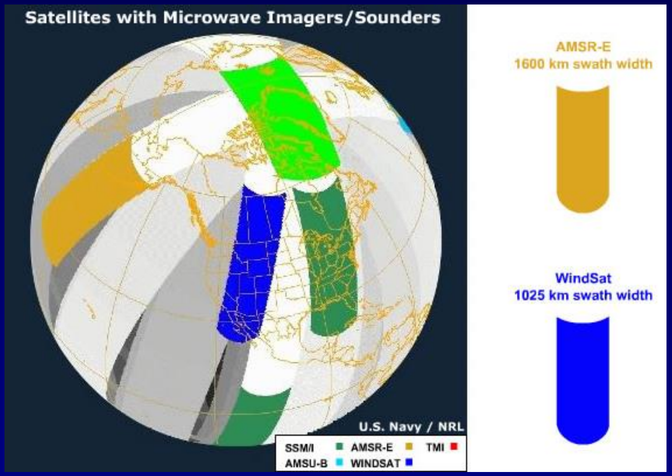


# Microwave Transmittance



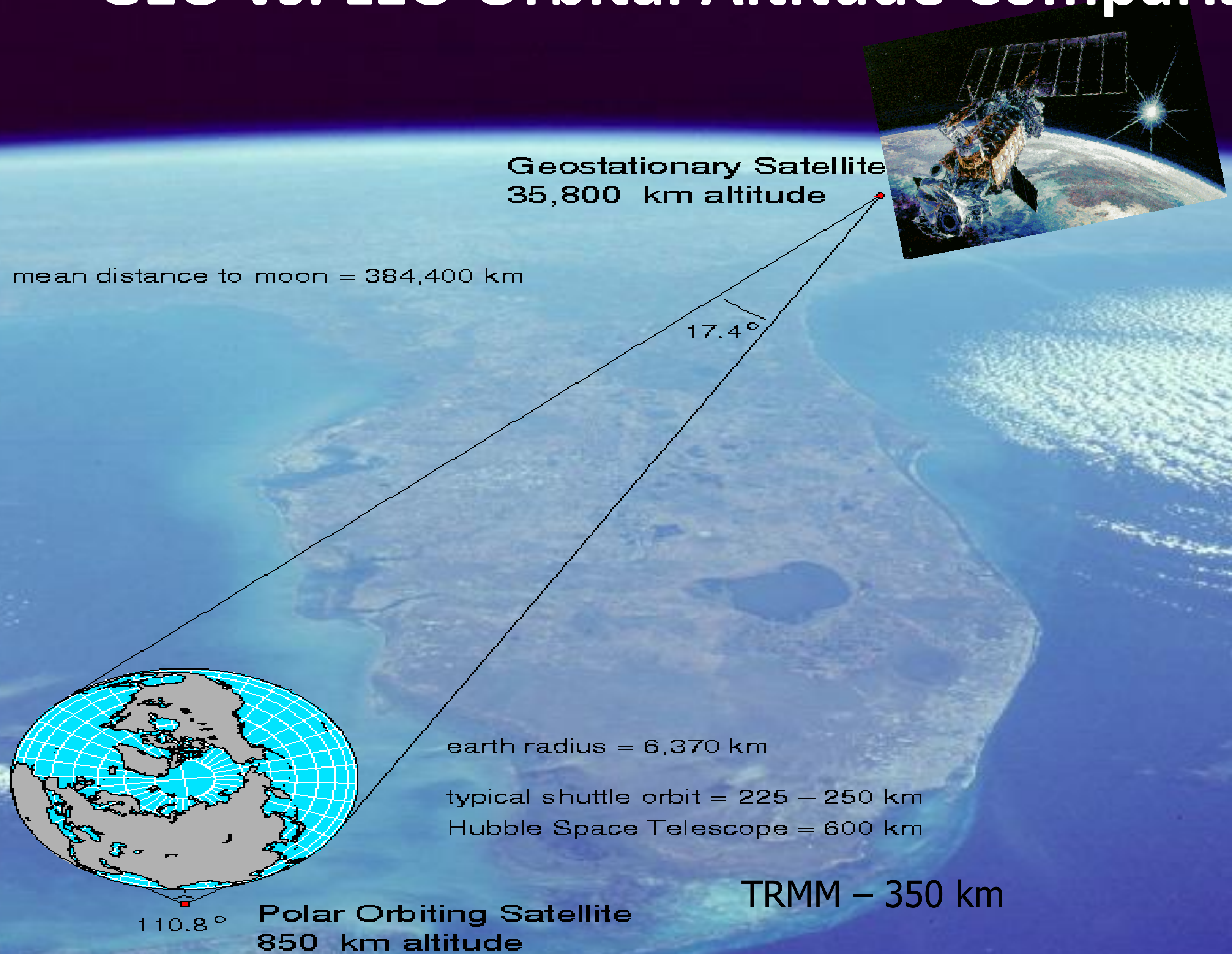
# Current/Operational Passive Microwave Imagers and Sounders/Platforms

- AMSU-A/B: 6 satellites (NOAA 18/19) and European MetOP-A/B
- SSM/I: 1 DMSP satellite (F-15)
- SSMIS: 3 DMSP satellites (F-16, F-17, F-18)
- GMI–GPM: JAXA/NASA
- AMSR2-GCOM W1: Japan (JAXA)
- WindSat: Navy NRL Coriolis (37-GHz Only)
- ATMS: NASA



# Orbital and Scan Characteristics

# GEO vs. LEO Orbital Altitude Comparison




TRMM – 350 km



Image courtesy of http://www.nrlmry.navy.mil

# Sun-Synchronous Daily Orbital Path

**~12 hr to observe the entire Earth**
**Same location twice daily (ascending/descending)**

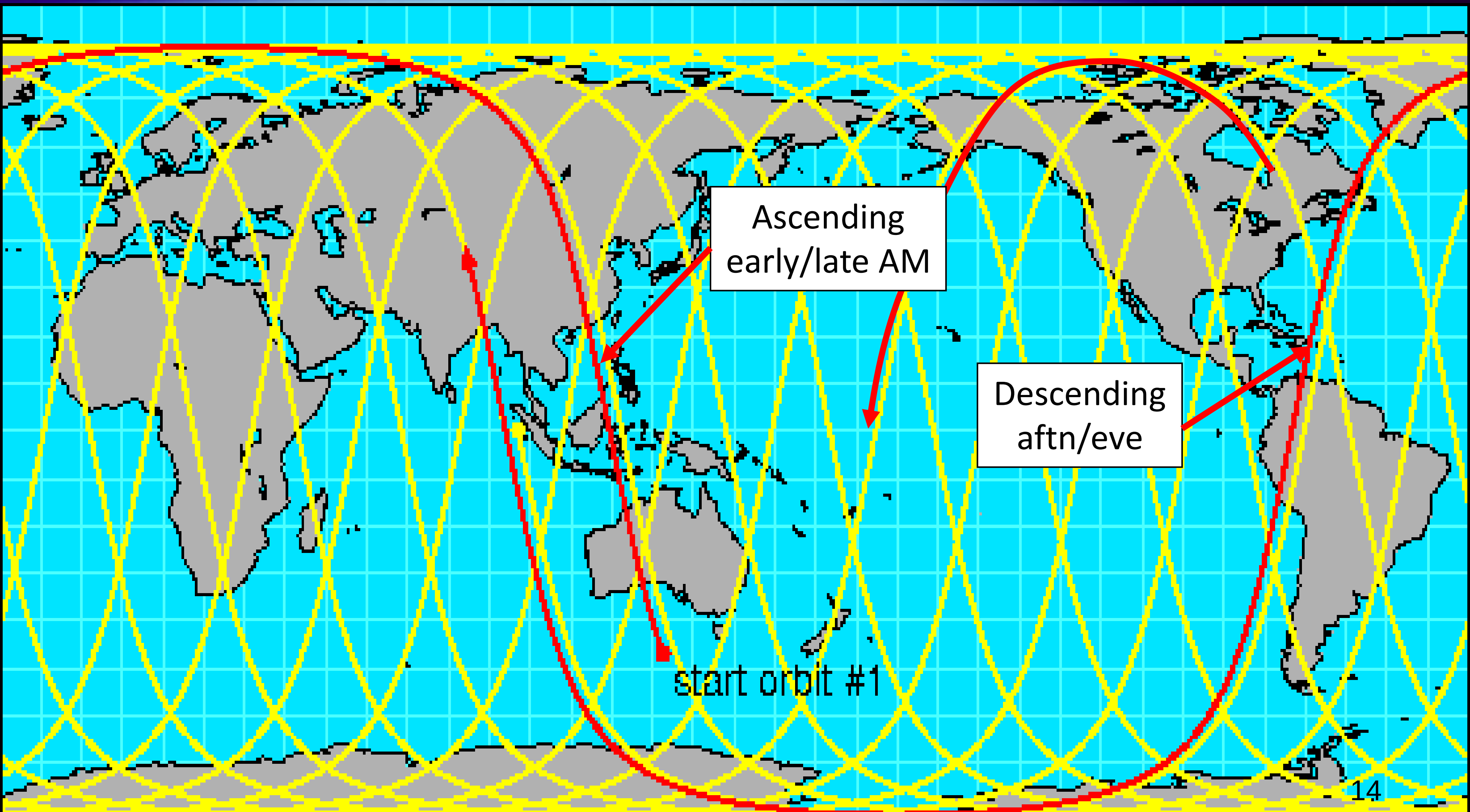
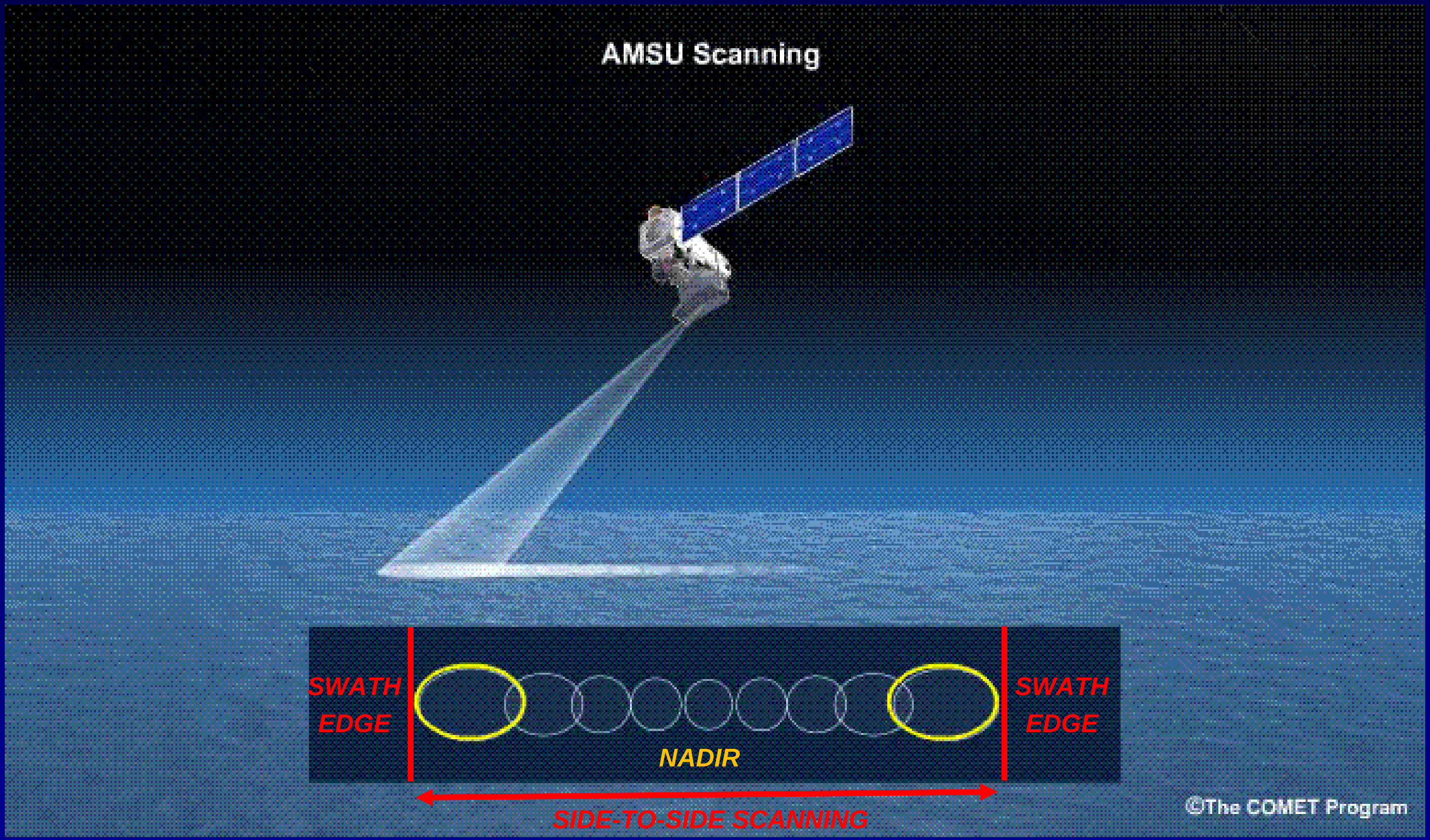


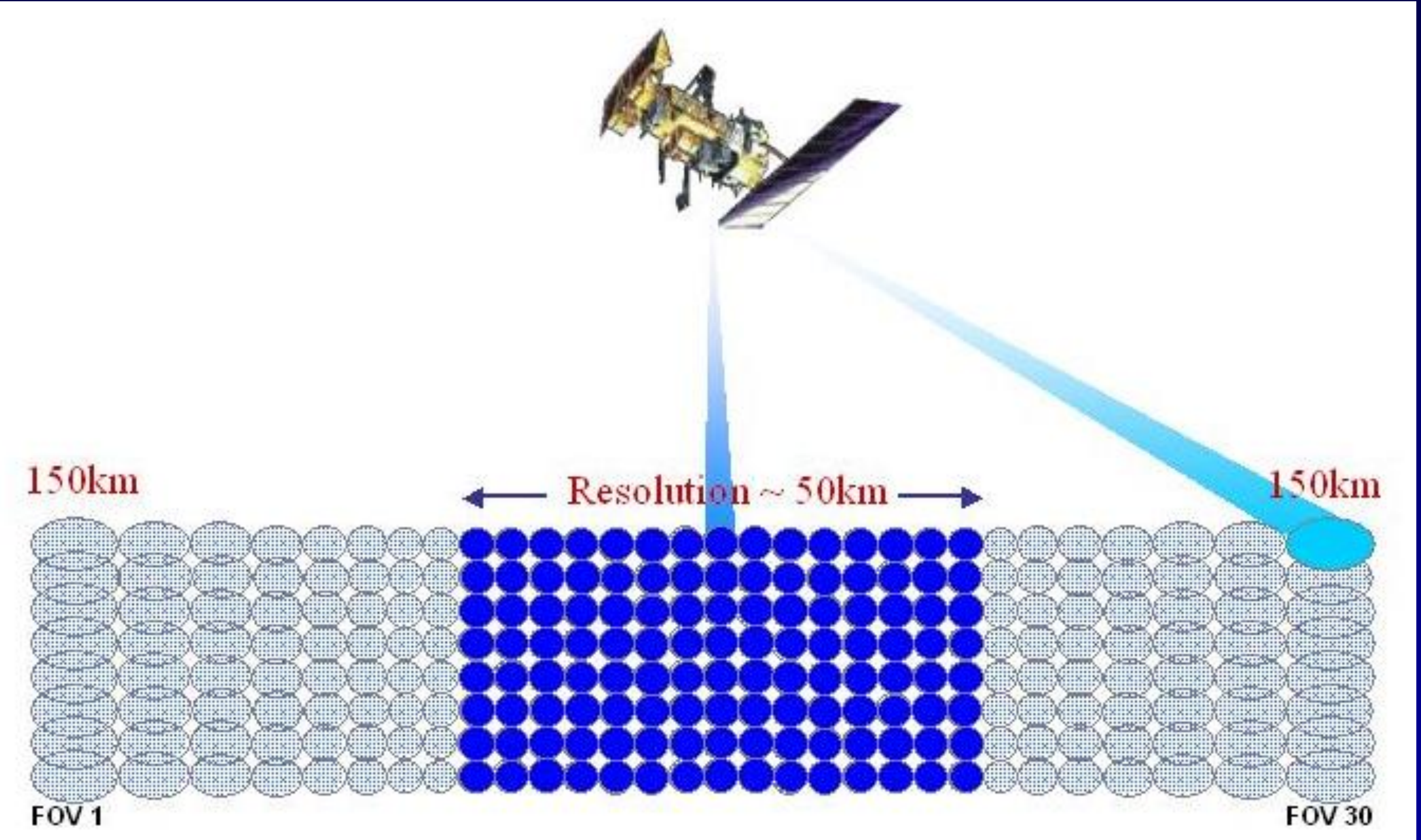

Image courtesy of http://www.nrlmry.navy.mil

# Cross Track Scan Strategy



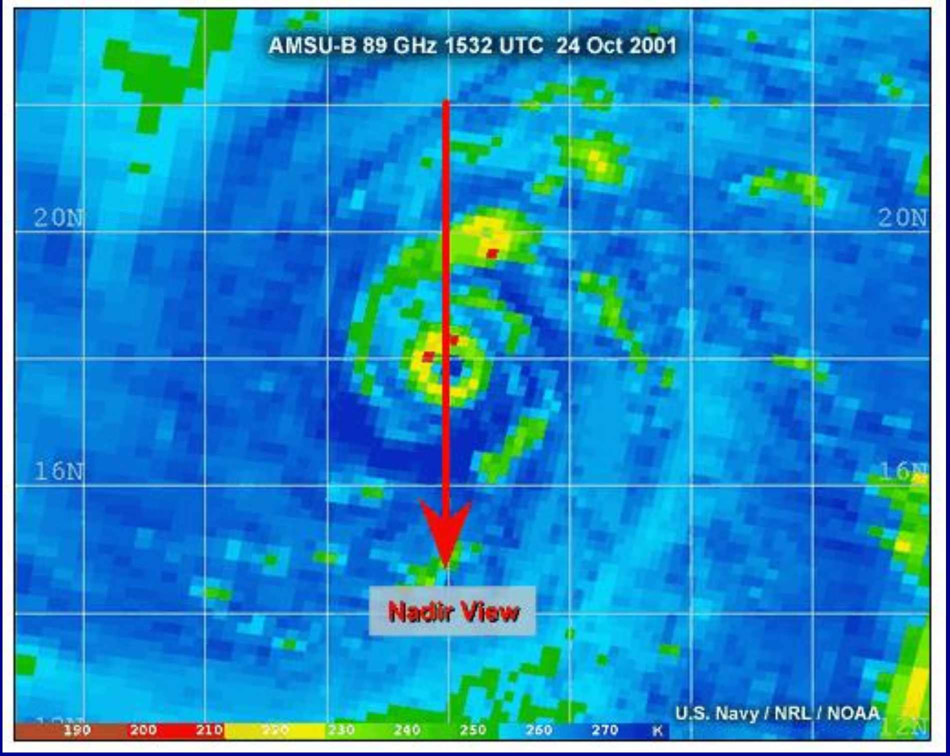

- **Advantage**: Larger coverage swath relative to conical scan
- **Disadvantage**: Resolution varies across the swath (coarser resolution at swath edge relative to nadir)

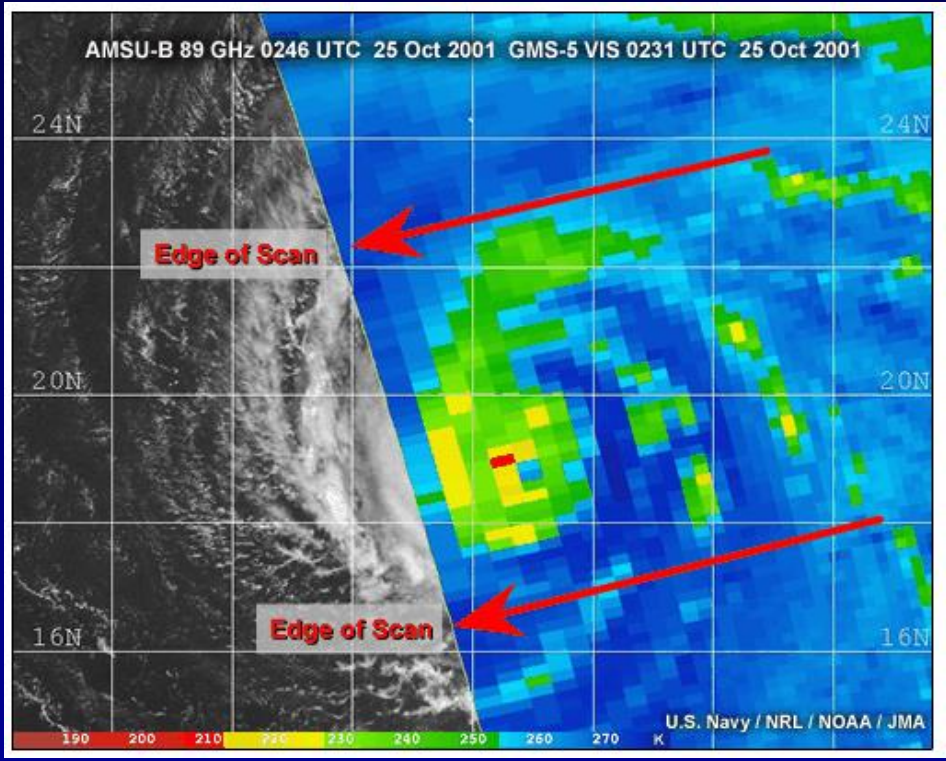
# Cross Track Scan Strategy



AMSU Scanning Geometry and Resolution

# Cross Track Scan Strategy

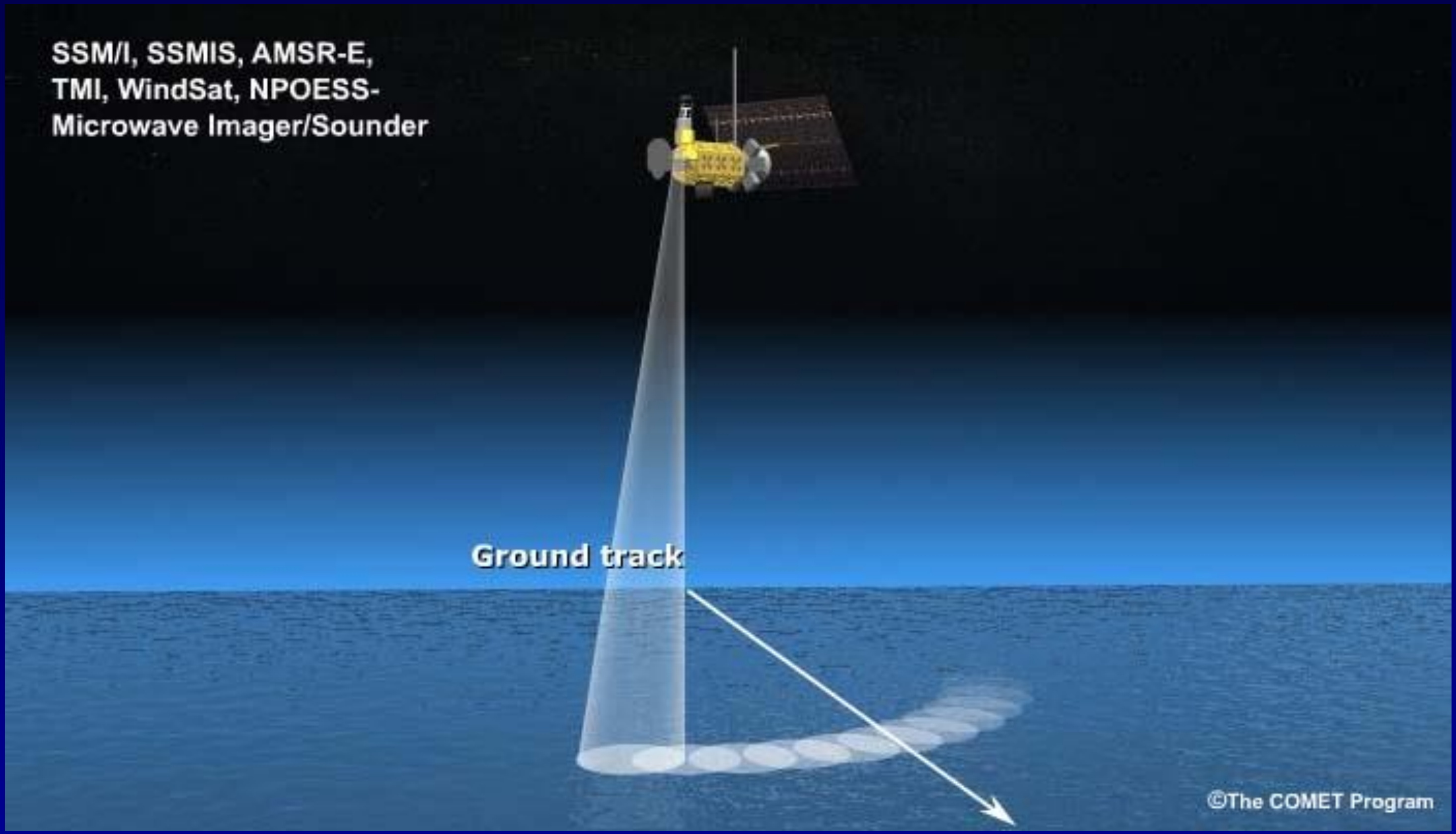



Note degradation in resolution at edge of scan compared to nadir

Images courtesy COMET

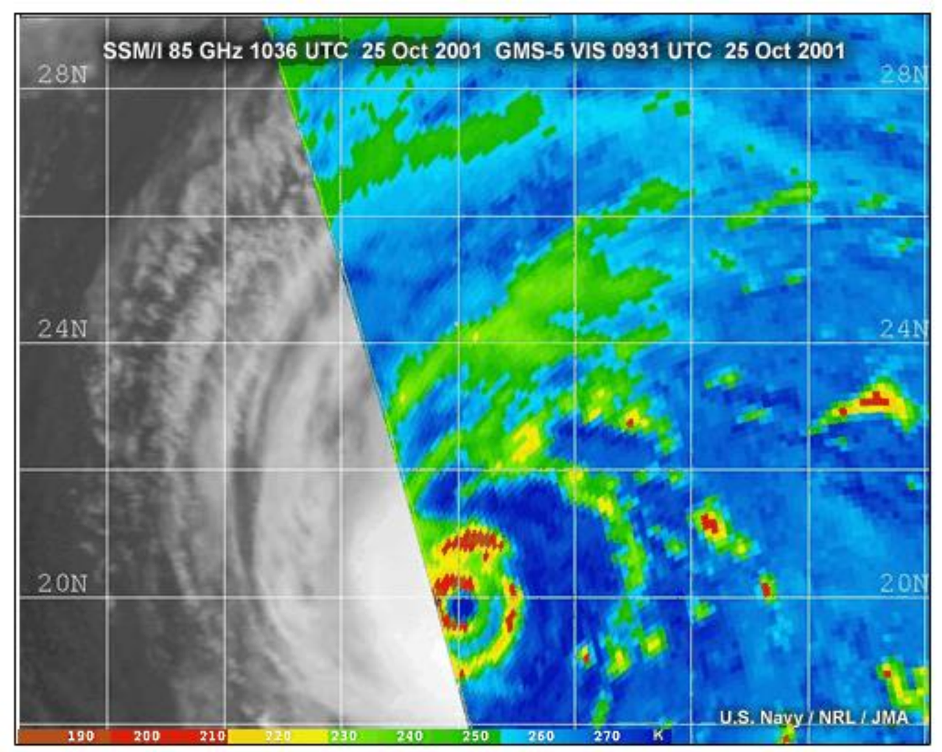
# Conical Scan Strategy

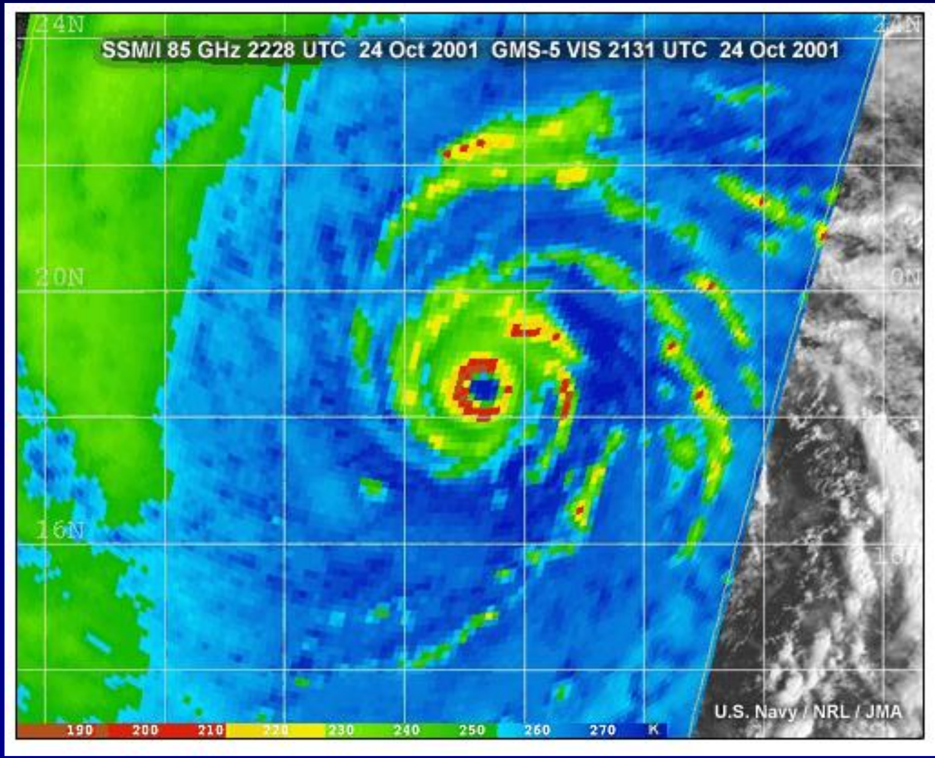



- Advantage: Resolution remains constant because scan footprints are the same size throughout the entire swath

- Disadvantage: Narrower coverage swath relative to cross-track scan

# Conical Scan Strategy



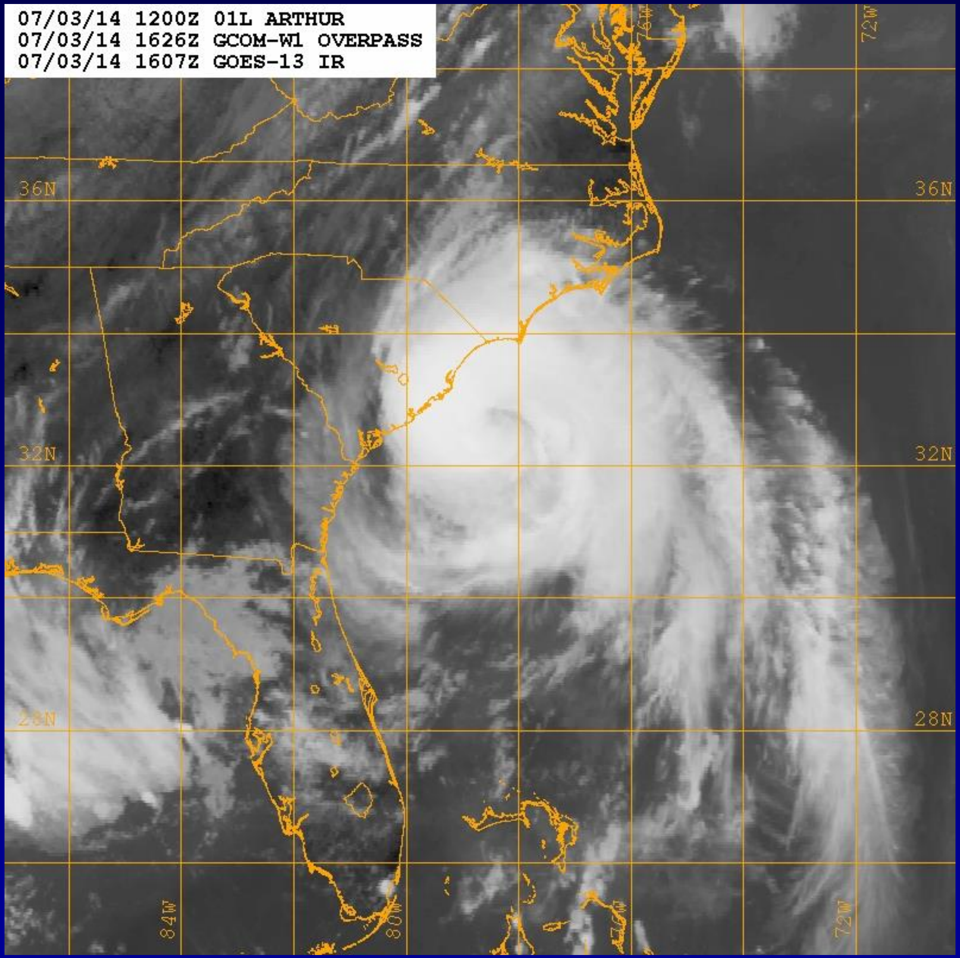

Resolution remains constant across swath

Images courtesy COMET

# Imagery Characteristics and Applications

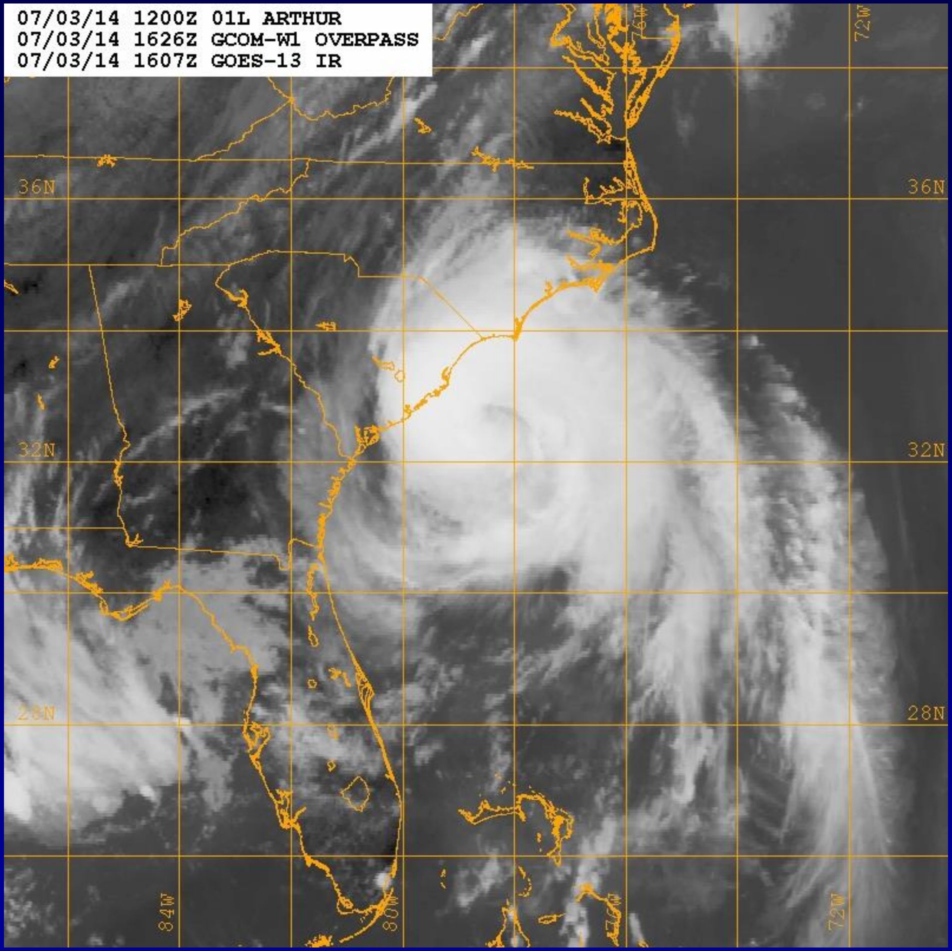
# 85-GHZ Imagery Interpretation

- Imagery can penetrate through clouds and reveal internal storm structure
- Land appears warm relative to water surfaces
- Water surfaces and deep convection appear relatively cold (due to scattering from ice)
- Low-level moist air masses act to warm brightness temperatures over water surfaces
- Imagery is better at locating tropical cyclone centers than conventional visible and infrared
- Imagery is able to distinguish deep convection, but can not always see low-level circulations associated primarily with low-level clouds
- Offers higher spatial resolution than imagery at lower microwave frequencies



# 37-GHZ Imagery Interpretation

- Precipitating clouds and land surface appear warm against a relatively cold ocean background
- Cold features: sea surface only
- Imagery highlights low-level cloud features and storm structure
- Imagery identifies cirrus-covered eyes and gives a ‘true’ low-level center instead of a mid/upper-level center (as in 85-91 GHz imagery)

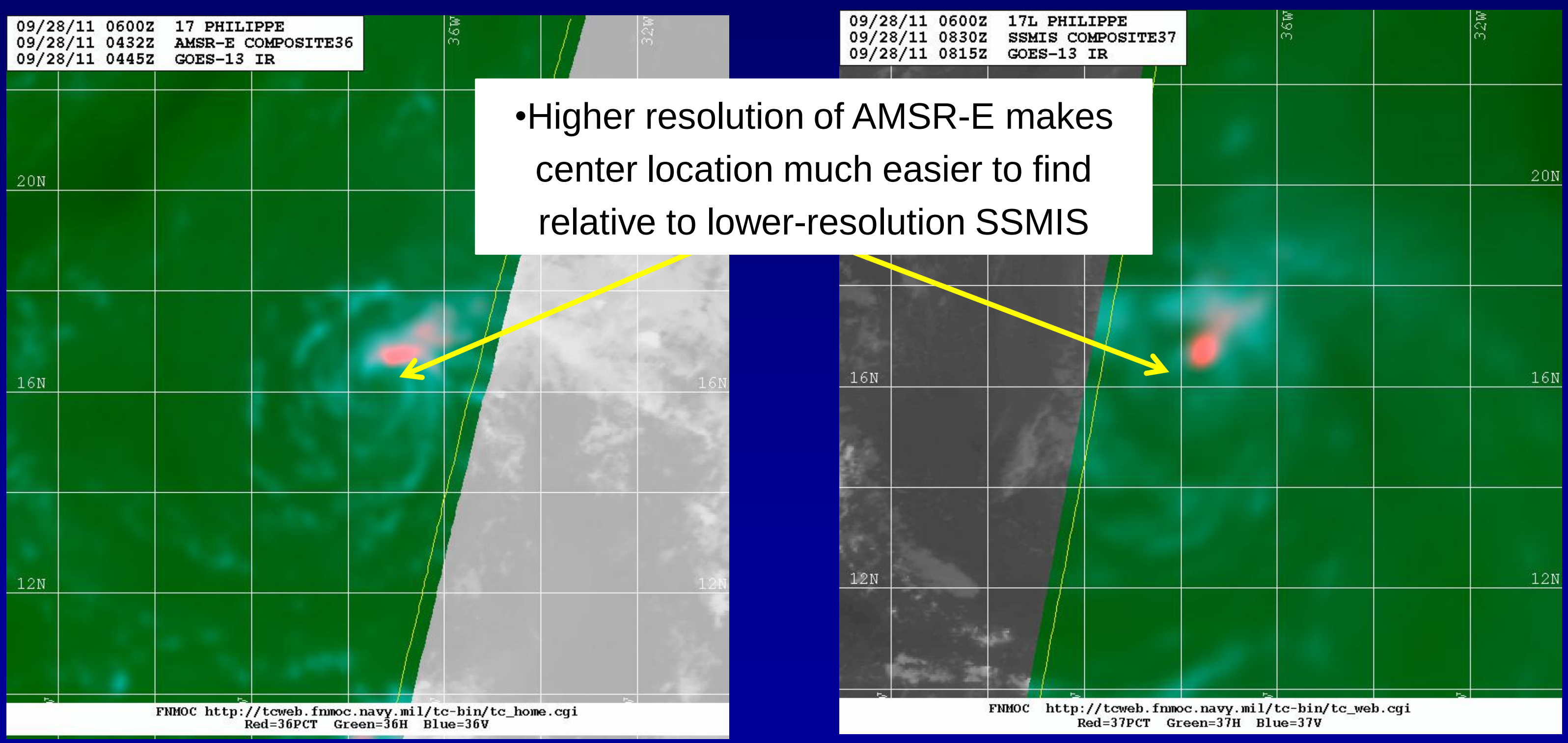


# Advantages of Using 85-GHz and 37-GHz Imagery for TC Analysis

- In a sense, “sees” through clouds
- Identification of circulation center (critical step in initiating TC advisories)
- Acquire positioning of TCs in difficult situations (especially in early stages of development and at night)
- View of convective rain bands is more directly related to intensification of the TC
- Monitoring structural changes such as eyewall formation and eyewall replacement cycles

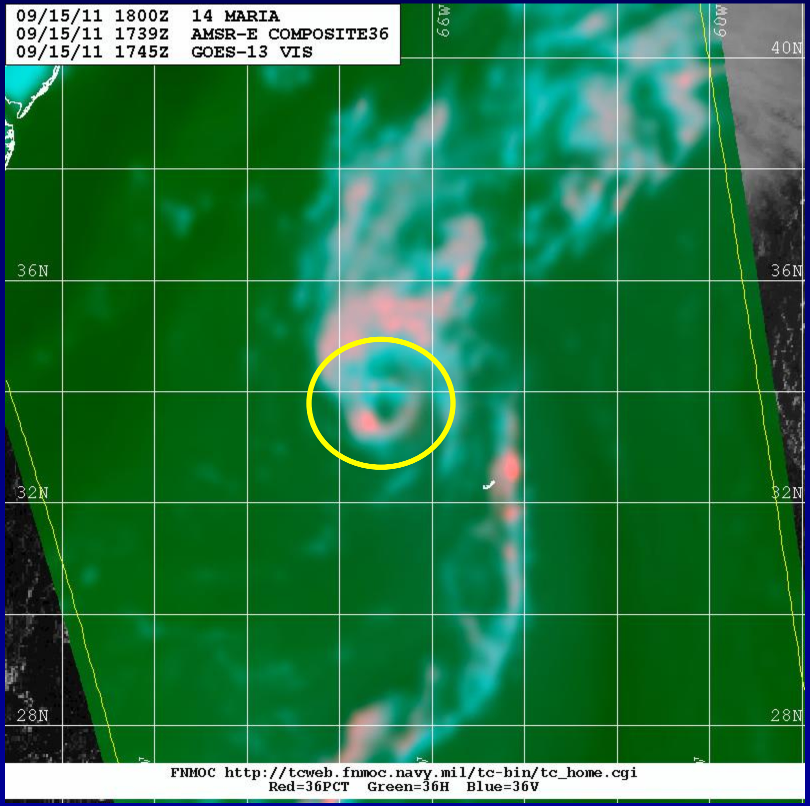
# Effects of Resolution

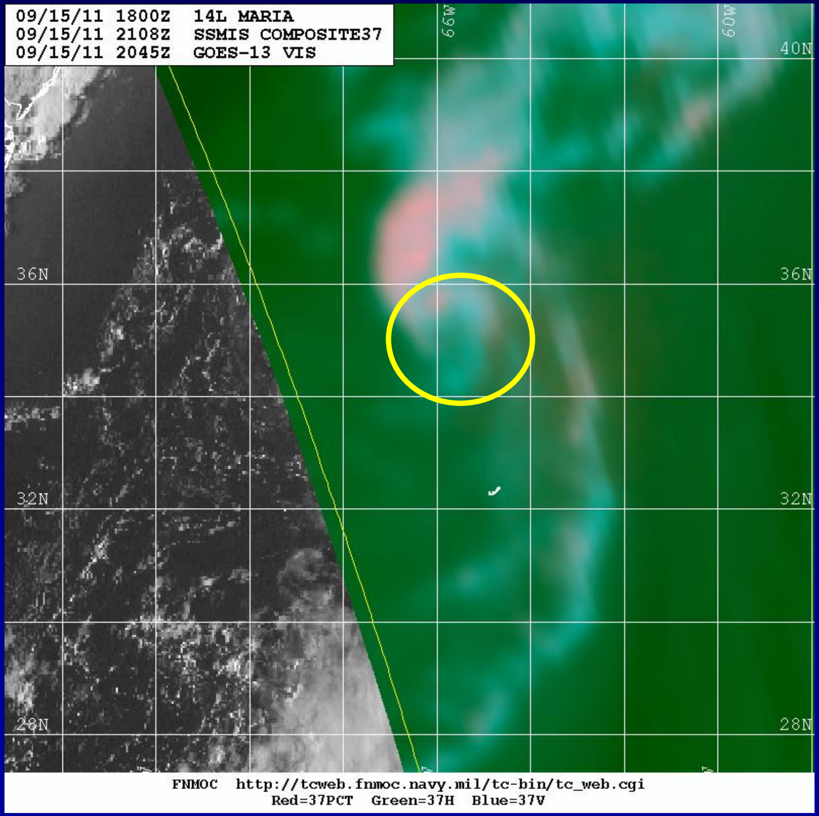
- Comparison of 36/37-GHz color composite imagery over TS Philippe from AMSR-R (left) and SSMIS (right) at 0432 UTC and 0830 UTC 28 September 2011, respectively – Images courtesy FNMOC TC webpage



# Effects of Resolution

- Resolution differences also affect the ability to resolve low to mid-level eyewall structure

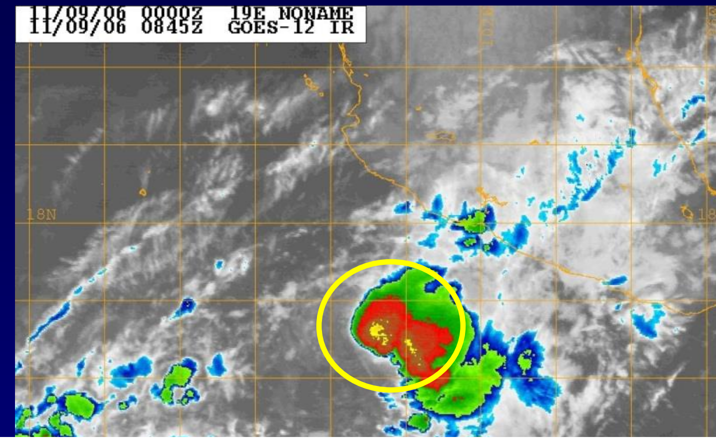


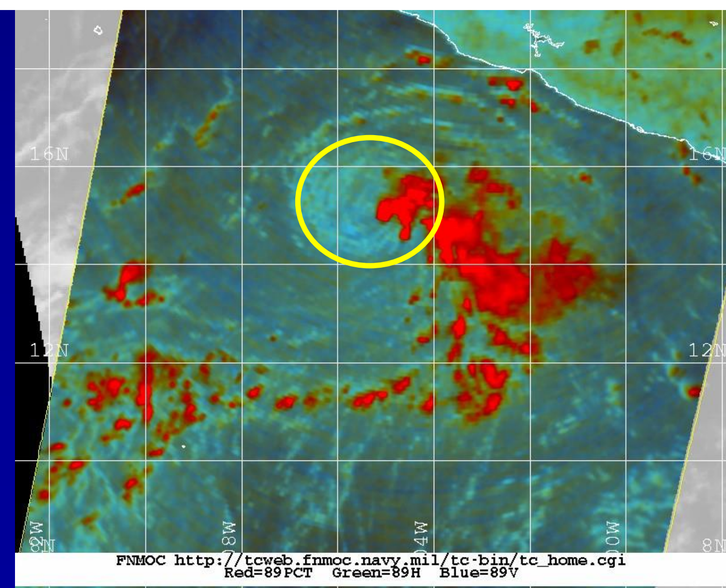

•Comparison of 36/37-GHz color composite imagery over Hurricane Maria from AMSR-E (left) and SSMIS (right) at 1739 UTC and 2018 UTC 15 September 2011, respectively – Images courtesy FNMOC TC webpage

# Importance of Center Location

- Locating the center of a tropical cyclone is critical to establishing initial motion, initializing model guidance, and assessing the organization and intensity of the cyclone
- Microwave imagery, especially at the 36/37-GHz channels helps improve position estimates for Dvorak intensity estimates and provide better fix-to-fix continuity
- <u>Dvorak estimates are very sensitive to incorrect center locations at certain stages of development</u>, especially for sheared systems and systems with embedded centers in infrared imagery




There is a large difference in the Dvorak intensity estimate if the center is located in the deep convection or exposed well to the west
Tropical Storm Rosa – 9 November 2006



# Parallax Error in Center Fixing

- Satellite-derived position error exists, potentially up to 20 km (~10.8 n mi)  from actual position

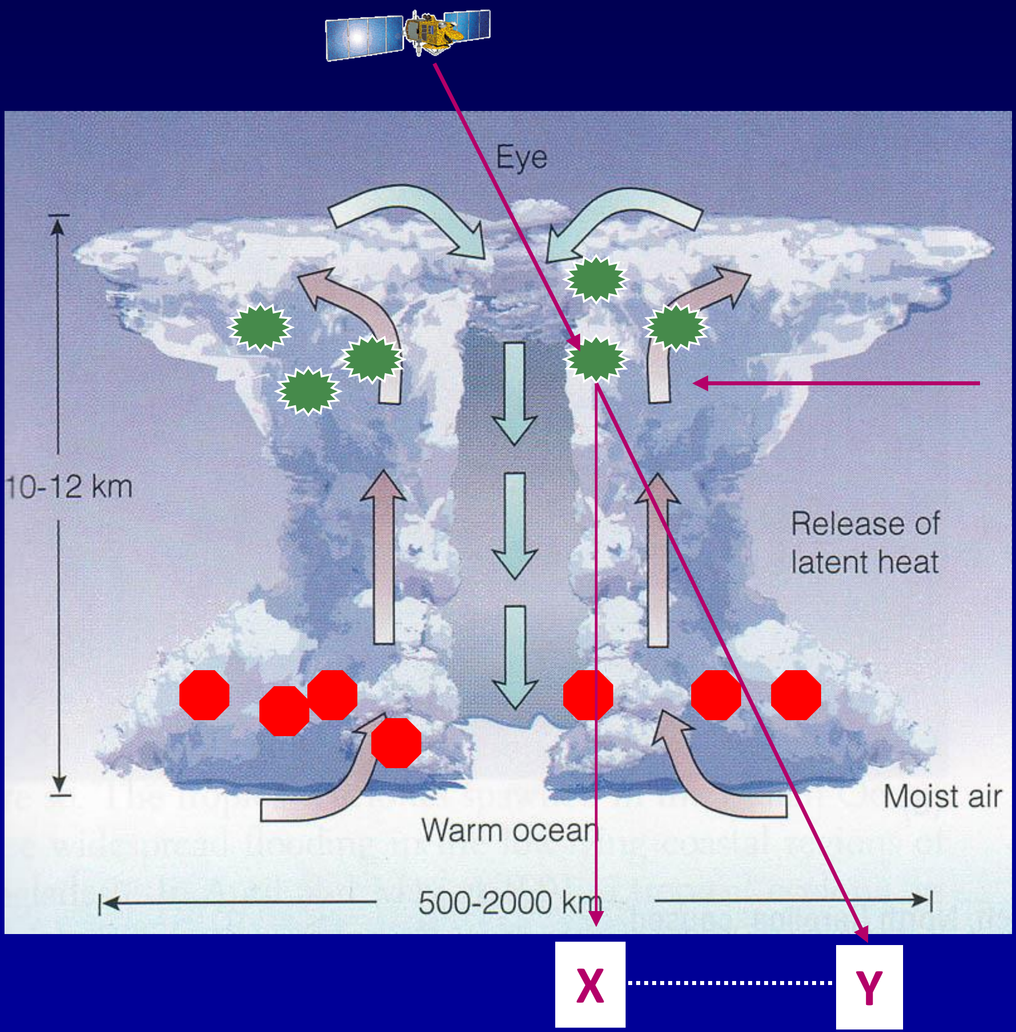
- Occurs due to conical viewing angle and/or viewing geometry of the satellite

- Higher parallax error in 85-GHz images since scattering hydrometeors produce a signature much higher in the eyewall at  85 GHz  than at  37 GHz

# 85-GHz Parallax

Ice Crystals (85 GHz)

Raindrops (37 GHz)



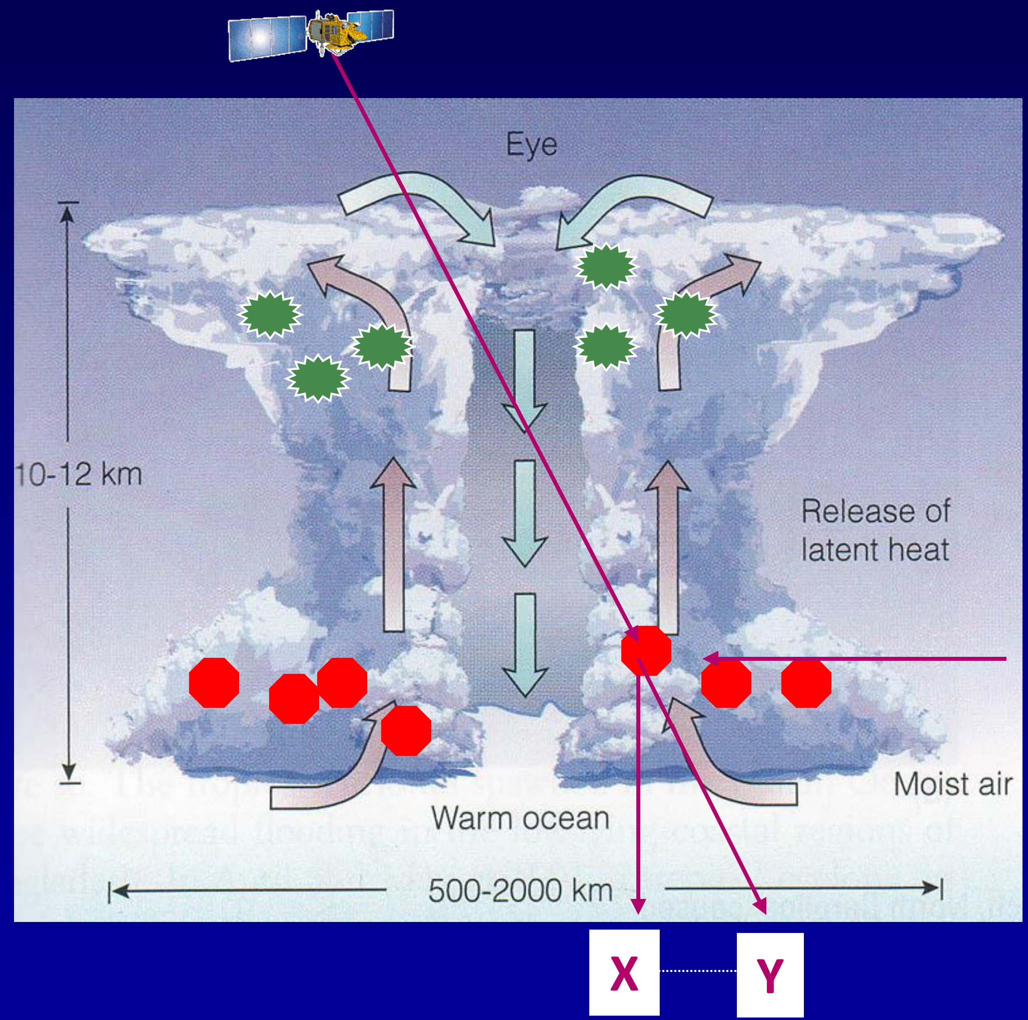

Effective Level of hydrometeors

85 GHz Parallax

# 37-GHz Parallax

Ice Crystals (85 GHz)

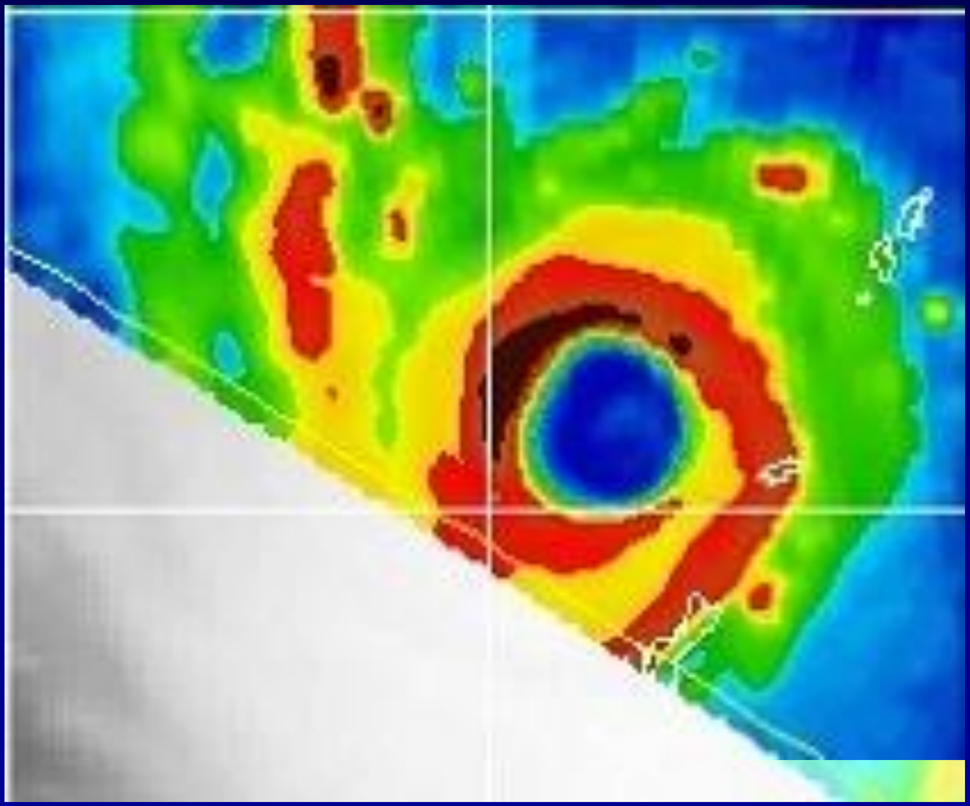
Raindrops (37 GHz)




Effective Level of hydrometeors

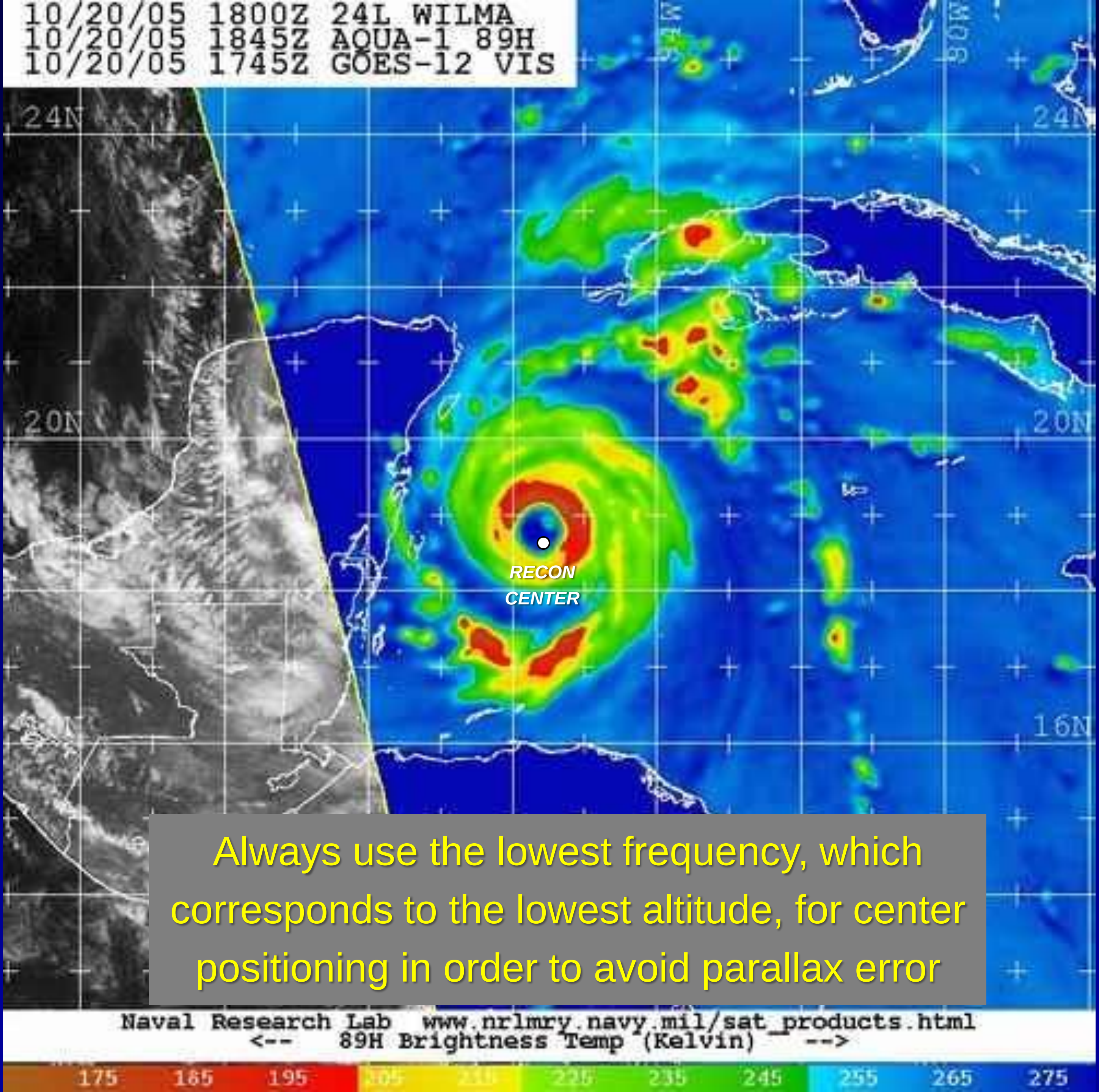
37 GHz Parallax

# Eye Size Example



85 H

37 V

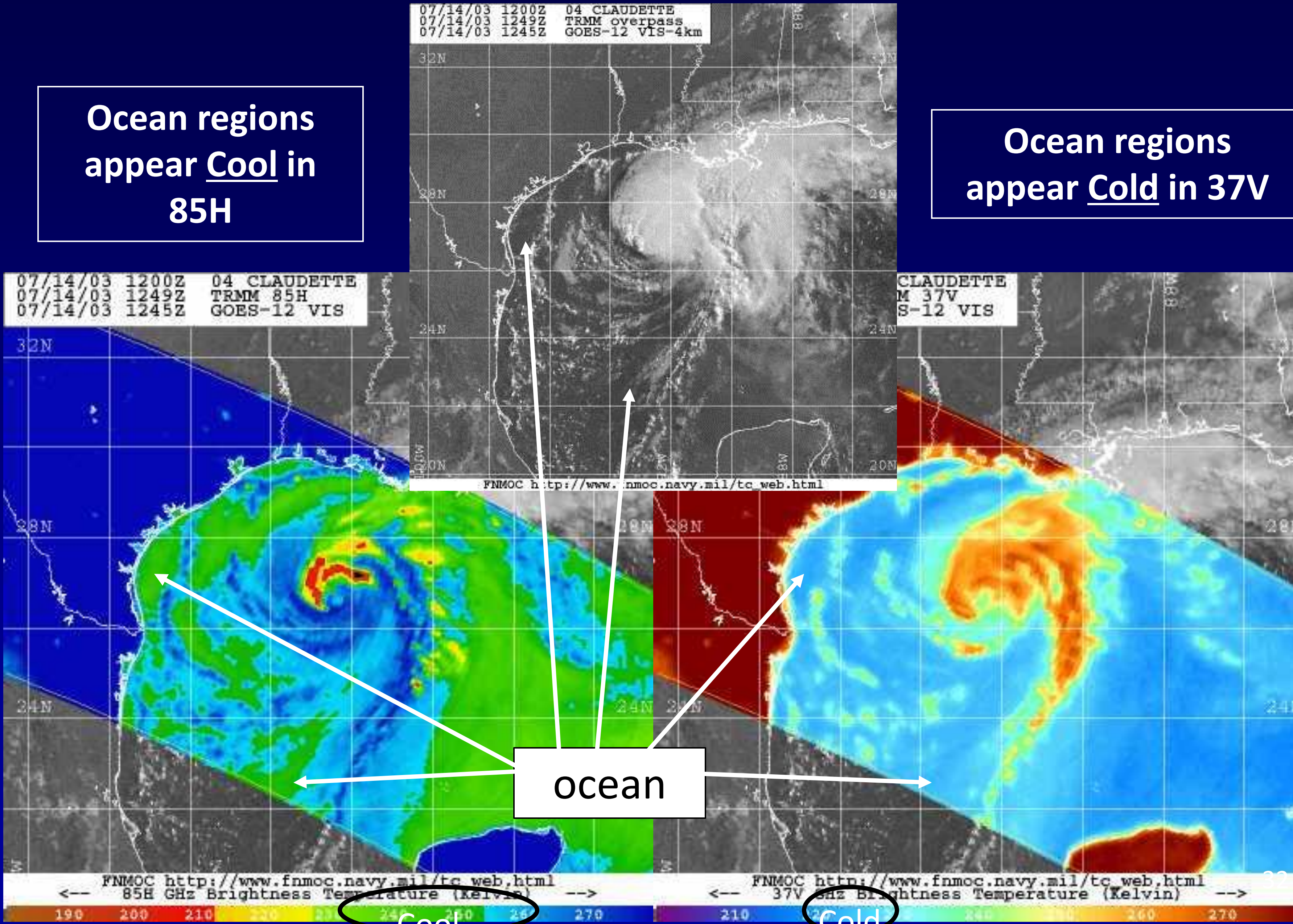



Always use the lowest frequency, which corresponds to the lowest altitude, for center positioning in order to avoid parallax error

# Single Frequency Interpretation

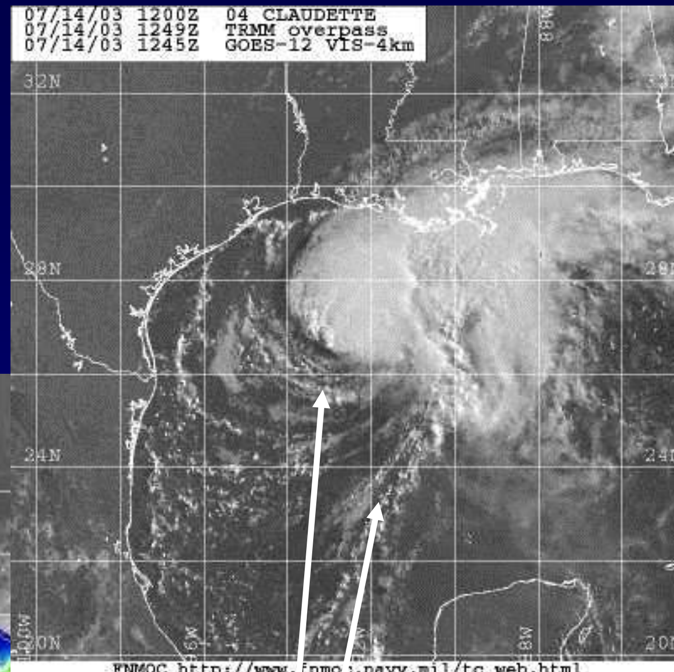
Ocean regions appear Cool in 85H

Ocean regions appear Cold in 37V

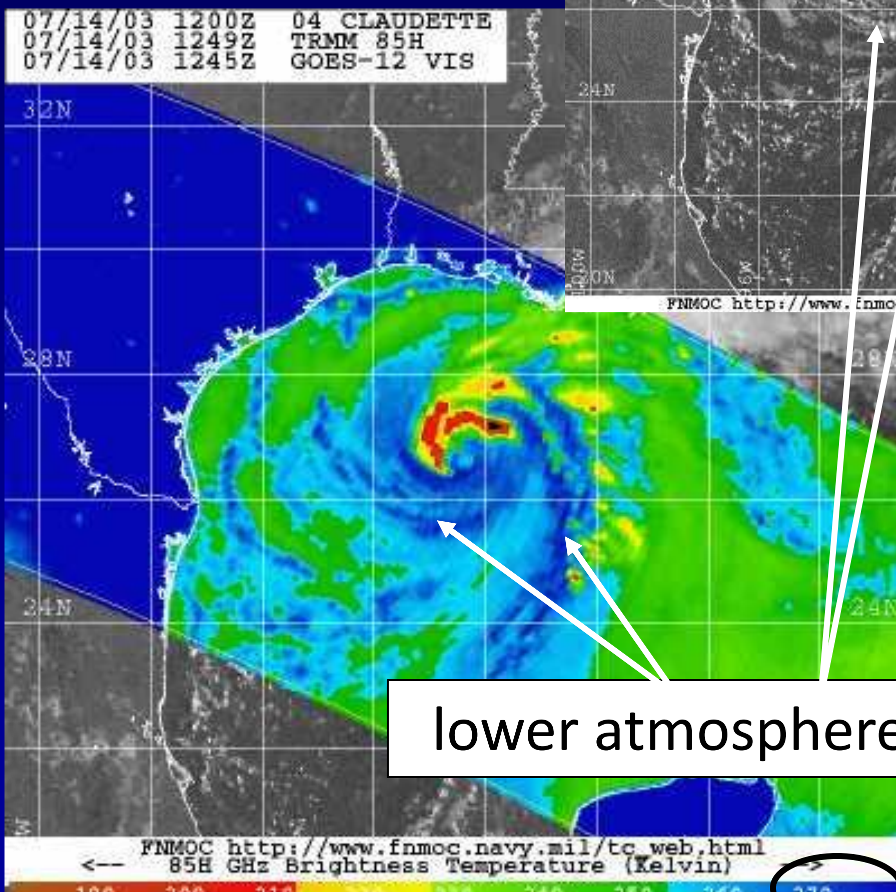


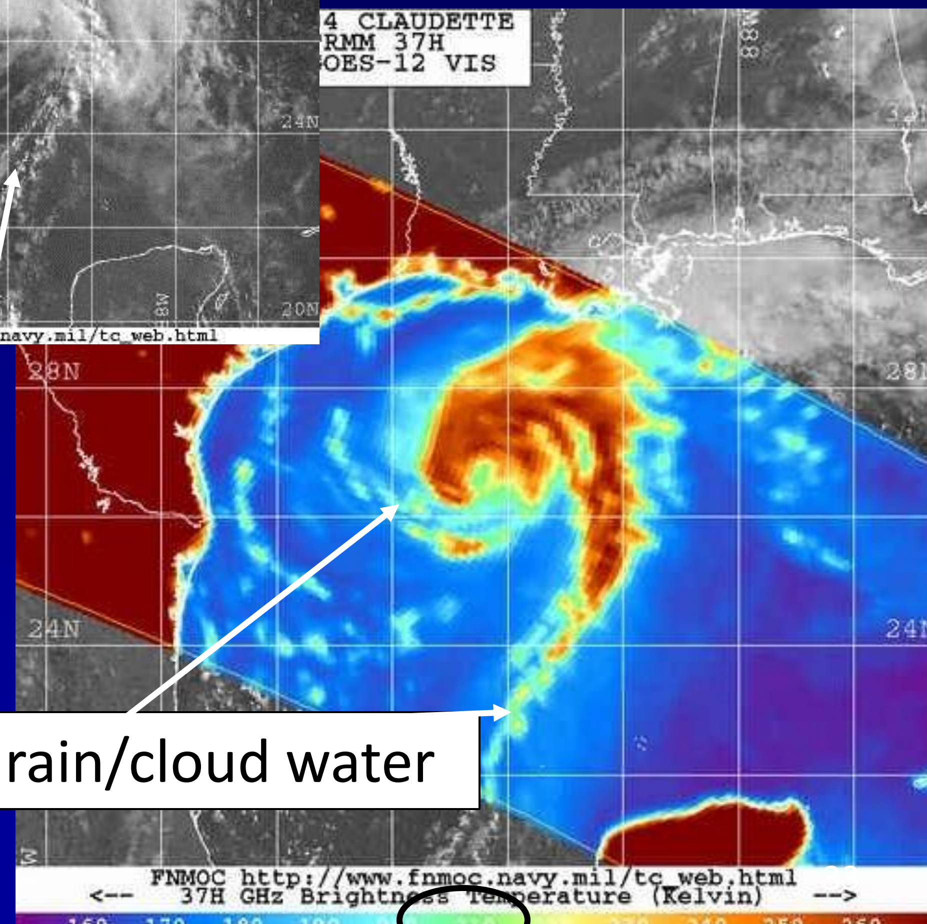
# Single Frequency Interpretation

Rain appears **Warm** in 85H




Lower-based Rain appears **Cool** in 37H



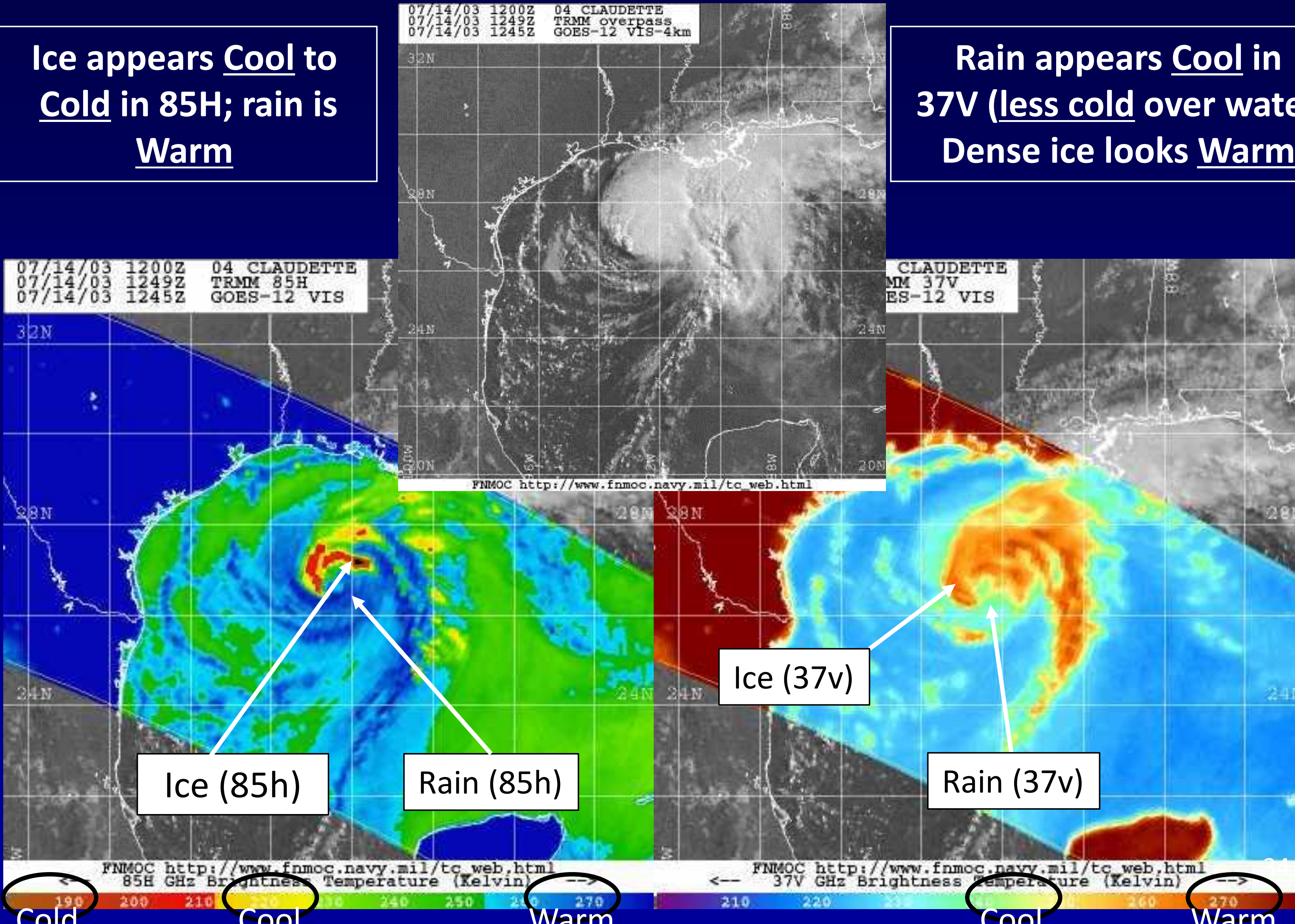



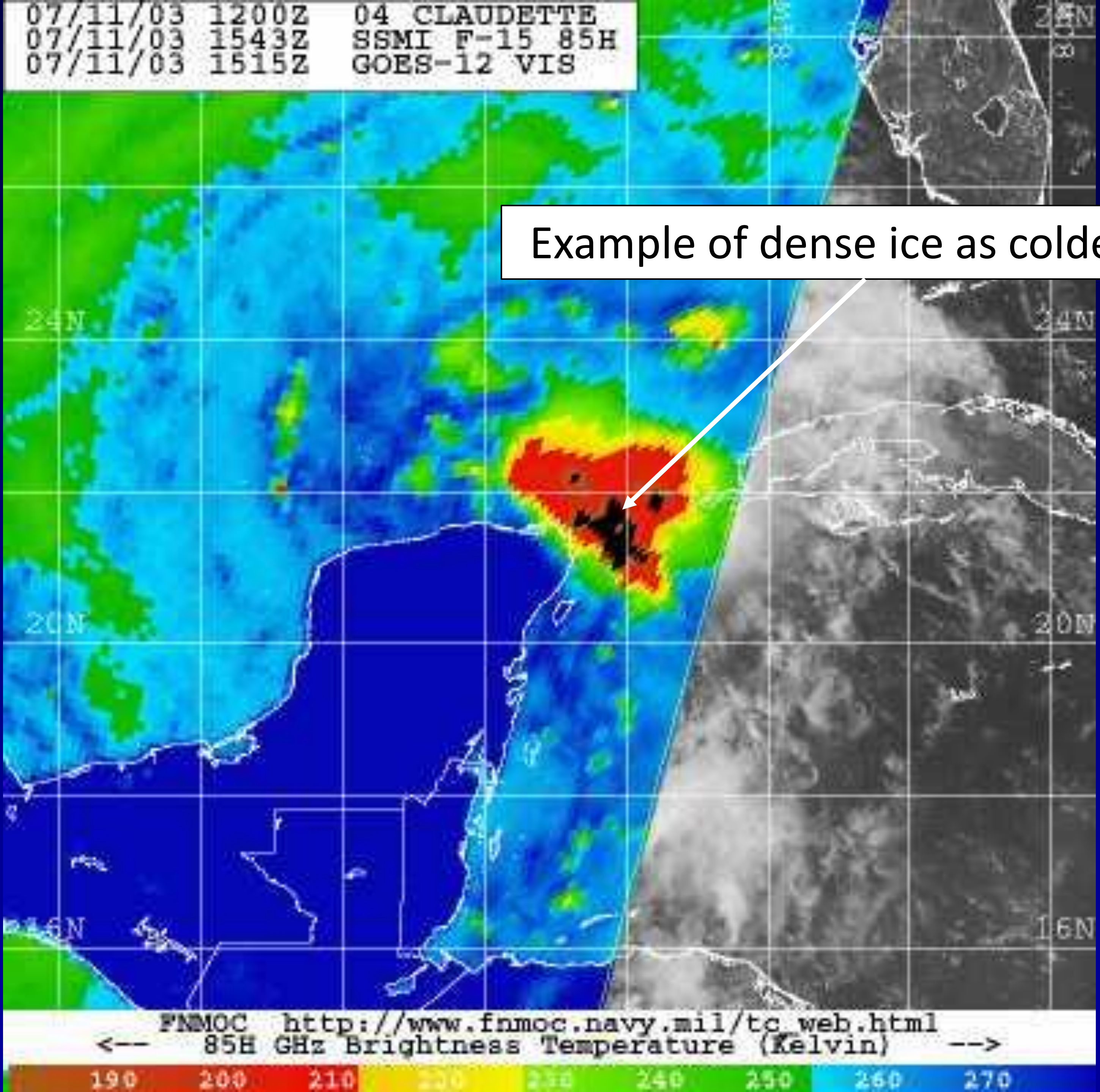

lower atmosphere rain/cloud water

# Single Frequency Interpretation

Ice appears Cool to Cold in 85H; rain is Warm

Rain appears Cool in 37V (less cold over water) Dense ice looks Warm



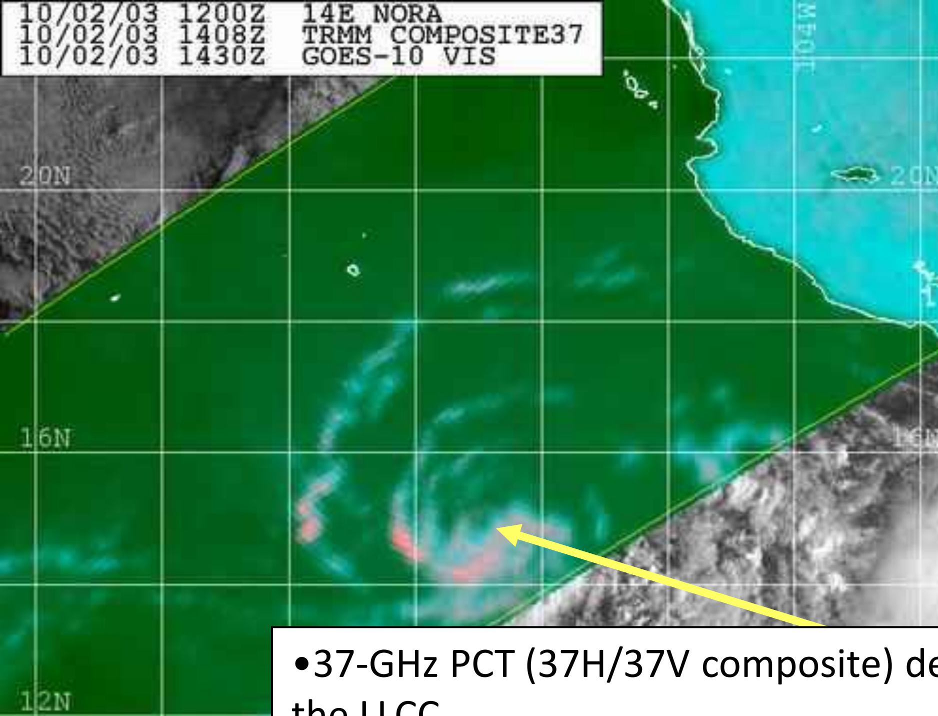


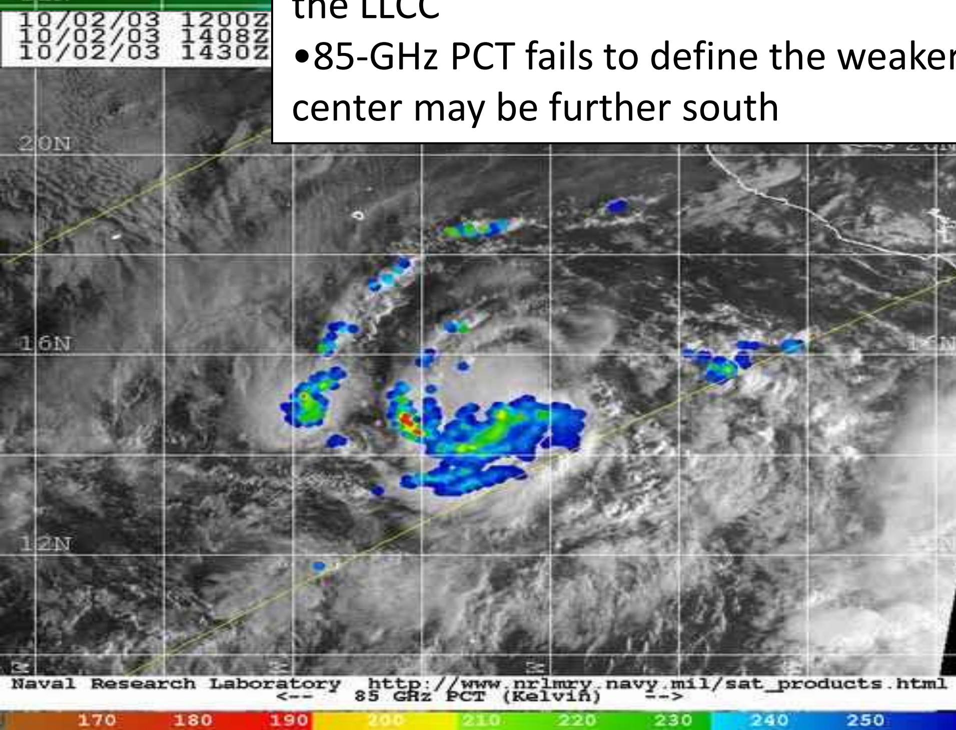

Example of dense ice as coldest $T_b$

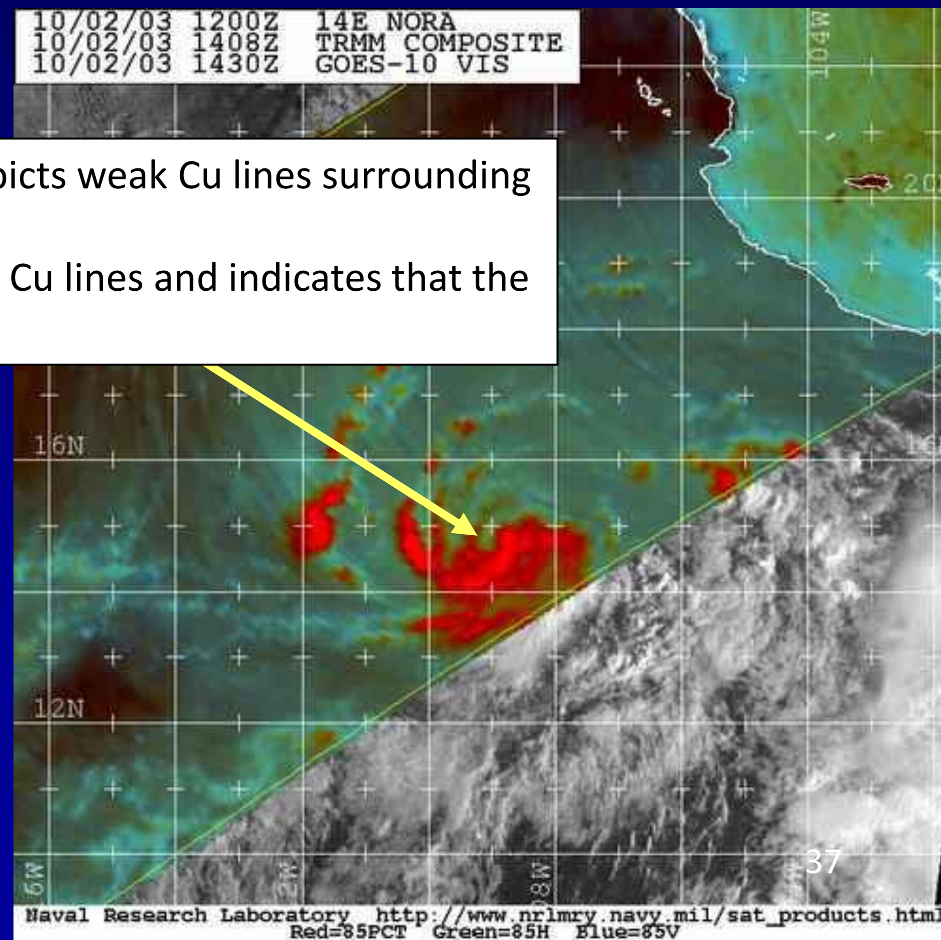
# Color Composite Imagery

- Significant ambiguities (convection/sea surface, land features) exist when interpreting single frequency 85/37-GHz images
- Polarization Correction Temp (PCT) and color composite images correct $T_b$ in regions of little or no clouds or rain (low emissions) to approximately the surface air temperature
- Color composite images combine PCT with V and H polarizations to remove ambiguities between convection and the sea surface
  - 85 color composite- PCT (red), V (blue), H (green)
    - Deep convection (red)
    - Low-level clouds, water vapor, warm precipitation (blue-green)
    - Relatively cloud-free (gray or black)
  - 37 color composite- PCT (red), V (green), H (blue)
    - Deep Convection/intense ice scattering (pink)
    - Rain/clouds (cyan)
    - Sea surface (green)

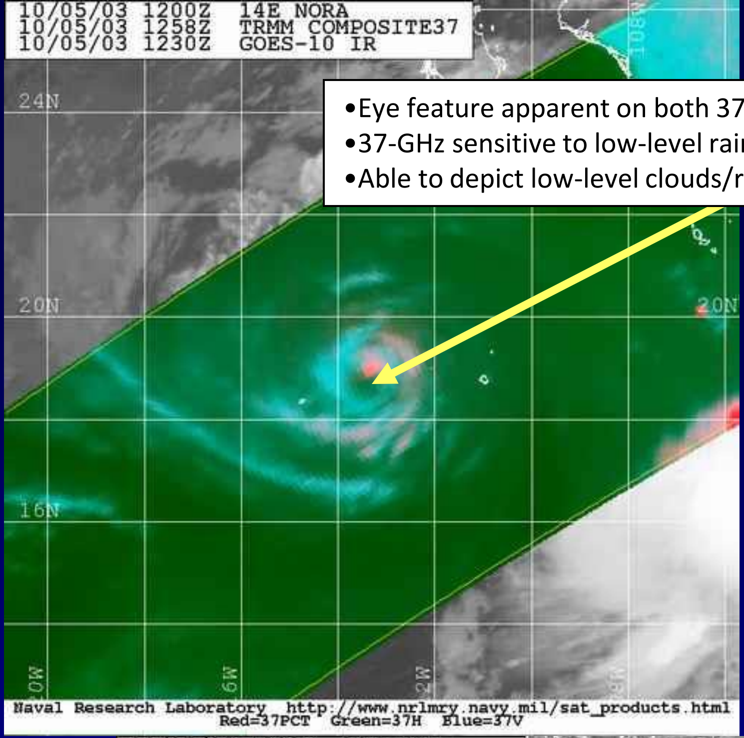
# Color Composite

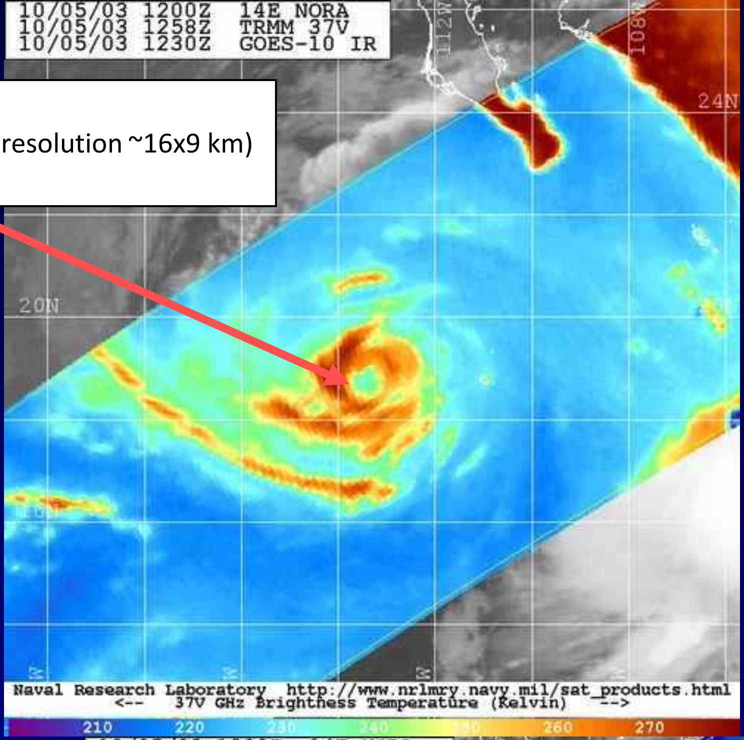


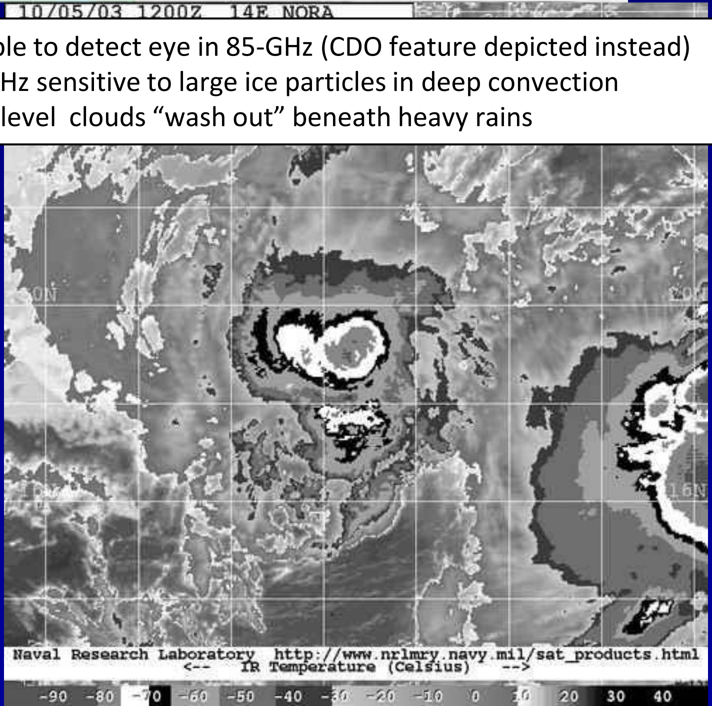




- 37-GHz PCT (37H/37V composite) depicts weak Cu lines surrounding the LLCC
- 85-GHz PCT fails to define the weaker Cu lines and indicates that the center may be further south

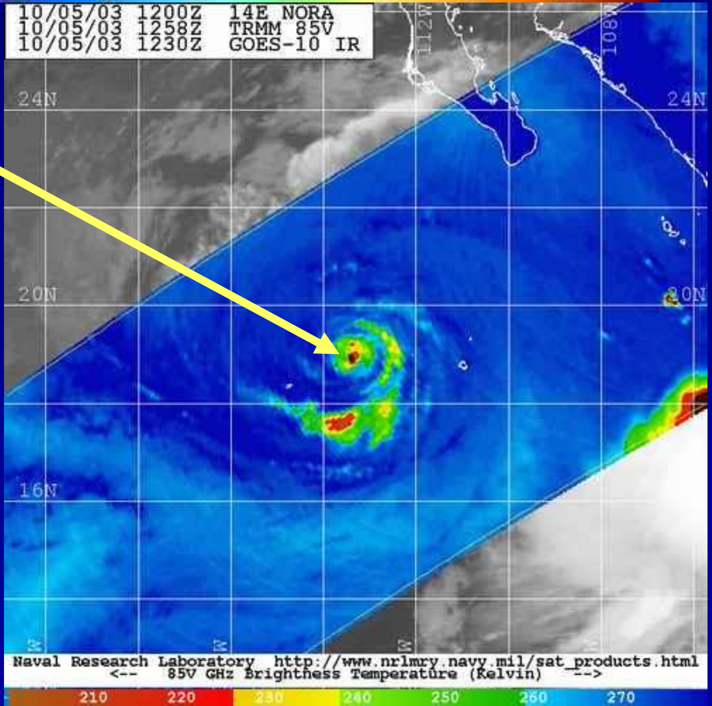


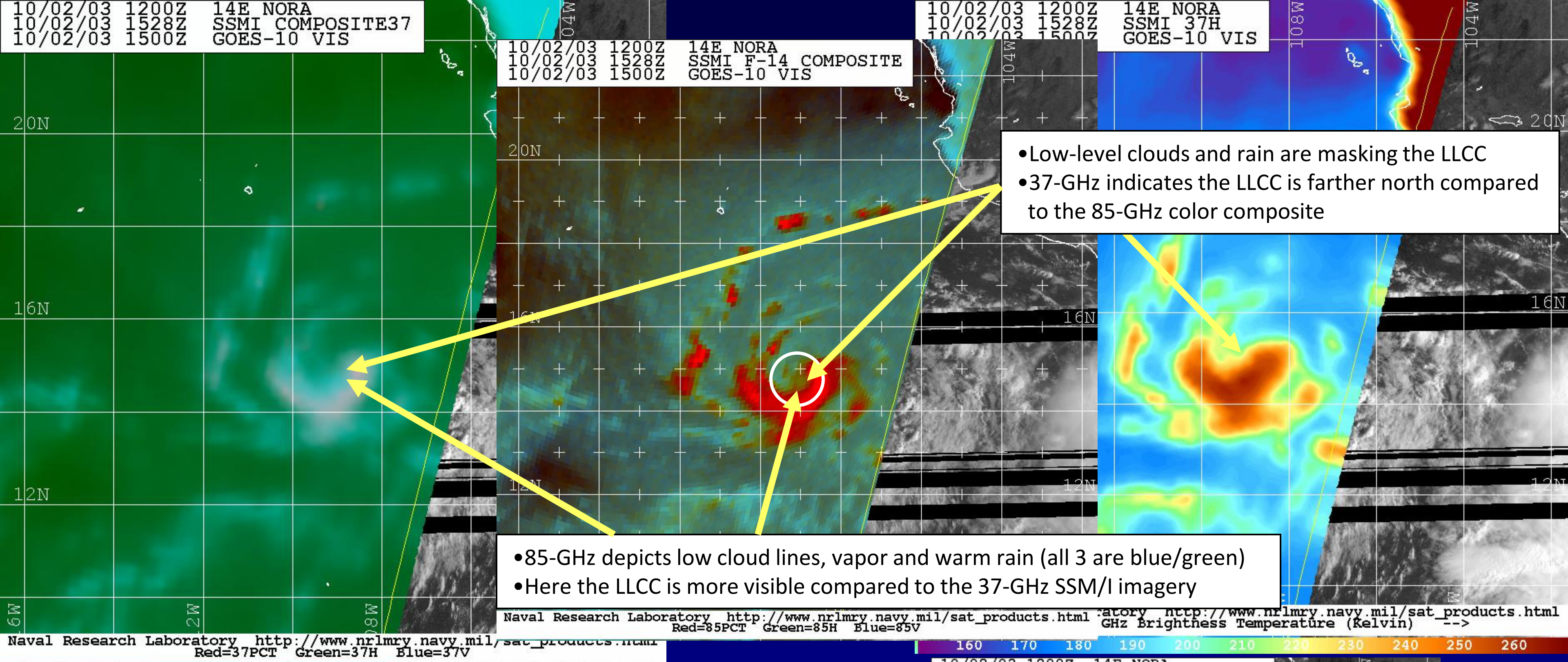




•Eye feature apparent on both 37-GHZ images
•37-GHz sensitive to low-level rain (high spatial resolution ~16x9 km)
•Able to depict low-level clouds/rainbands

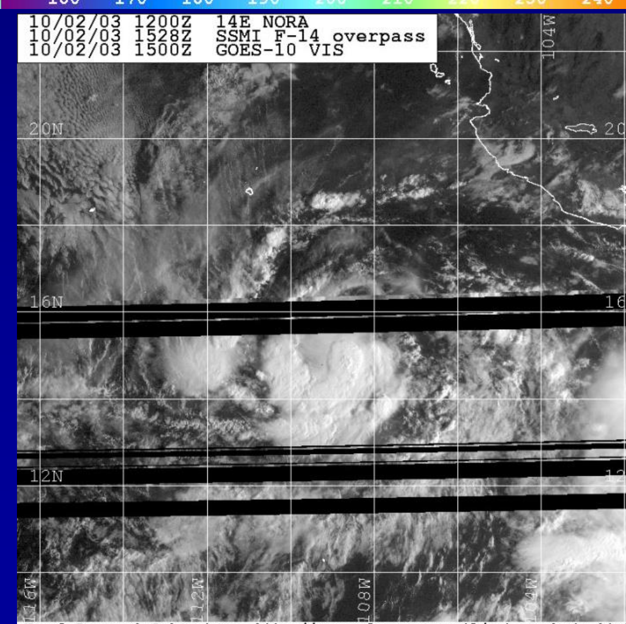


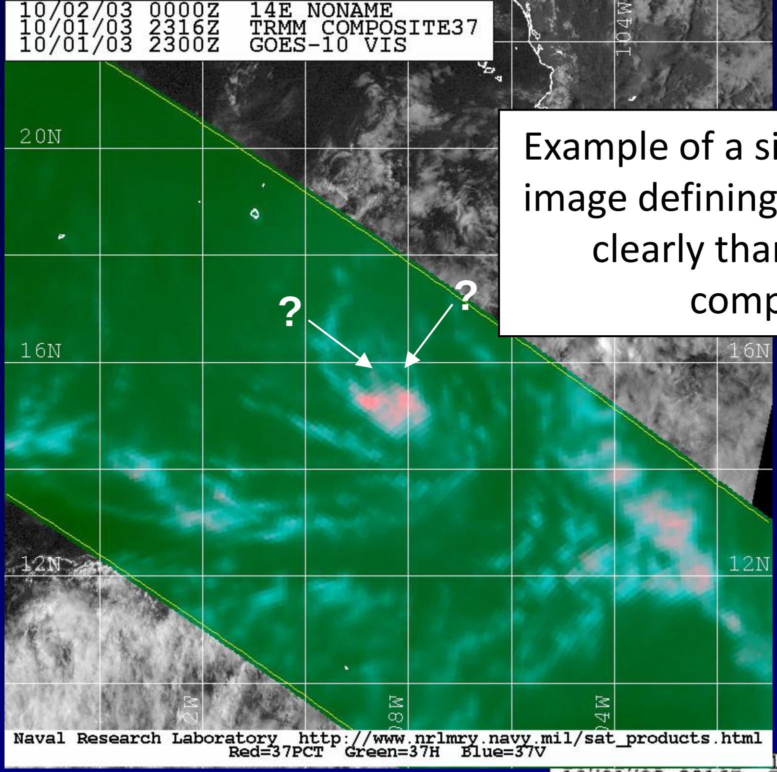

•Unable to detect eye in 85-GHz (CDO feature depicted instead)
•85-GHz sensitive to large ice particles in deep convection
•Low-level clouds “wash out” beneath heavy rains



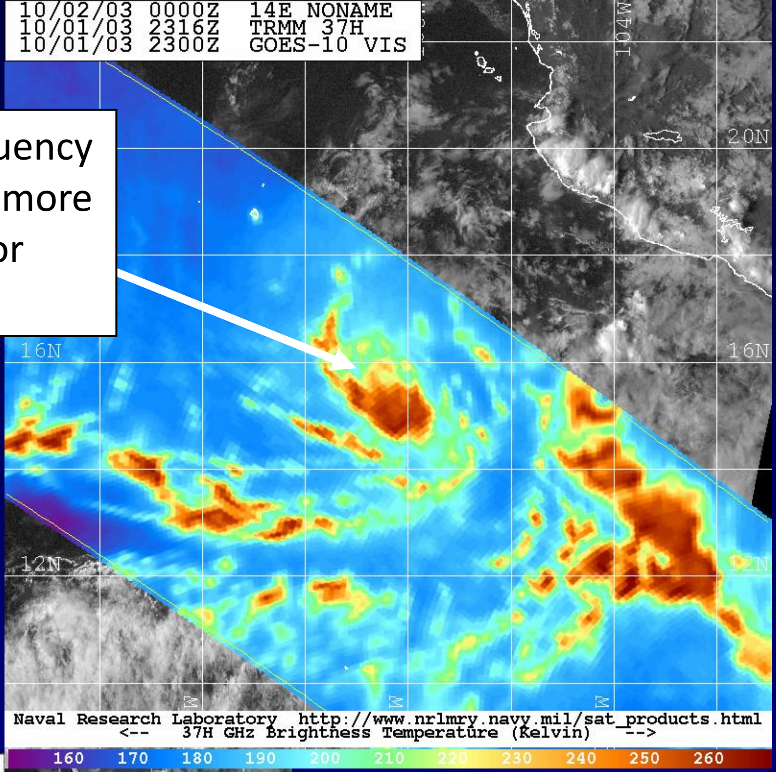


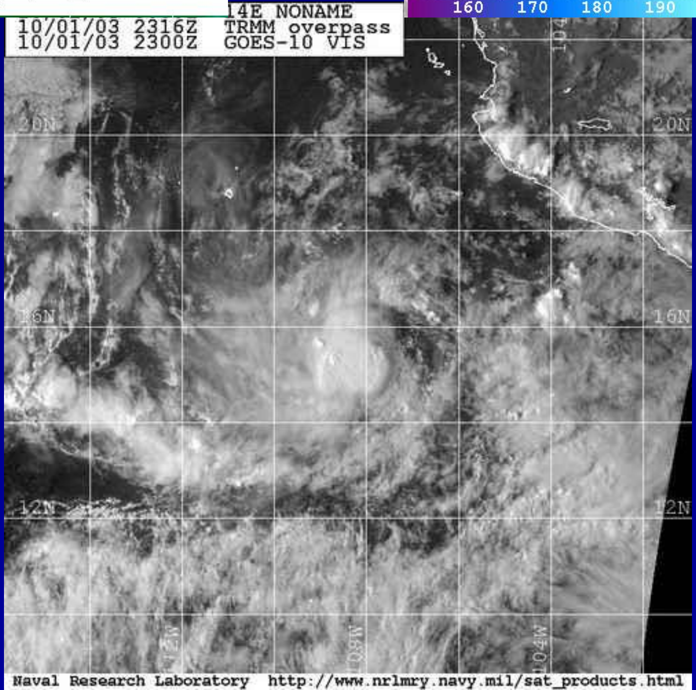

- 85-GHz color composite helps verify the possible solution seen on the 37-GHz color composite
- 37-GHz SSM/I and SSMIS spatial resolution is coarser (37x28 km) than the 37-GHz TRMM
- As a result, during relatively weak stages of a TC, SSM/I and SSMIS 37GHz H/V are difficult stand-alone images to interpret → recommend using corrected images instead






Example of a single frequency image defining the LLCC more clearly than the color composite

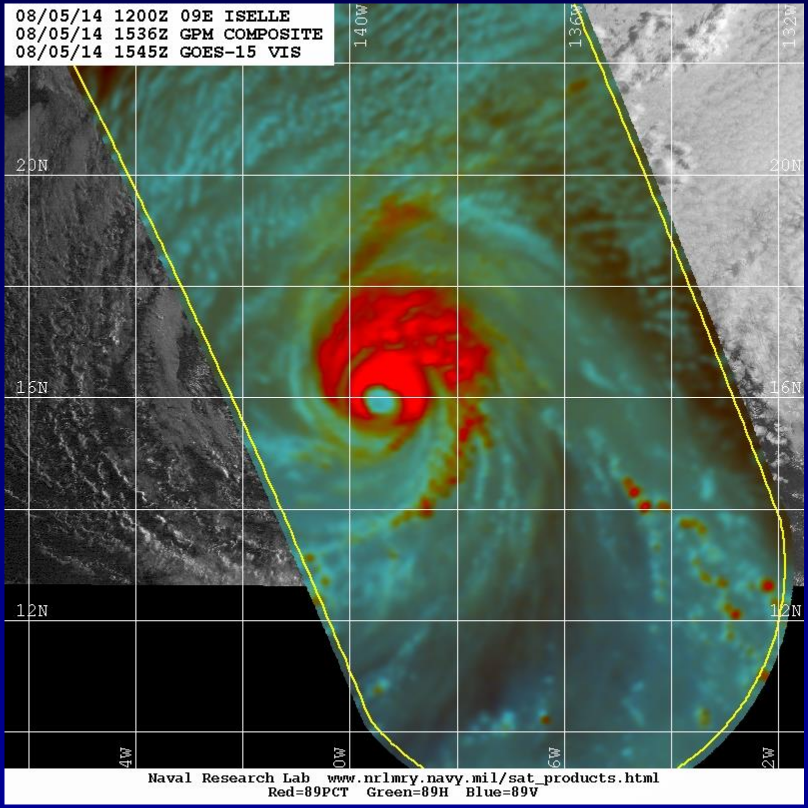


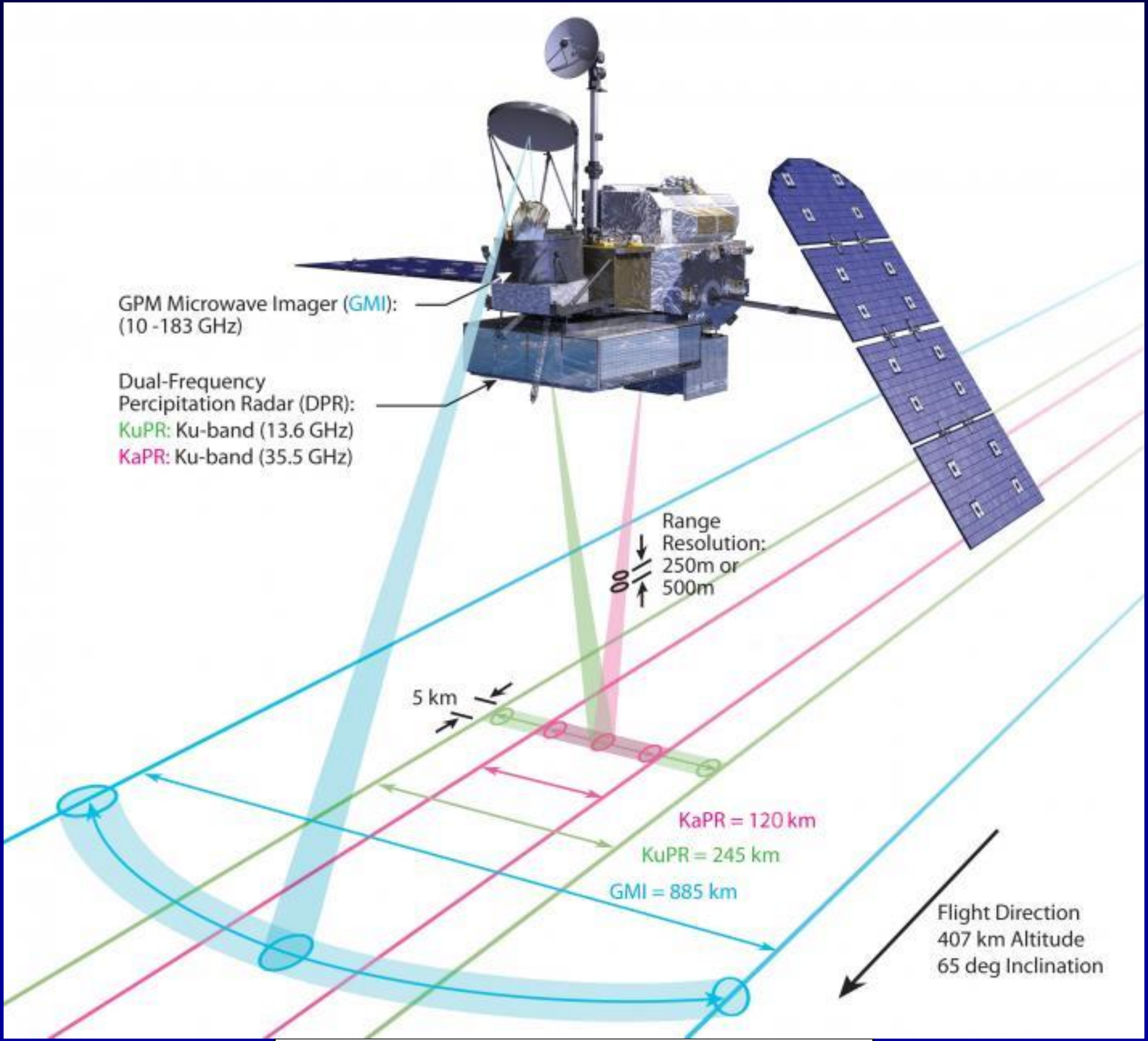
# Spaceborne Radars

# GPM – Global Precipitation Measurement Mission

- Follow-on to TRMM launched 27 February 2014
- Passive radiometer and dual frequency radar
- Radiometer has 885-km wide swath with 13 channels
  - ~ 6-km resolution footprint at 89 GHz
- Higher-inclination orbit (65°) than TRMM, so less low latitude coverage




Hurricane Iselle 1536 UTC 5 August 2014




**GPM Data Swaths – Courtesy NASA**

# Access to Online Microwave Imagery

# FNMOC Tropical Cyclone Webpage

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

https://www.fnmoc.navy.mil/tcweb/cgi-bin/tc_home.cgi?YEAR=2019&MO=Apr&BASIN=SHEM&STORM_NAME=25S.LORNA&PROD=track_vis&TYPE=ssmi&PHOT=yes&ARCHIVE=Latest&NAV=tc&DISPLAY=Active&ACTIVES=19-SHEM-24S.KENNETH,19-SHEM-25...

Apps | NHC | HSU Intranet | Hurricane Diagnosti... | Recon Time Series | atcf2tcr Files | ATCF2GIS | TC-genesis probs | HSU-Wiki | NCO Helpdesk Ticket | HSU Shift Log | TAFB | Gmail

## FNMOC Satellite Data Tropical Cyclone Page

2019 Storms

All | Active | Year

Atlantic

East Pacific

Central Pacific

West Pacific

Indian Ocean
- 91B.INVEST

Southern Hemisphere
- 92S.INVEST
- 25S.LORNA
- 24S.KENNETH

Display: Latest | Prev. | Track&Image | Pass_Mosaic

Warn: Text | Track

Info: General | Tutorial | Disclaimer

Environment: TPW | TPW&NAVGEM_TPW | TPW&NAVGEM_850_Winds

SSMI | SSMIS | GMI | AMSU | ATMS | AMSR2 | WindSat | ASCAT | OSCAT | MODIS | NEXRAD | VIS | IR | OLS

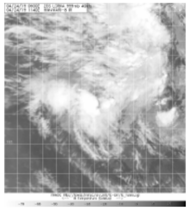
Age <= 6hrs old | Age <= 12hrs old | Age >12hrs old | 12:09:04 | UTC(Z)

25S.LORNA

Forecast by Joint Typhoon Warning Center/Naval Maritime Forecast Center
Graphic by Naval Maritimep Forecast Center/Joint Typhoon Warning Center

smsh252019.20190424075752 thumbnail

Latest Image

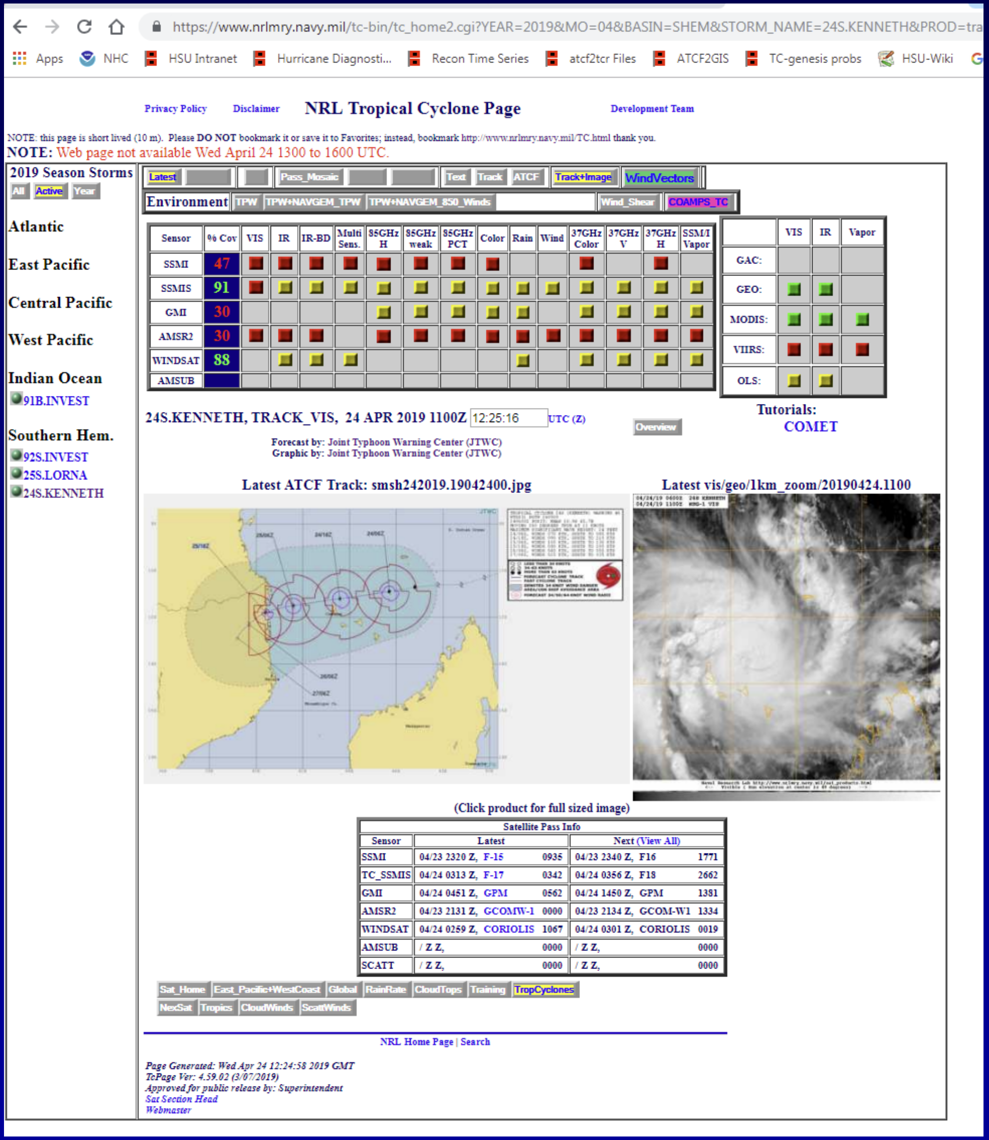


(Click product for full sized image 68125 Bytes and 217144 Bytes.)

| Sensor | Latest | Upcoming Passes (more) |
| --- | --- | --- |
| SSMI | 04/24 1014Z f15 1039 | 04/24 21:24Z F-15 4 |
| SSMIS | 04/24 1033Z f16 235 | 04/24 10:35Z F-16 235<br>04/25 01:19Z F-17 658<br>04/24 11:30Z F-18 747 |
| GMI | None | |
| MHS | 04/24 0408Z metopa 0 | 04/25 03:03Z N-18 335<br>04/24 23:09Z N-19 114<br>04/25 03:34Z MetOp-A 116<br>04/24 16:15Z MetOp-B 420 |
| WindSat | 04/23 1231Z coriolis 266 | 04/24 12:14Z WSAT 760 |
| ASCAT | None | 04/25 03:34Z MetOp-A 116<br>04/24 16:15Z MetOp-B 420 |
| OSCAT | None | |
| MODIS | 04/24 0810Z Aqua 194 | 04/25 19:45Z AQUA 226<br>04/25 04:27Z TERRA 561 |

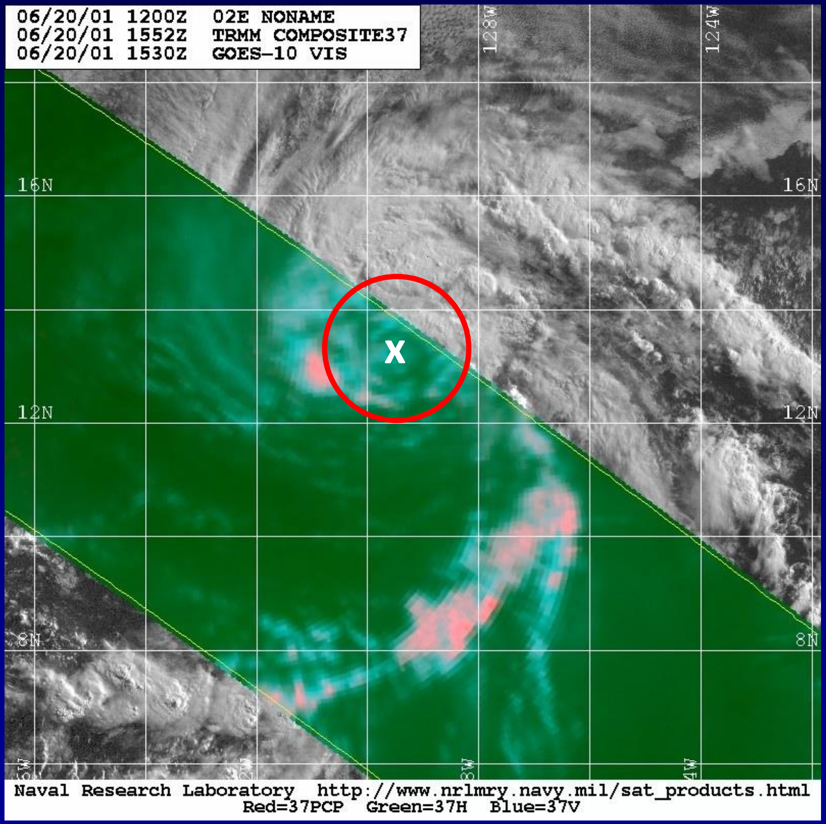
# NRL Tropical Cyclone Webpage

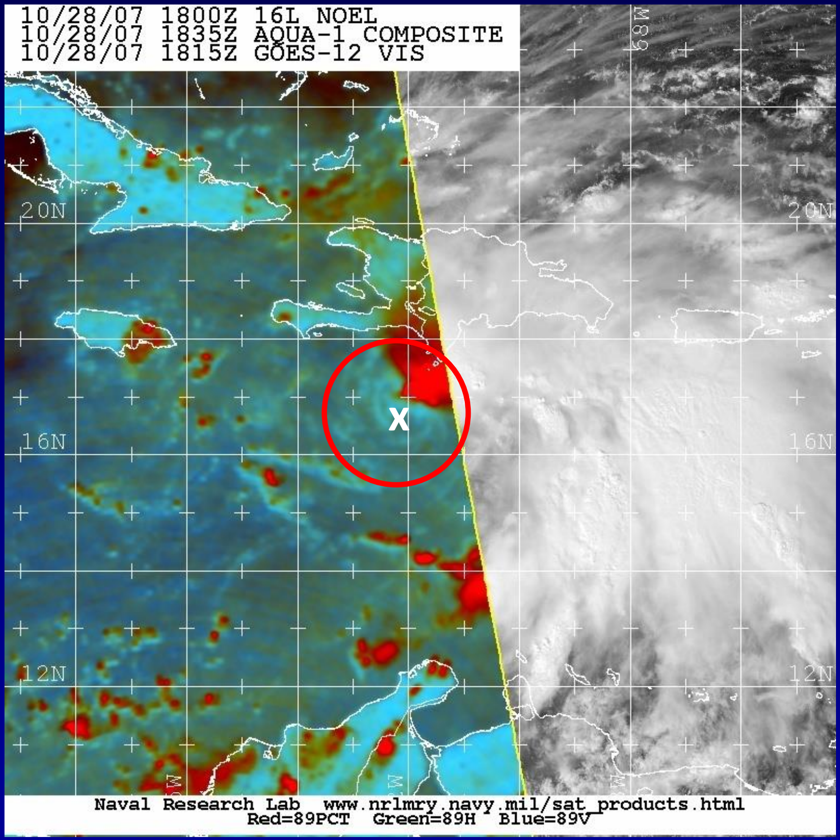
https://www.nrlmry.navy.mil/TC.html



# Tropical Cyclone Positioning Using Passive Microwave Data

# Positioning in Microwave Imagery

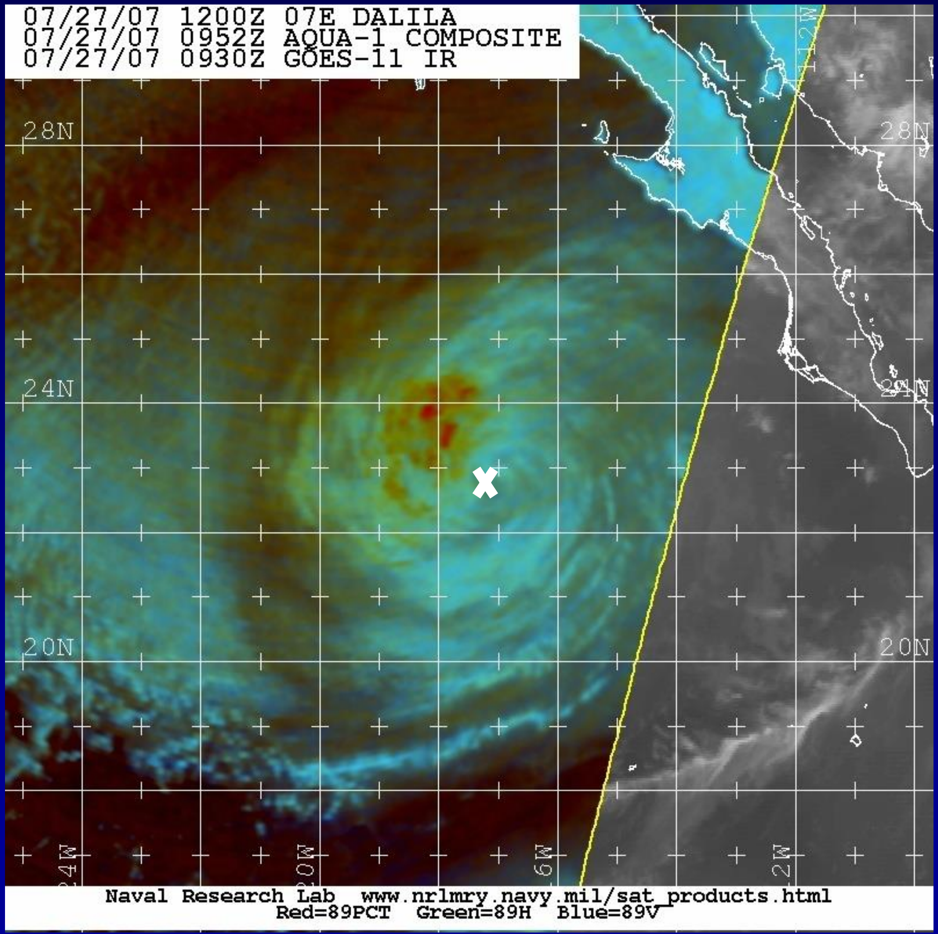


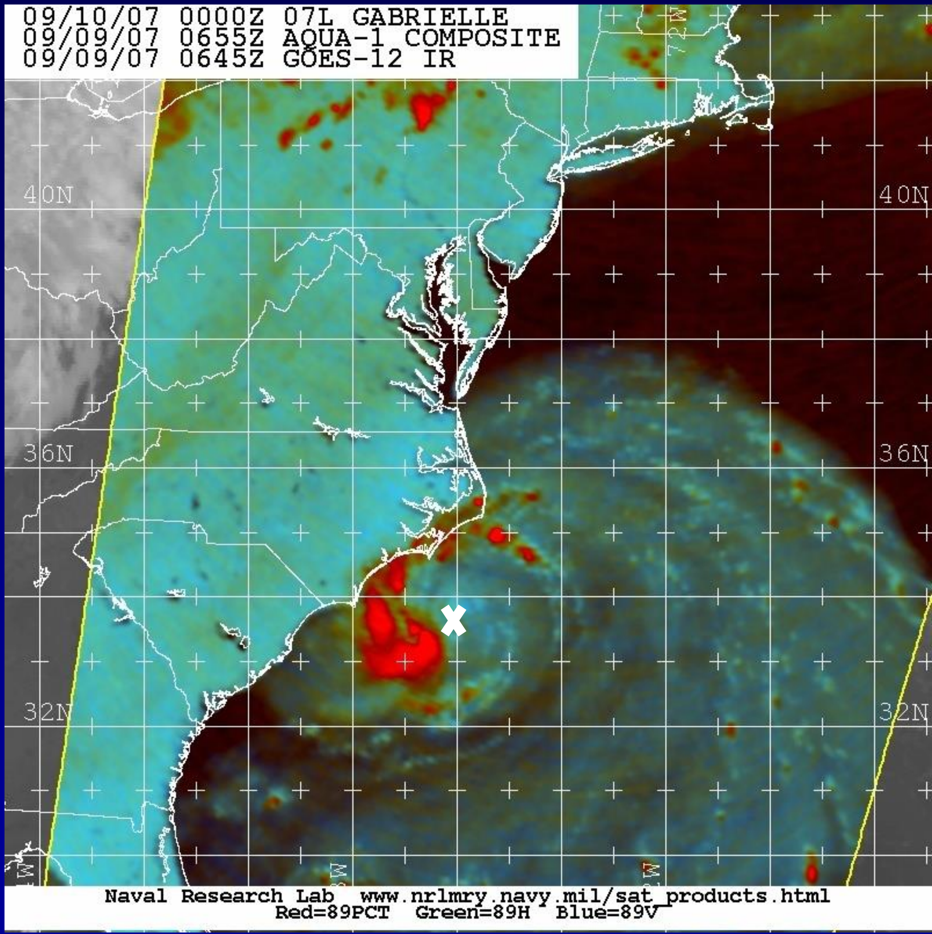




Try to position in the <u>rain-free dry</u> area—out of the convection

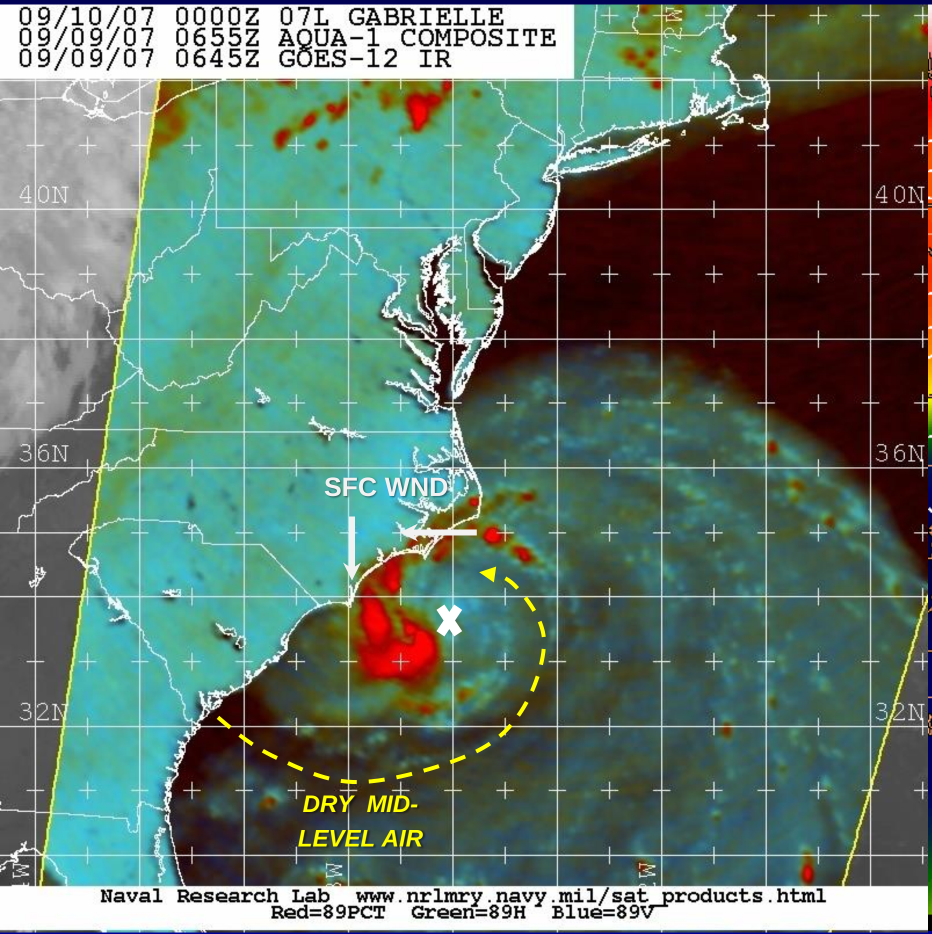
# Positioning in Microwave Imagery

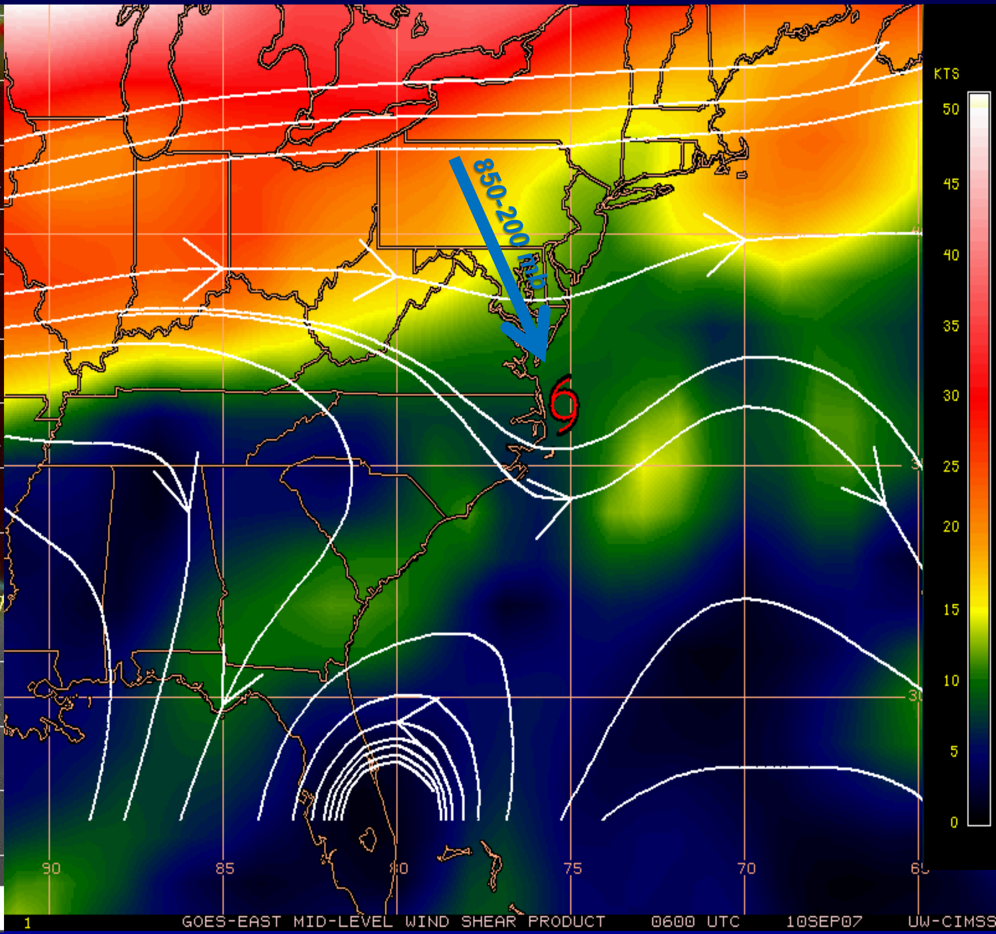
## Look for convective free darker areas



# Effect of Vertical Wind Shear on Center Positioning in Microwave Imagery

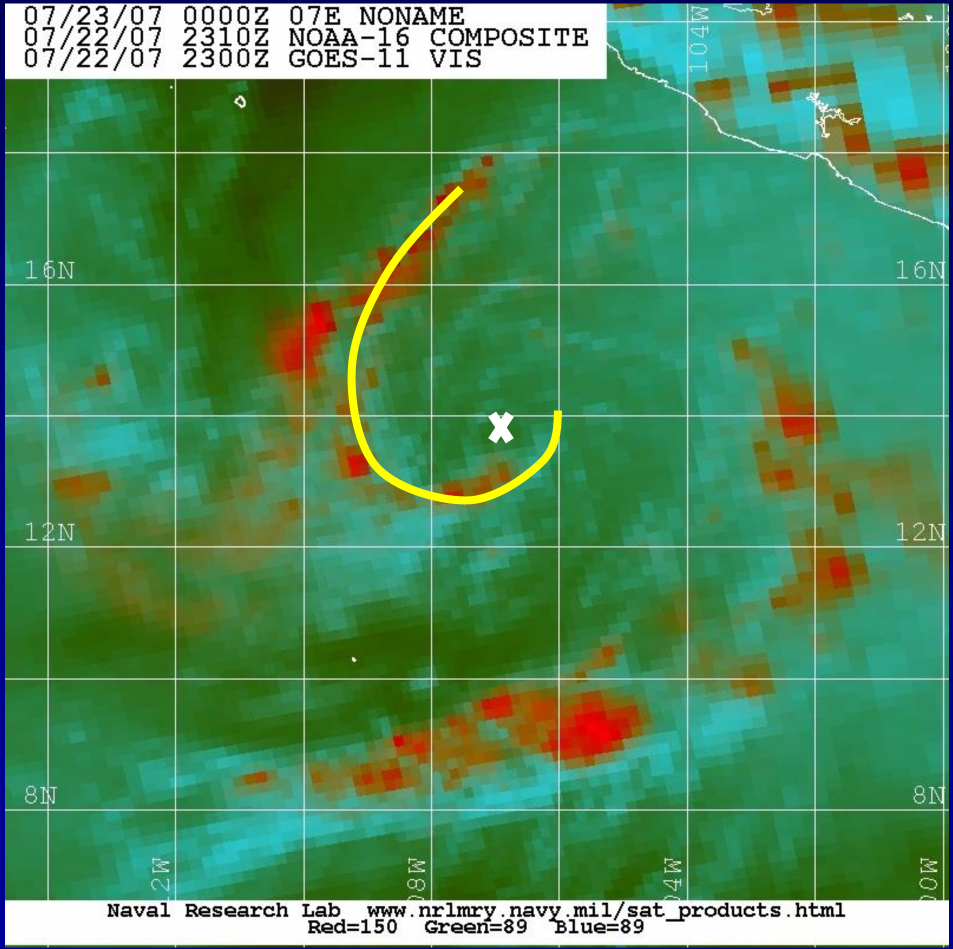


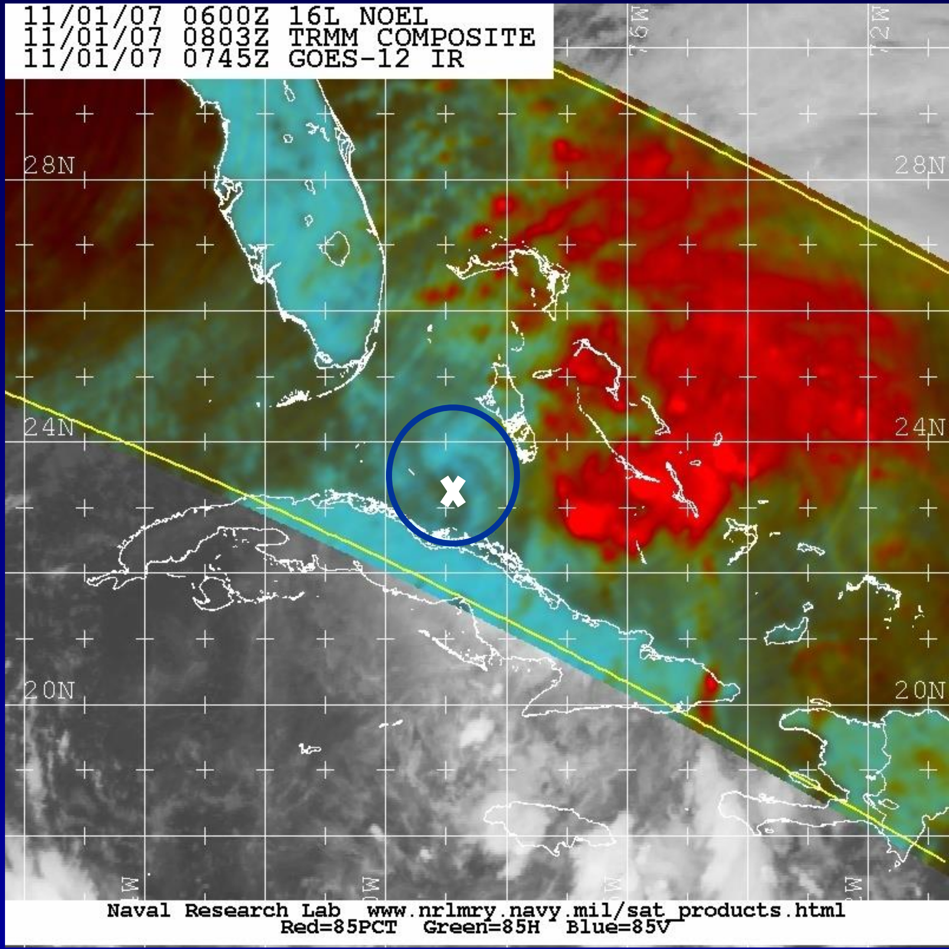



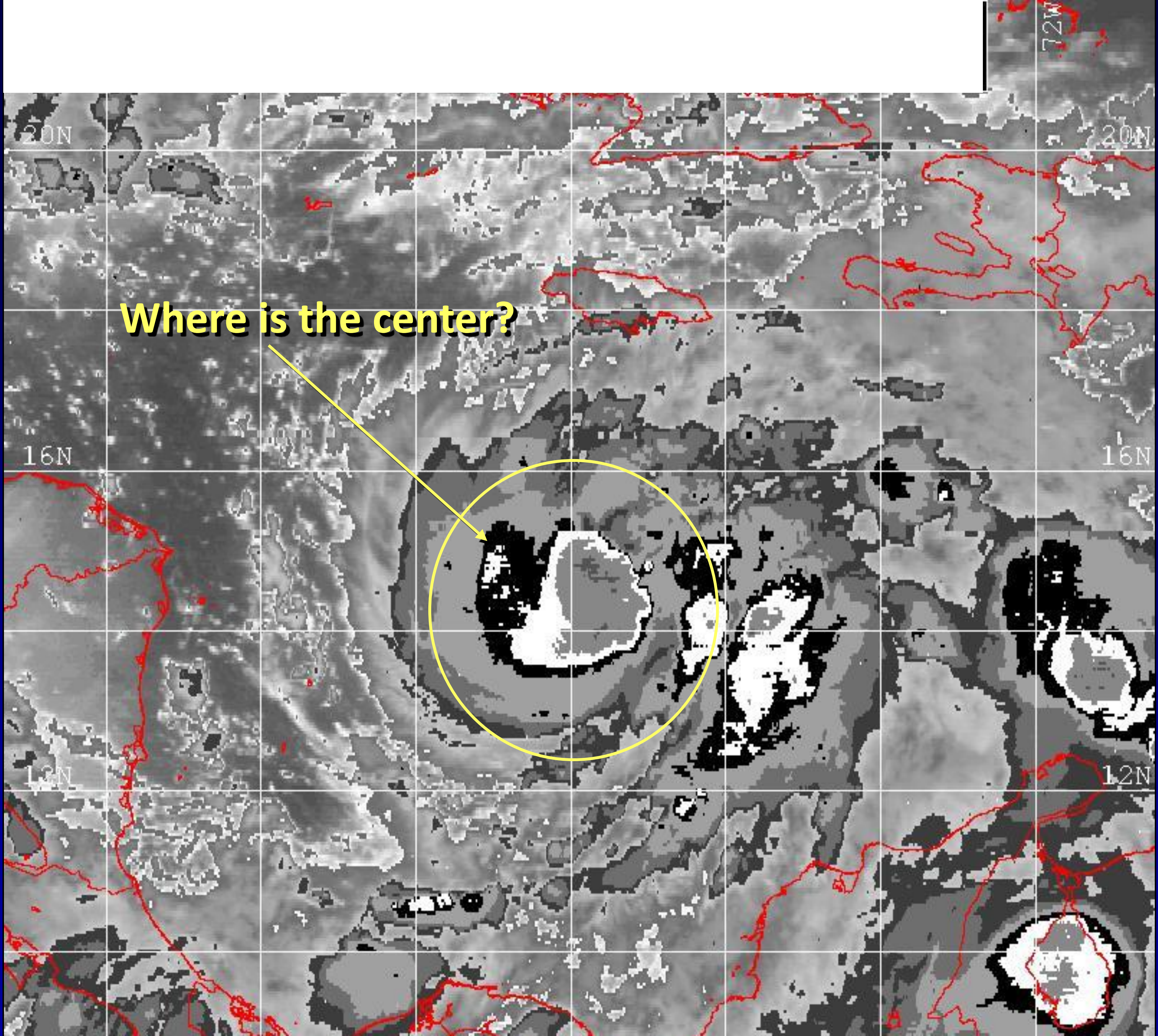

Anticipating the location of the LLCC based on vertical wind shear creating asymmetry in the deep convection pattern helps, ***BUT*** it can not always be used as an absolute as this case clearly indicates.

# Positioning in Microwave Imagery

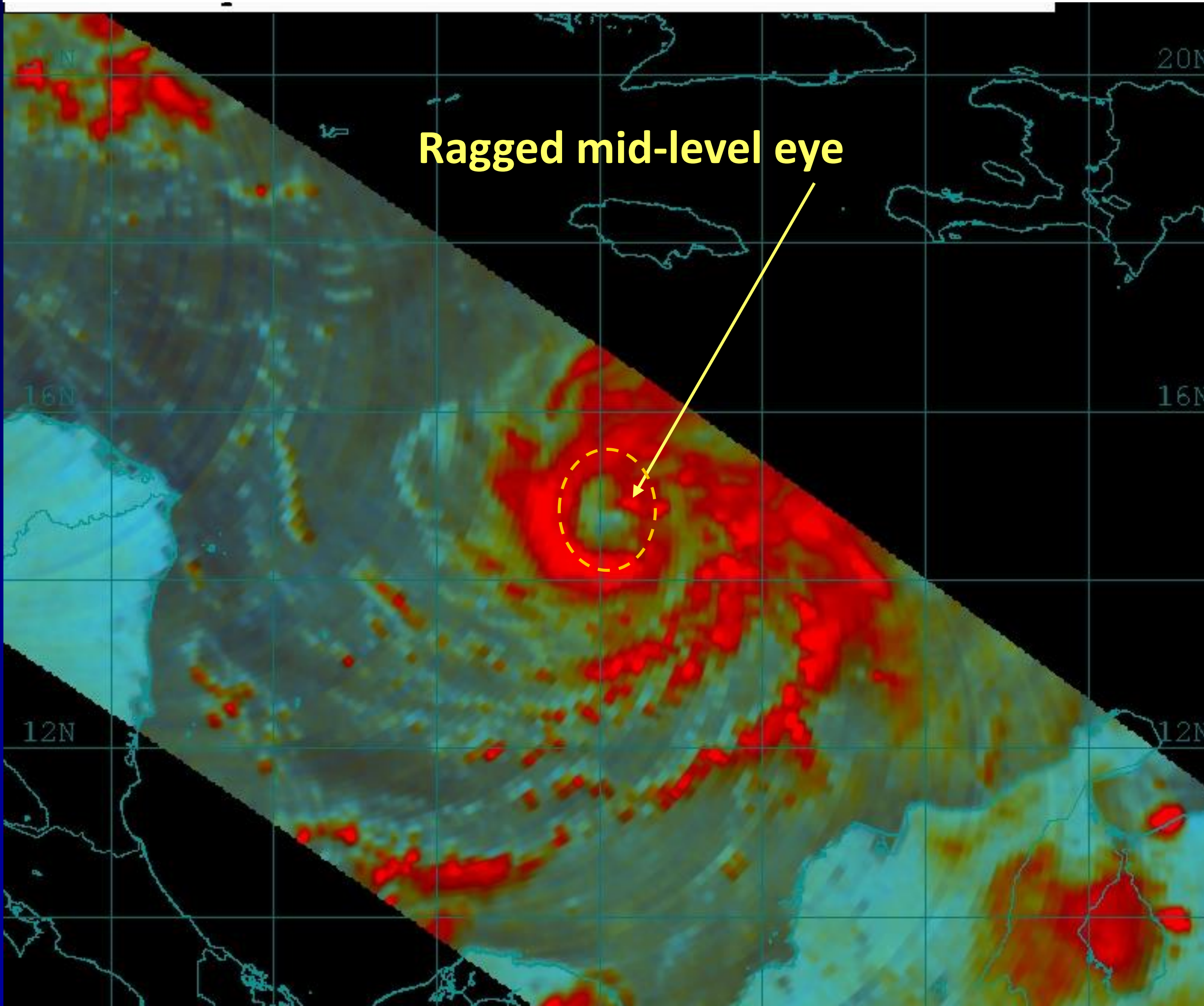
## Look for low cloud curvature



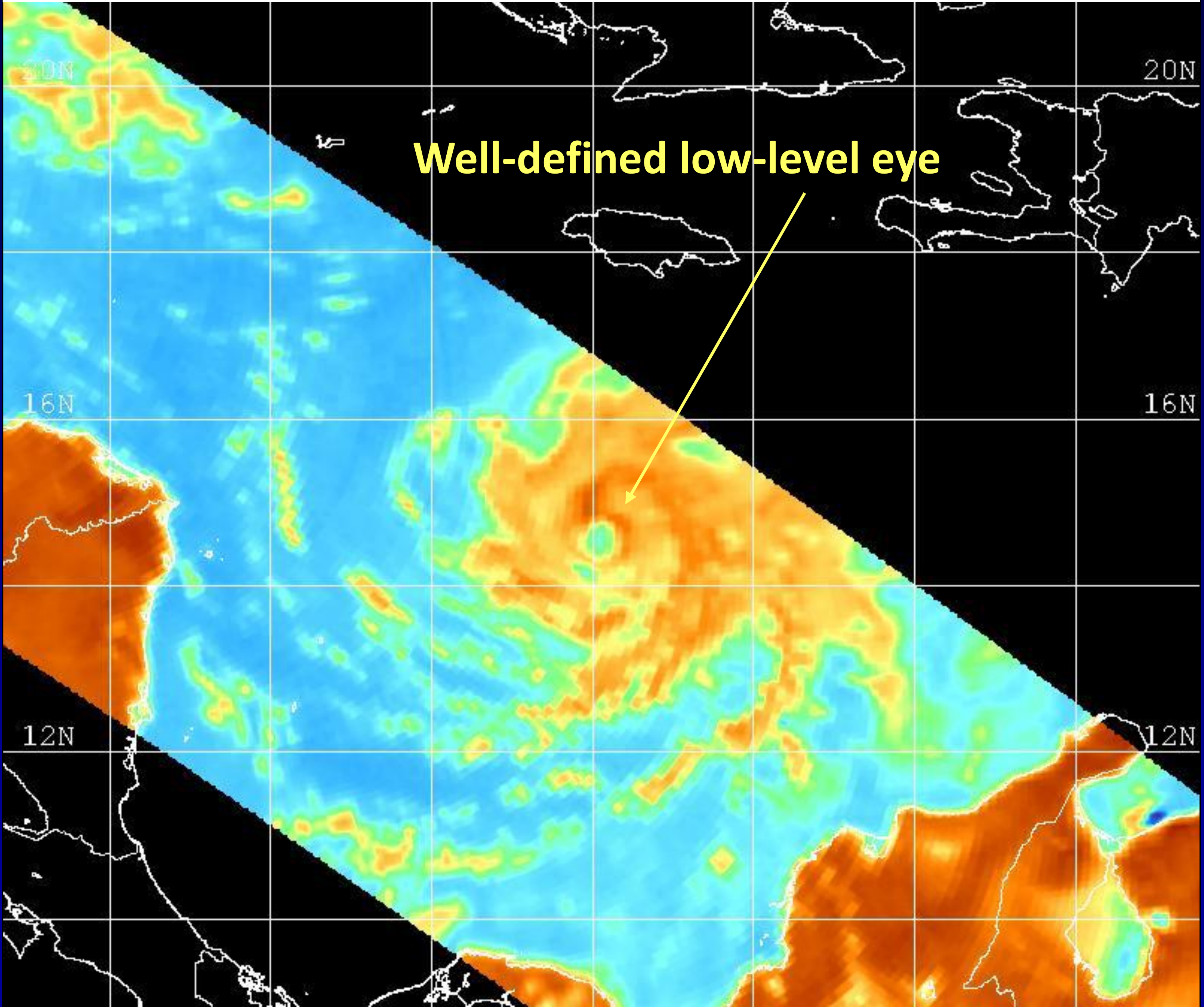



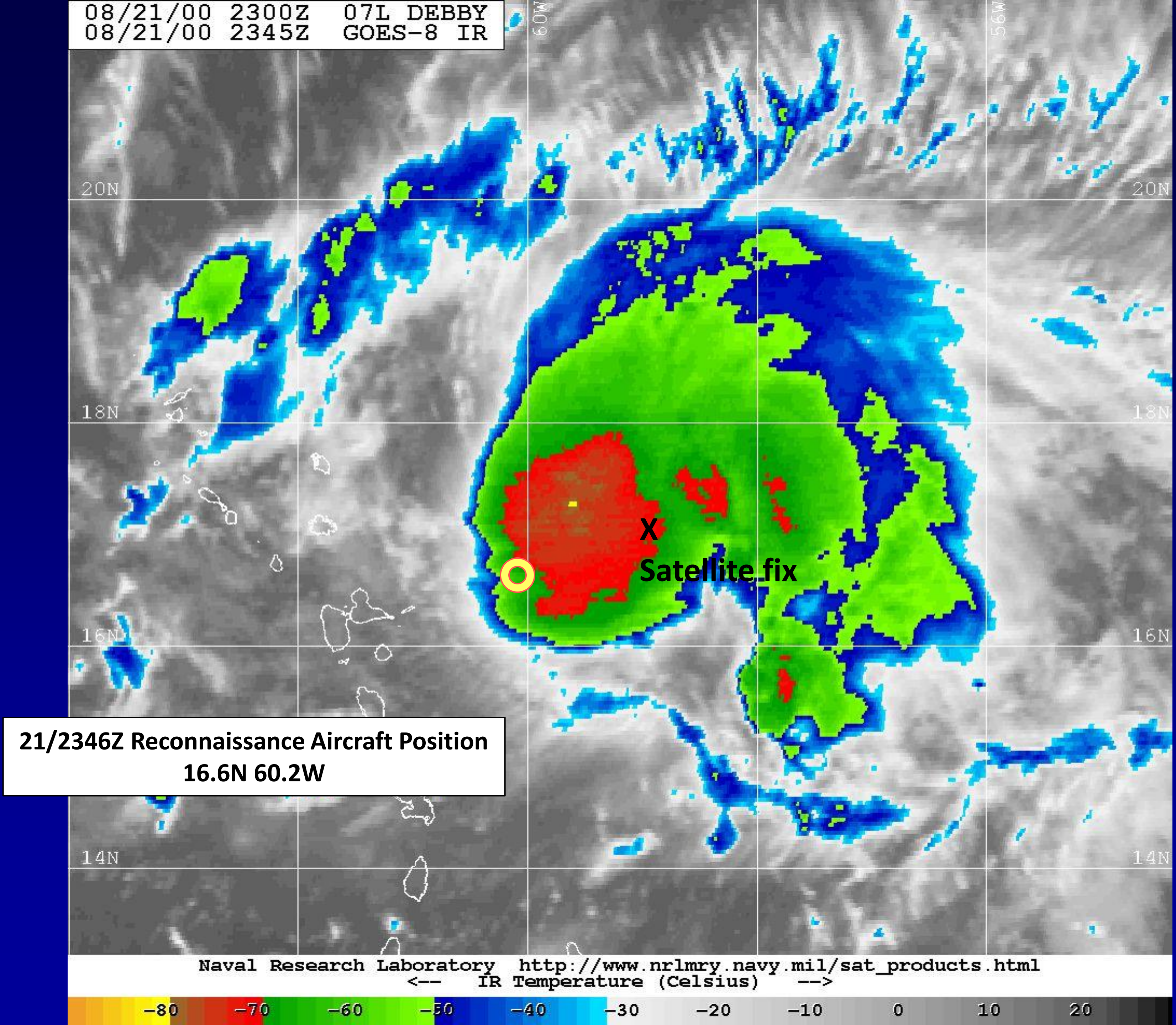

Where is the center?
20N
16N
12N
72W

# 85 GHz Color-Composite Example

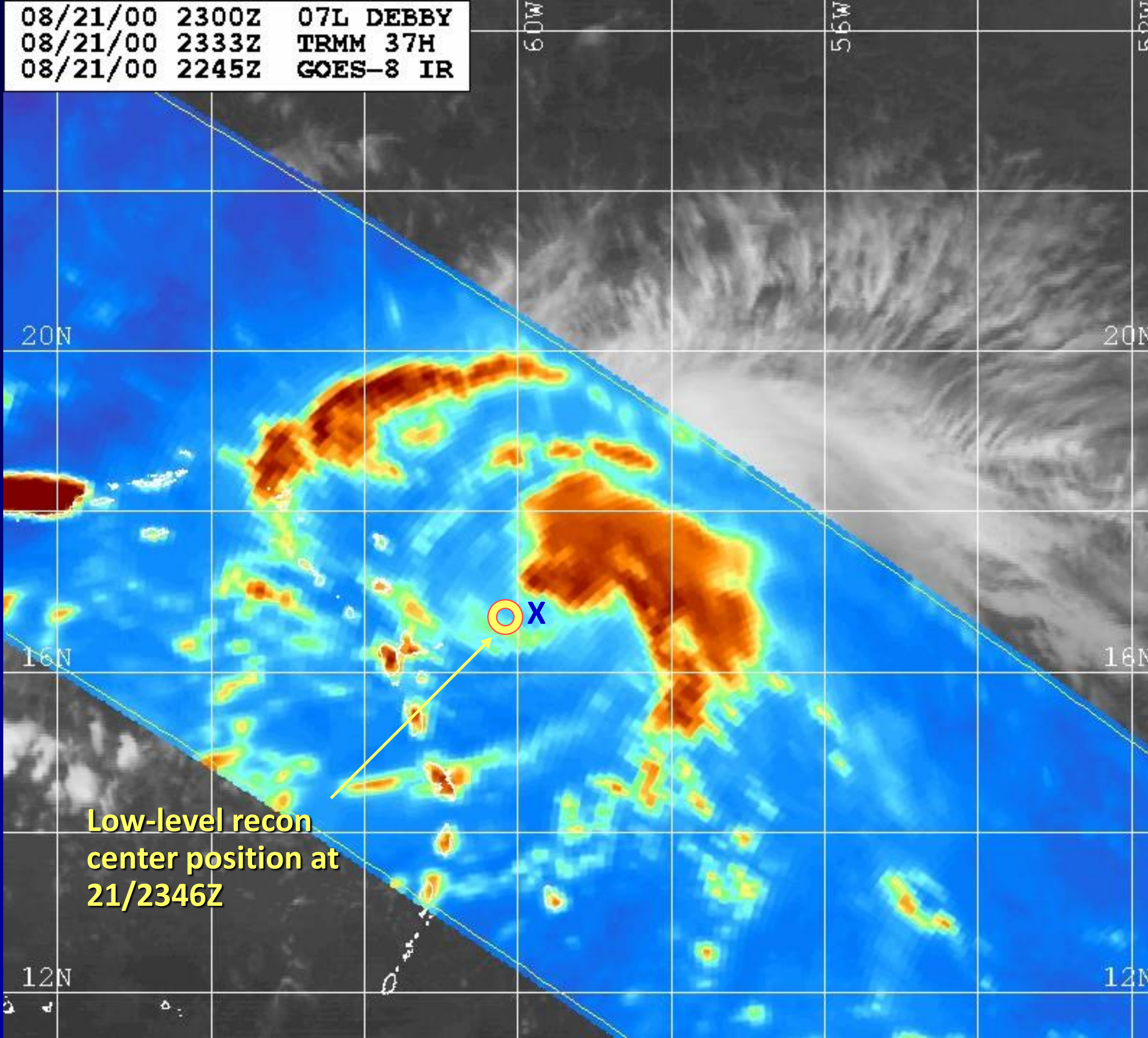


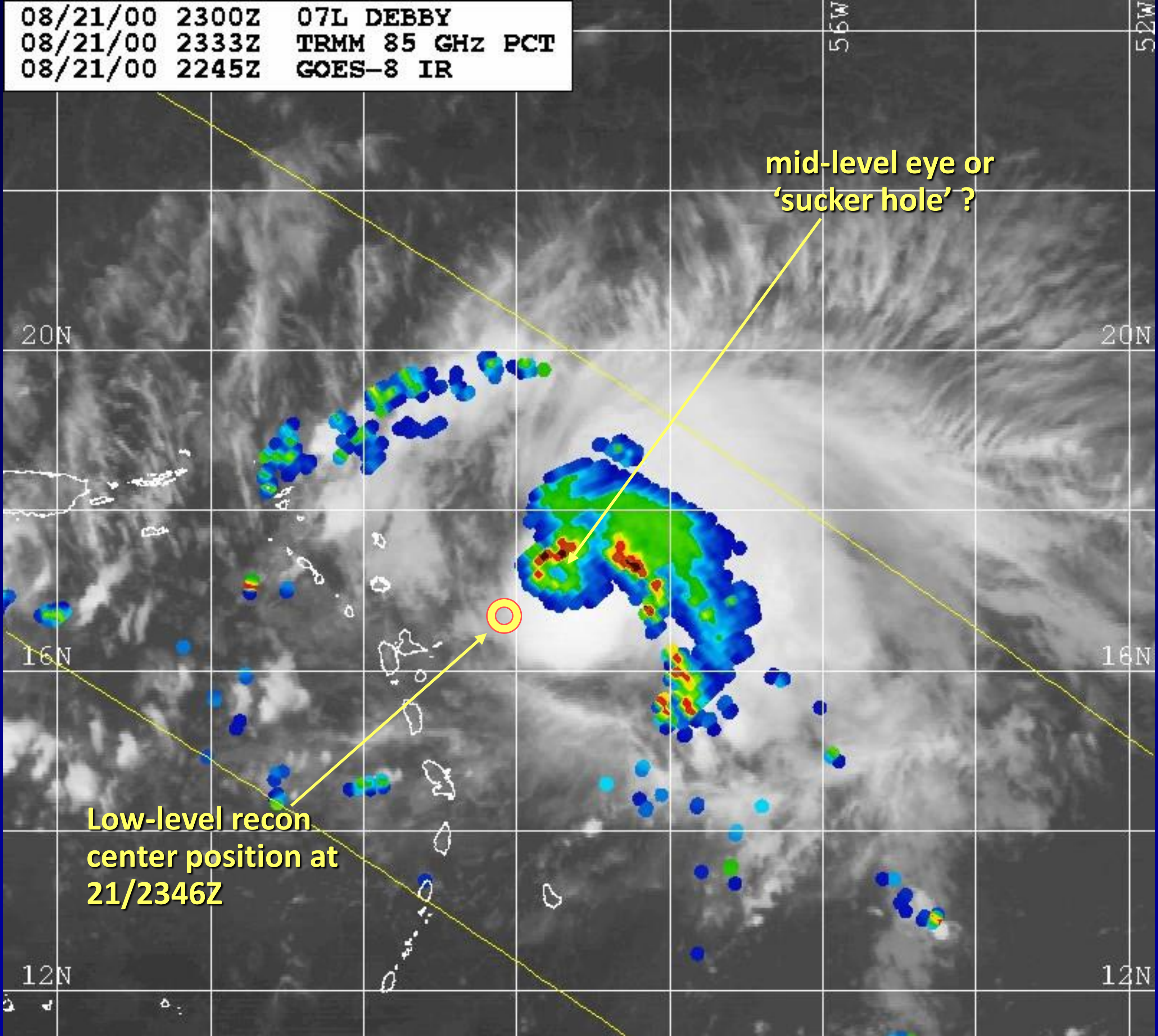
# 37 GHz Example

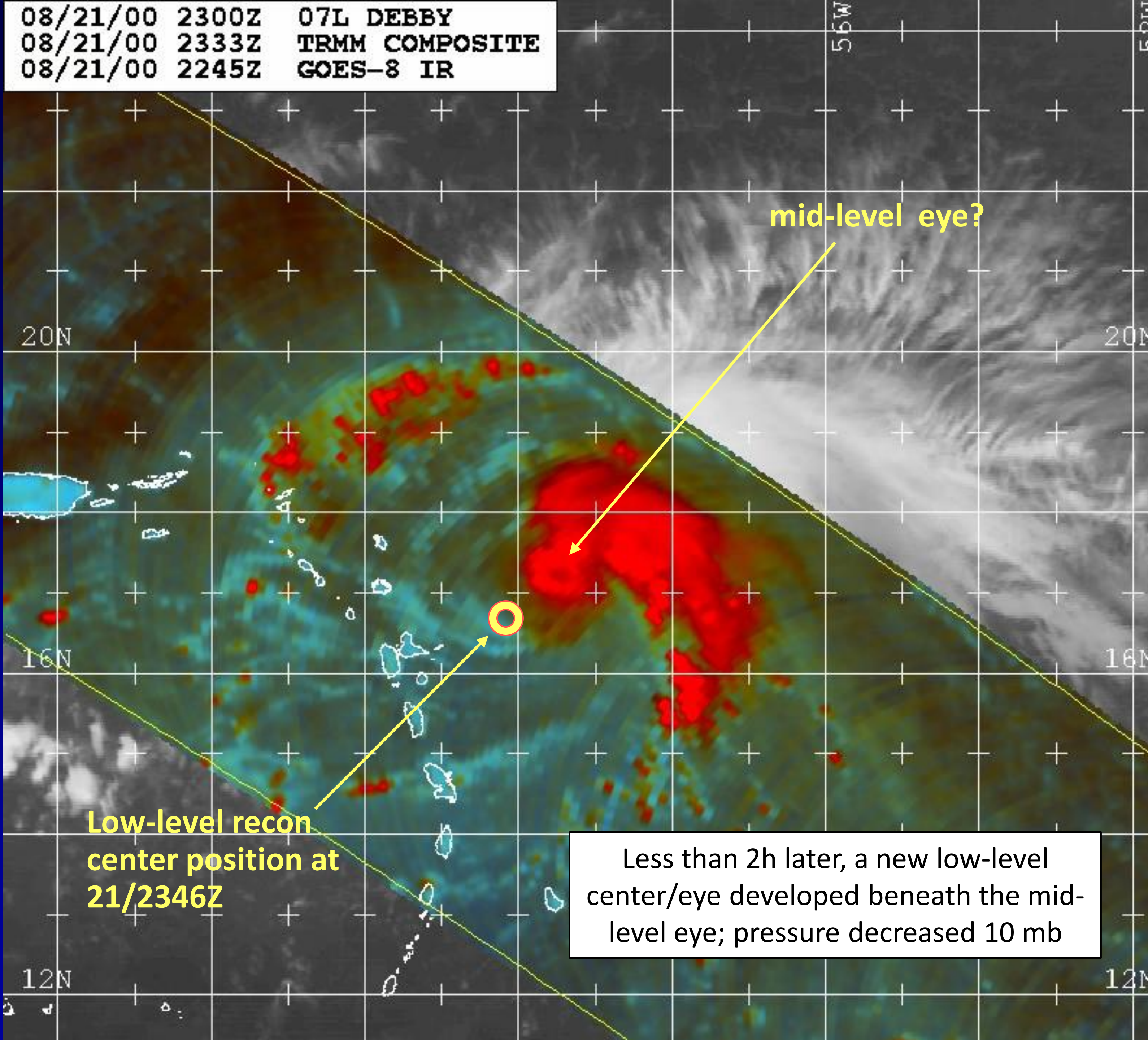




08/21/00 2300Z 07L DEBBY
08/21/00 2345Z GOES-8 IR
60W
56W
20N
18N
16N
14N
X
Satellite fix
21/2346Z Reconnaissance Aircraft Position
16.6N 60.2W
Naval Research Laboratory http://www.nrlmry.navy.mil/sat_products.html
<-- IR Temperature (Celsius) -->
-80 -70 -60 -50 -40 -30 -20 -10 0 10 20


08/21/00 2300Z 07L DEBBY
08/21/00 2333Z TRMM 37H
08/21/00 2245Z GOES-8 IR
60W
56W
52W
20N
16N
12N
X
Low-level recon center position at 21/2346Z


08/21/00 2300Z 07L DEBBY
08/21/00 2333Z TRMM 85 GHz PCT
08/21/00 2245Z GOES-8 IR
56W
52W
20N
16N
12N
mid-level eye or
'sucker hole' ?
Low-level recon
center position at
21/2346Z


08/21/00 2300Z 07L DEBBY
08/21/00 2333Z TRMM COMPOSITE
08/21/00 2245Z GOES-8 IR
56W
52W
20N
16N
12N
mid-level eye?
Low-level recon center position at 21/2346Z
Less than 2h later, a new low-level center/eye developed beneath the mid-level eye; pressure decreased 10 mb

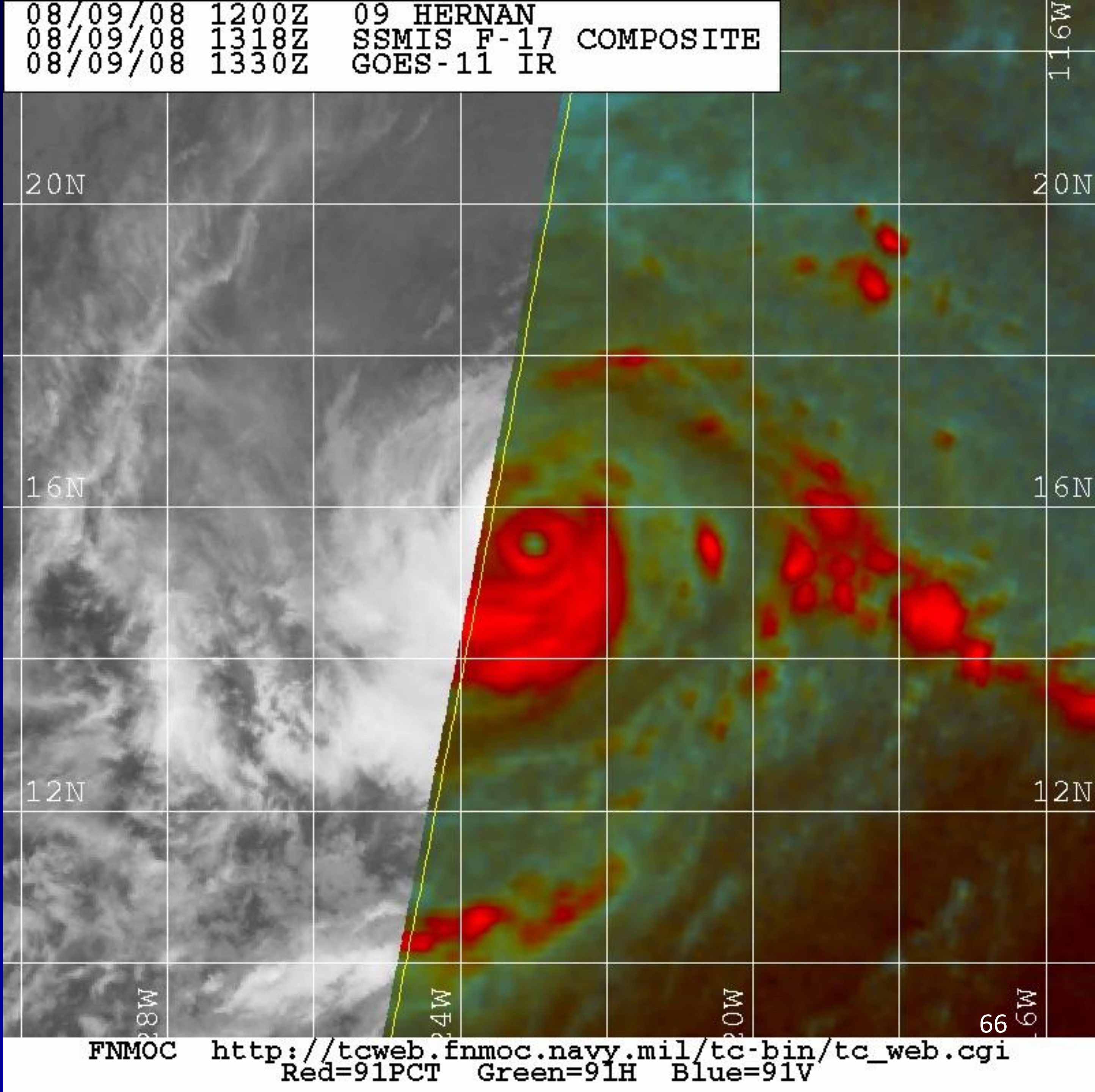
# Expanded Use of Microwave Imagery for Tropical Cyclone Analysis

- Improve position estimates for Dvorak intensity estimates
  - Helps locate center when obscured by clouds
  - *Incorrect center location can yield incorrect intensity estimates*, especially when using embedded center or shear patterns

- Monitoring internal TC structure
  - Eye formation/dissipation
  - Eyewall replacement cycles

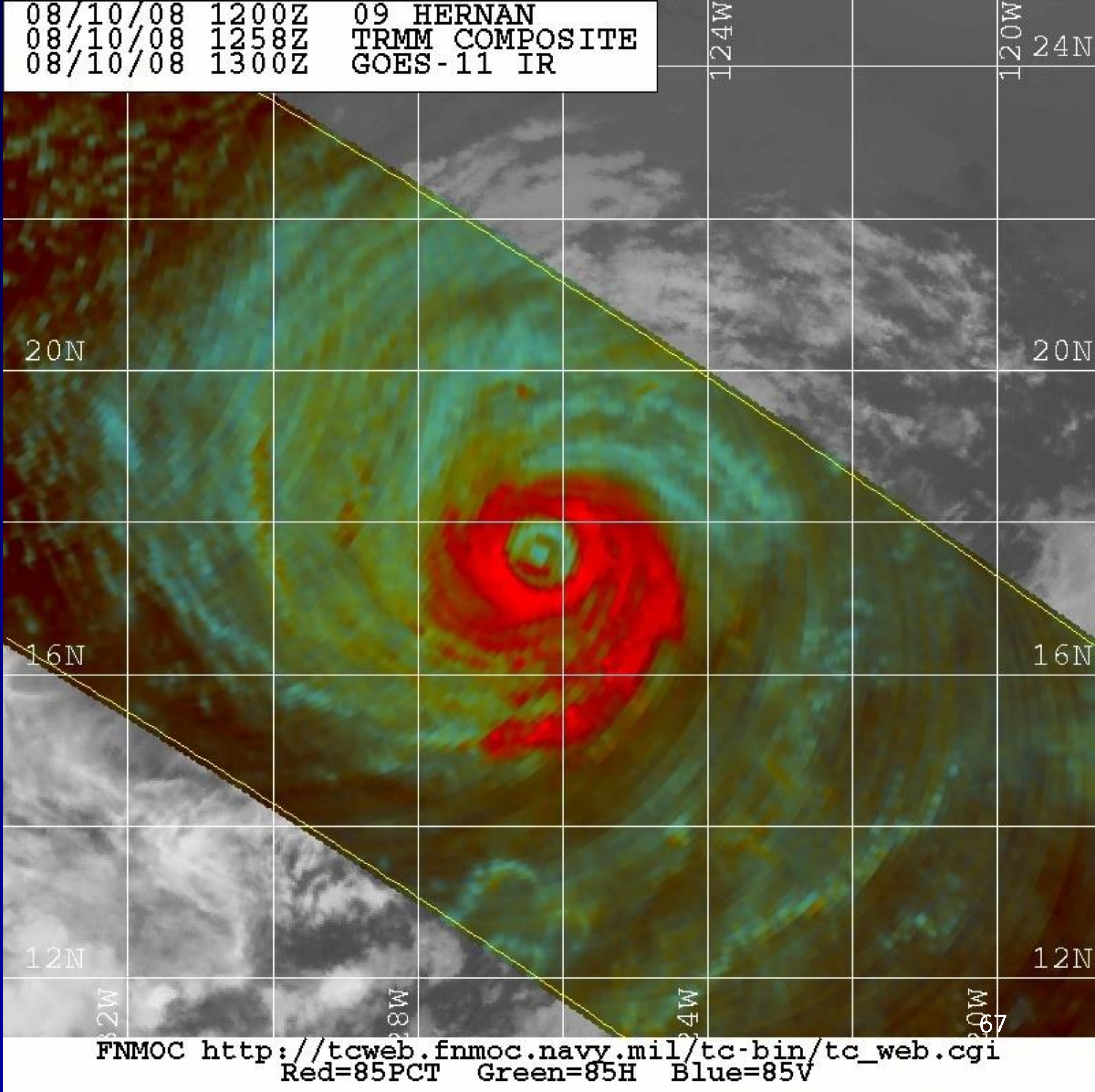
Hernan near peak intensity

9 Aug 2008

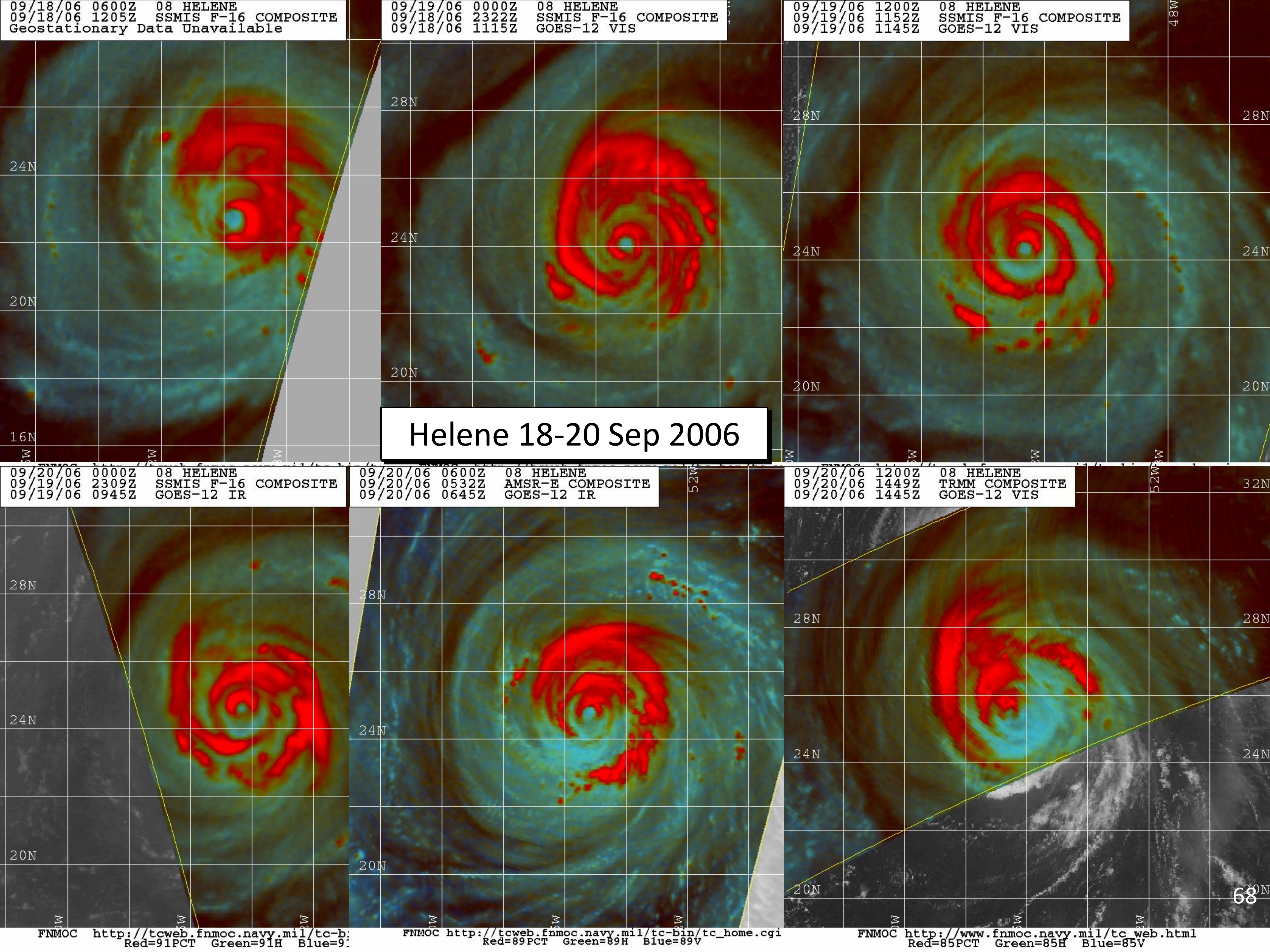


Hernan Eyewall Replacement Cycle 24 h later

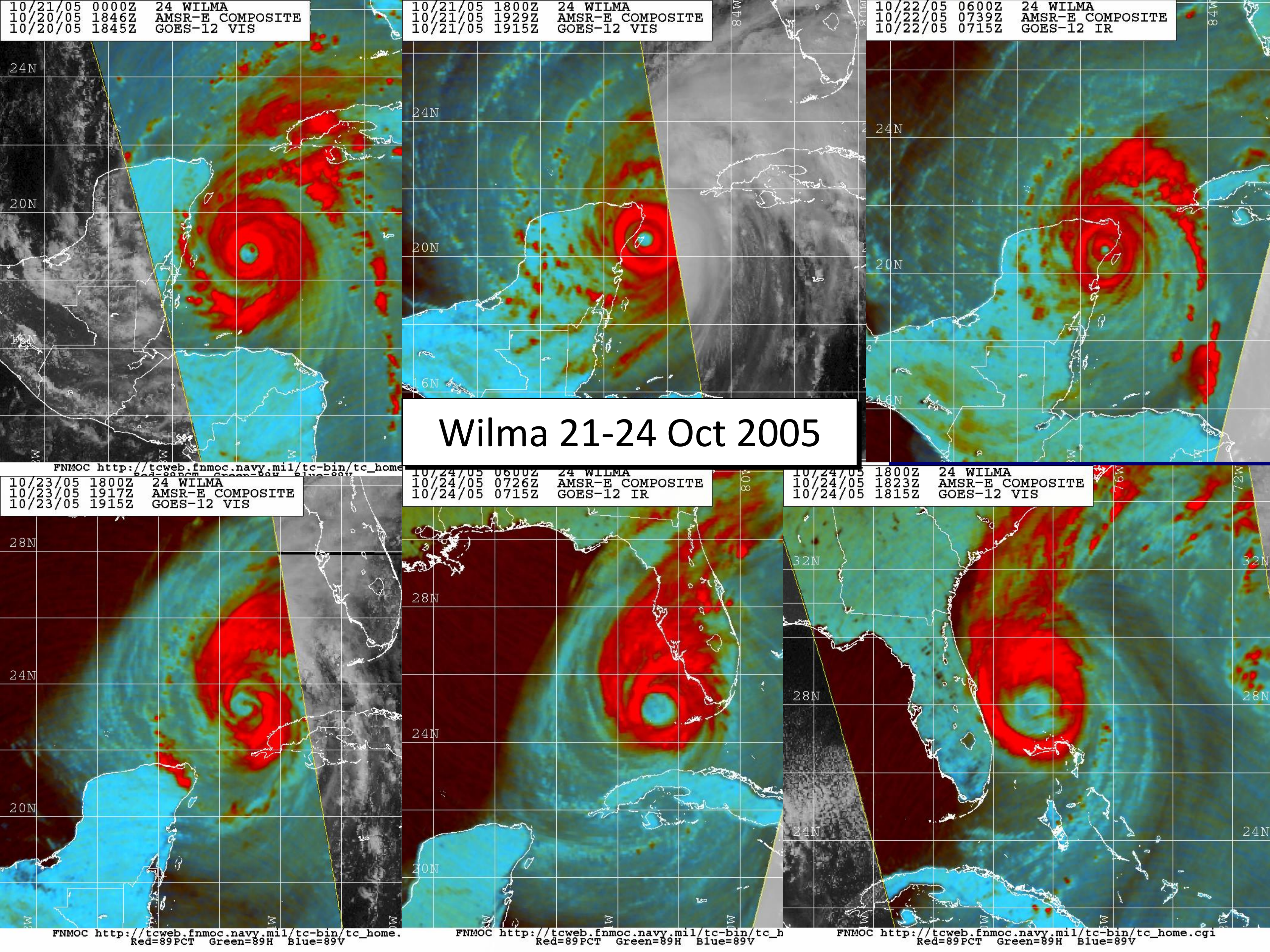
10 Aug 2008



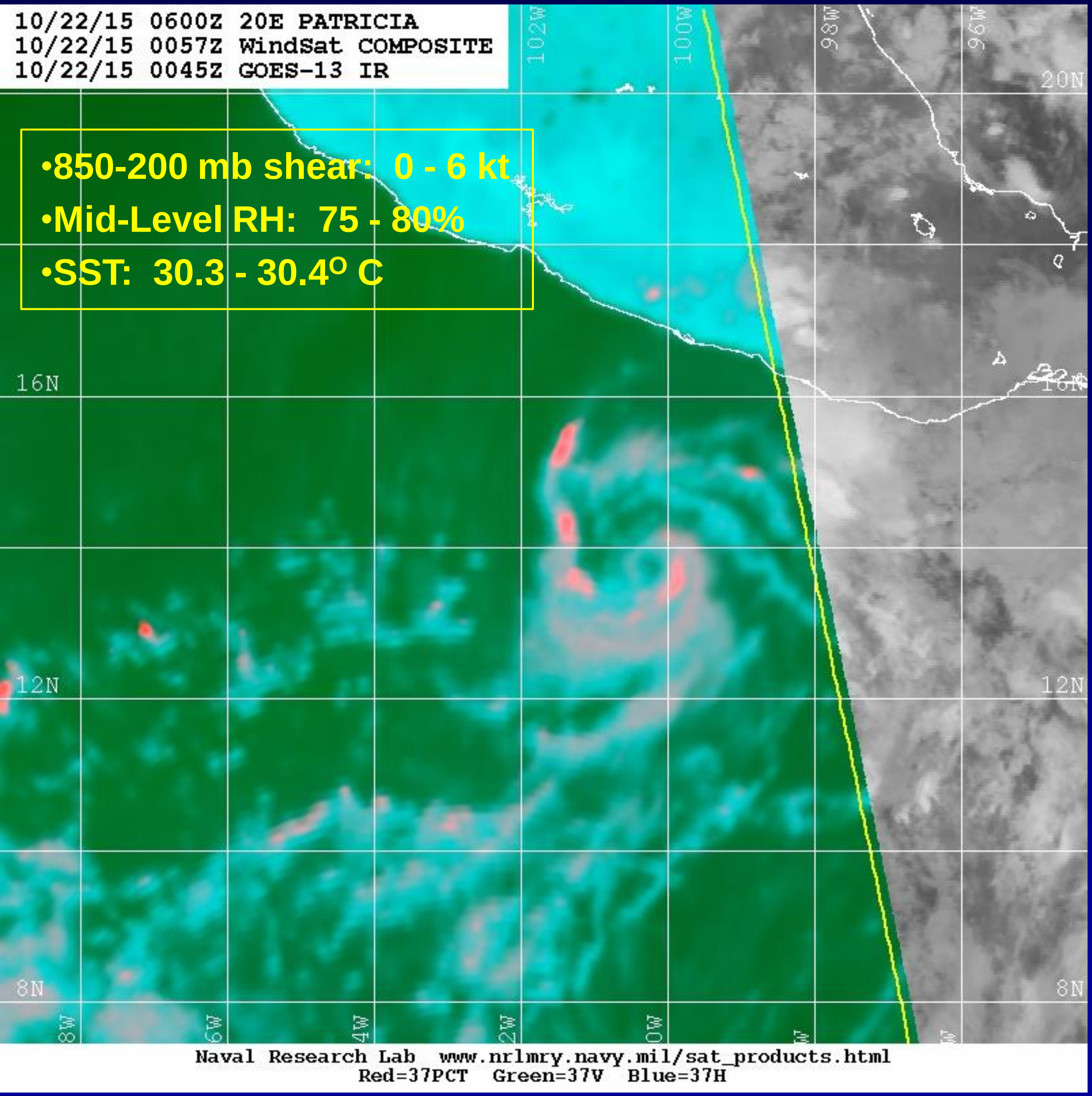
# Helene 18-20 Sep 2006



# Wilma 21-24 Oct 2005



# Precursor Structure Before Rapid Intensification




- A closed low-level ring of convection in 37-GHz imagery can be a precursor signal to rapid intensification *IF* other environmental factors (e.g., vertical wind shear) are favorable
- In the case shown here, Patricia strengthened an incredible 90 kt from 60 kt to 150 kt in only 24 hours!

# Satellite Ocean Surface Vector Winds

# Scatterometry Basics

- Scatterometer → ACTIVE microwave imager
- Microwave energy sensitive to roughness of ocean surface generated by the surface winds
  - Small capillary-scale Bragg Waves
- By viewing the same patch of ocean from several angles, it is possible to derive wind speed and direction

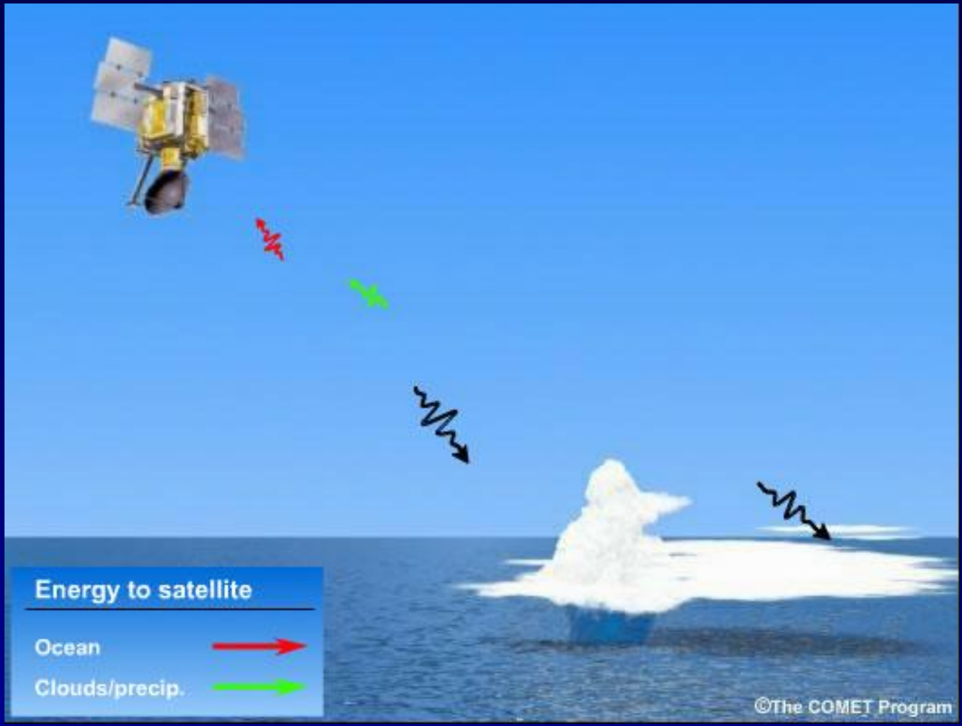
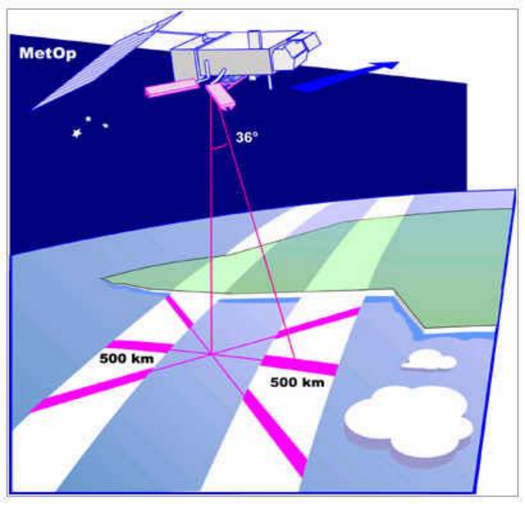



Image courtesy COMET

# Advanced SCATterometer (ASCAT)

Sensor: Microwave radar
Spacecraft: MetOp-1, 2, 3
Launch: 2006, 2012, 2017
Heritage: ERS-1, 2




Channel: 5.25 GHz, C-band

Swath: Two 520-km swaths, with 700-km nadir gap

Utility for TC Applications:

(1) Only long term operational scatterometer series
(2) C-band, less rain contamination, larger footprint
(3) 25- and 50-km wind vector products, good for winds up to gale force (low bias above 35-40 kt)
(4) Gap in swath center over the tropics is a major drawback for coverage

NOAA processed data -- http://manati.orbit.nesdis.noaa.gov/datasets/ASCATData.php

# Example of ASCAT Use

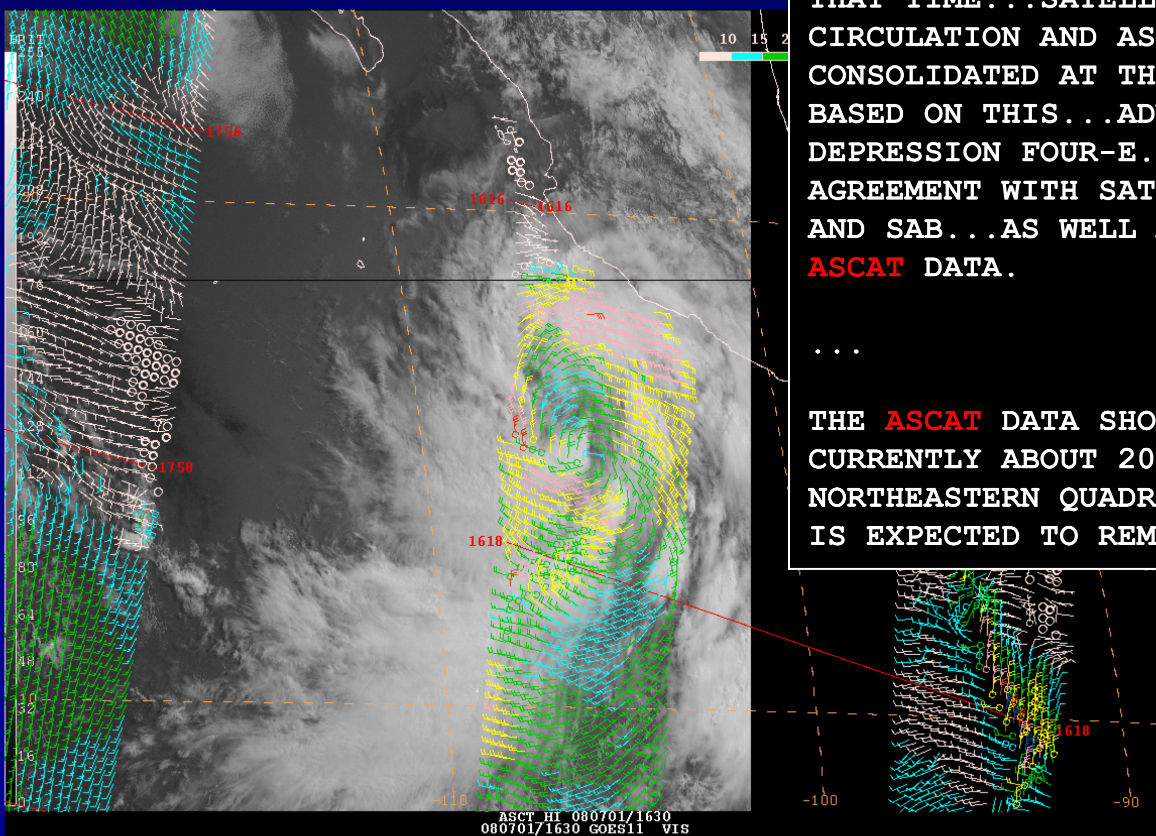
- Used as justification to initiate advisories on TD Four-E (later TS Douglas) and set initial intensity

TROPICAL DEPRESSION FOUR-E DISCUSSION NUMBER 1
NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL EP042008
800 PM PDT TUE JUL 01 2008

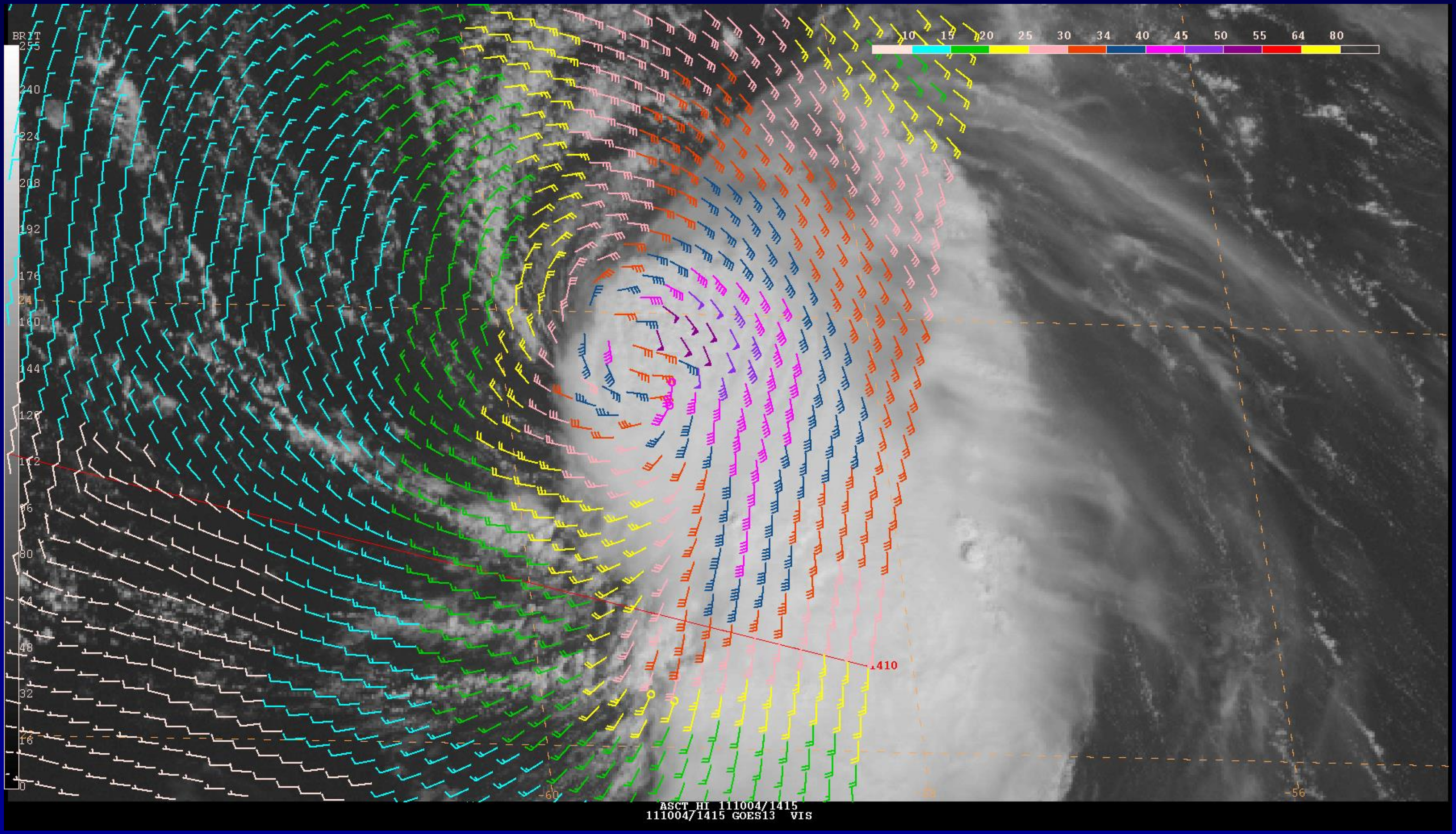
ASCAT DATA AT AROUND 16Z SHOWED THAT THE LOW PRESSURE AREA SOUTHWEST OF MANZANILLO MEXICO HAD A BROAD CENTER ELONGATED NORTH-NORTHWEST TO SOUTH-SOUTHEAST. SINCE THAT TIME...SATELLITE IMAGERY INDICATES THAT THE CIRCULATION AND ASSOCIATED SHOWER ACTIVITY HAS SOMEWHAT CONSOLIDATED AT THE SOUTHERN END OF THE ELONGATION. BASED ON THIS...ADVISORIES ARE INITIATED ON TROPICAL DEPRESSION FOUR-E. THE INITIAL INTENSITY IS 30 KT IN AGREEMENT WITH SATELLITE INTENSITY ESTIMATES FROM TAFB AND SAB...AS WELL AS THE OBSERVED WINDS IN THE EARLIER ASCAT DATA.

...

THE ASCAT DATA SHOWED 25-30 KT WINDS IN A BAND THAT IS CURRENTLY ABOUT 200 N MI FROM THE CENTER IN THE NORTHEASTERN QUADRANT. WHILE THE CENTER OF THE CYCLONE IS EXPECTED TO REMAIN WELL OFFSHORE...

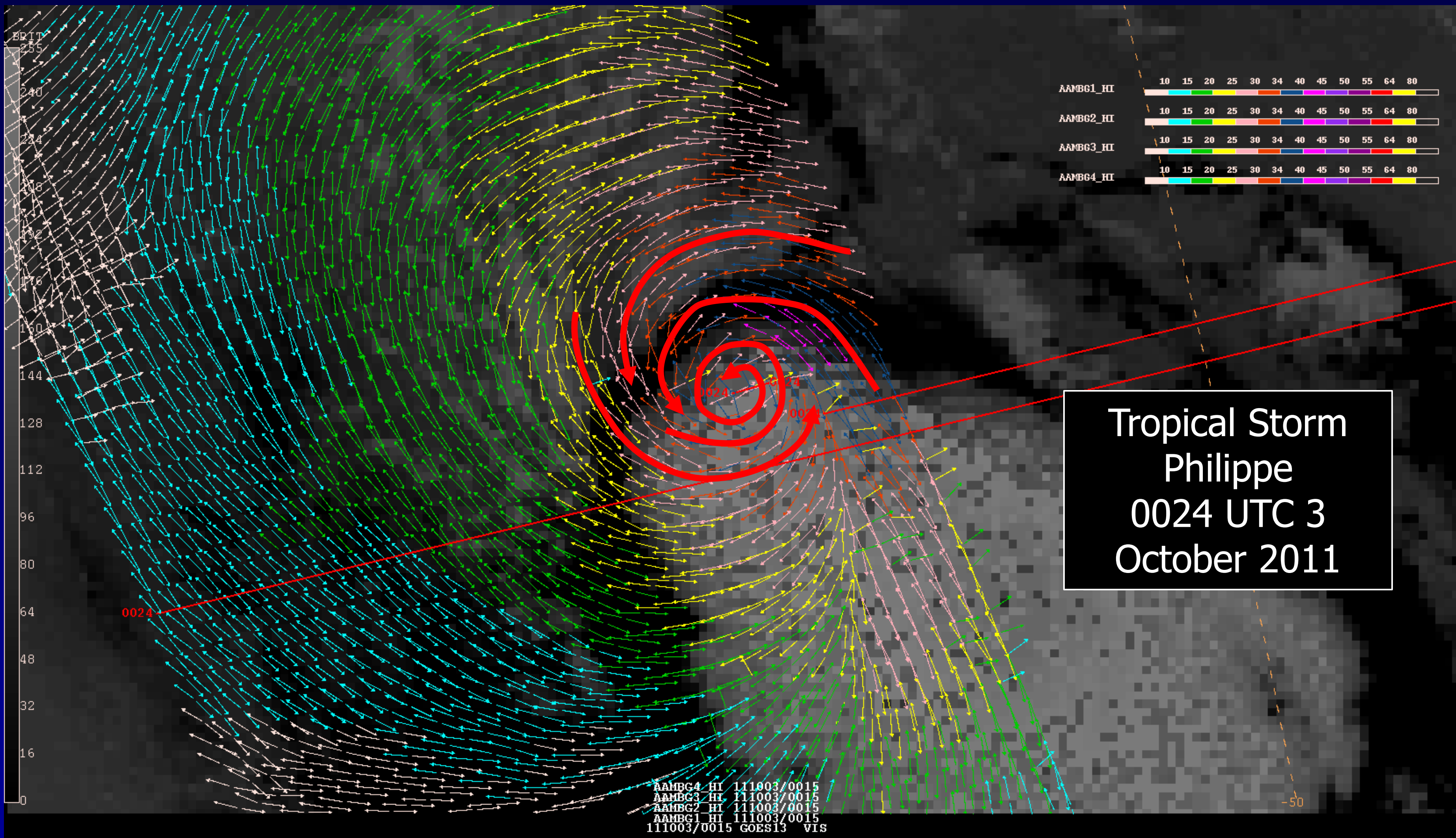


# ASCAT Use in TC Intensity Analysis




- ASCAT pass over Tropical Storm Philippe at 1410 UTC 4 October 2011 revealed the cyclone to be stronger (50-55 kt) than suggested by Dvorak satellite intensity estimates (45 kt)
- It is difficult to assess the peak intensity with ASCAT however due to spatial sampling considerations, especially in stronger TCs

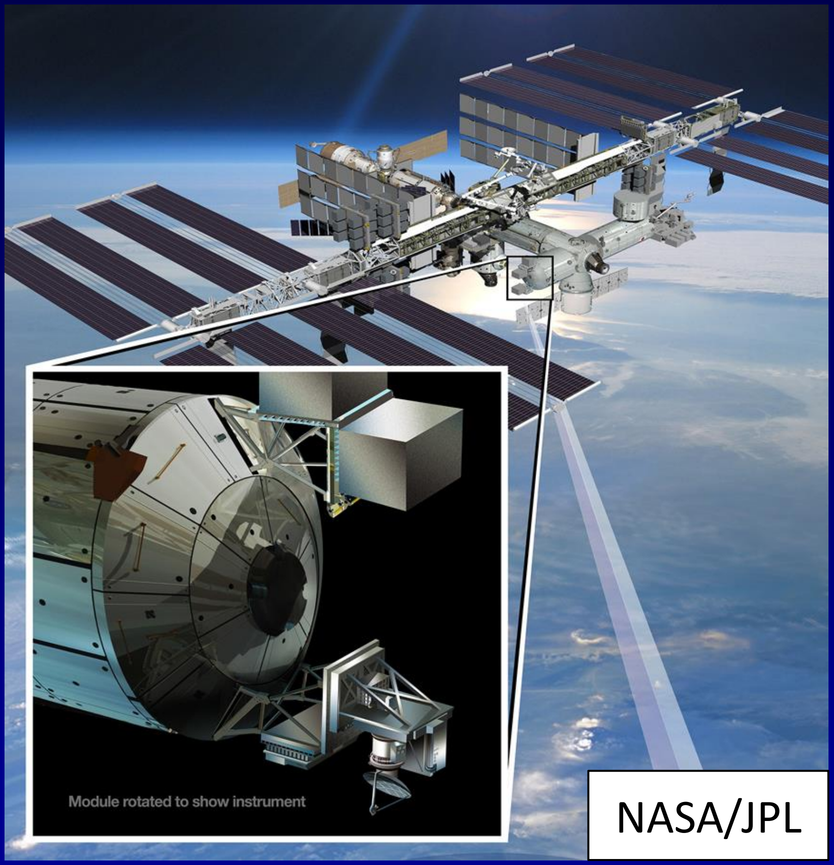
# ASCAT Use in TC Center Fixing




- Reduced rain contamination and prevalence of 3rd and 4th ambiguities in areas of low winds can help make center fixing easier with ASCAT if the pass samples the center location

# RapidScat

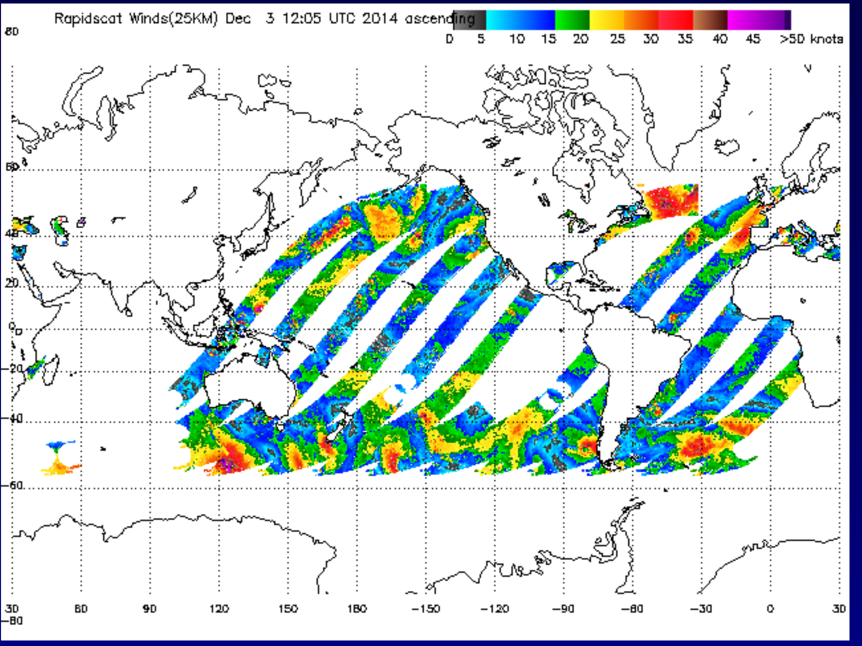
- Instrument built using spare parts from QuikSCAT
- Launched on 21 September 2014 and in orbit on the International Space Station (ISS)
- Ku-band pencil beam configuration
- 800-km wide measurement swath, but varies with altitude of ISS
- Near-real time data available from NESDIS (http://manati.star.nesdis.noaa.gov/datasets/RSCATData.php/RSCATData.php) and on NRL TC page

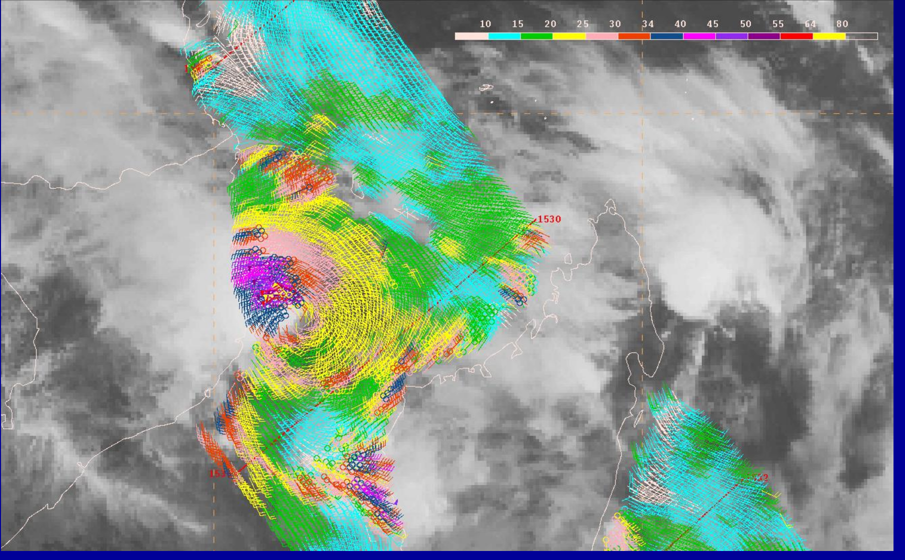


NASA/JPL

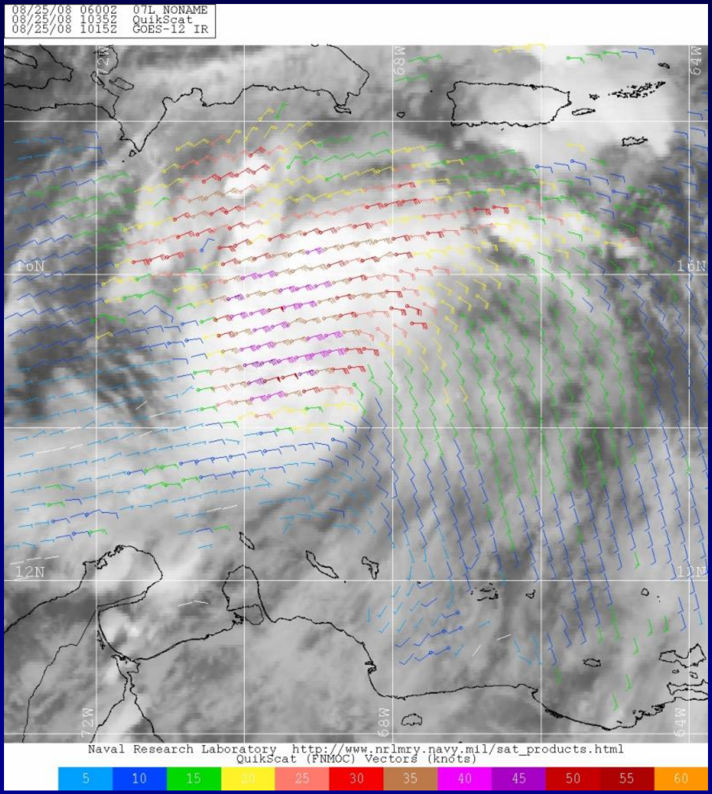
# RapidScat

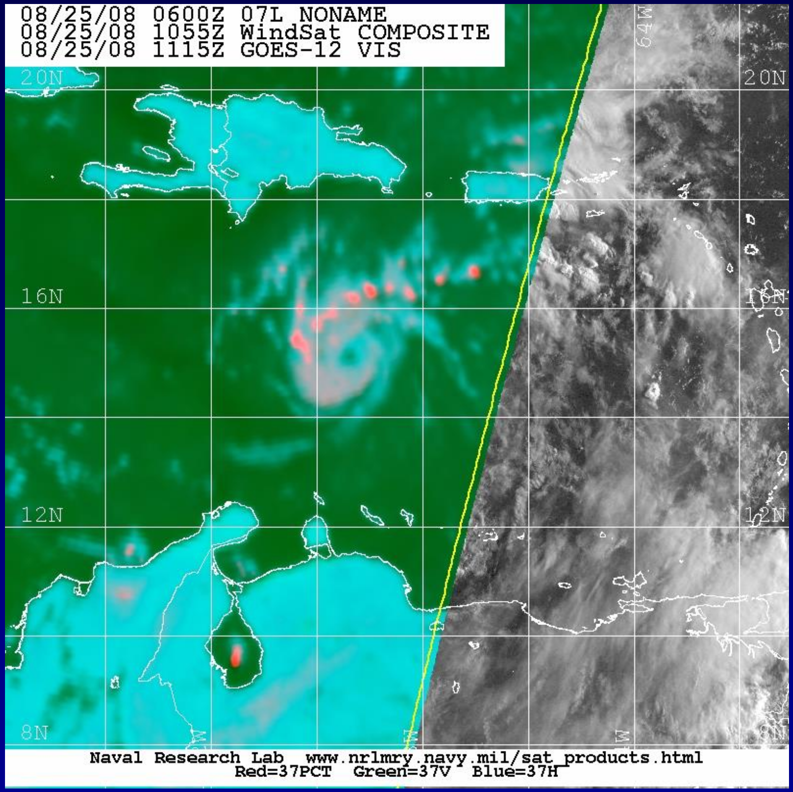
- ISS orbit extends to about 55° latitude, so coverage not optimized in low latitudes
- Ku-band retrievals are quite sensitive to rain, and will be rain inflated a low wind speeds even in the presence of light rain
- Interpretation in TCs is challenging due to rain
- Data will not always be available due to ISS maneuvers and activities (e.g., spacewalks)



# Using Microwave Imagery and Scatterometery Together




- Near co-located QuikSCAT and WindSat passes around 1045 UTC 25 August 2008 over TD 7 (later Hurricane Gustav)
- Advisories initiated at 15Z based partly on evidence of closed circulation from QuikSCAT pass
- Low-level circulation confirmed in microwave imagery from WindSat and aircraft recon found a Tropical Storm at 18Z

# Questions?