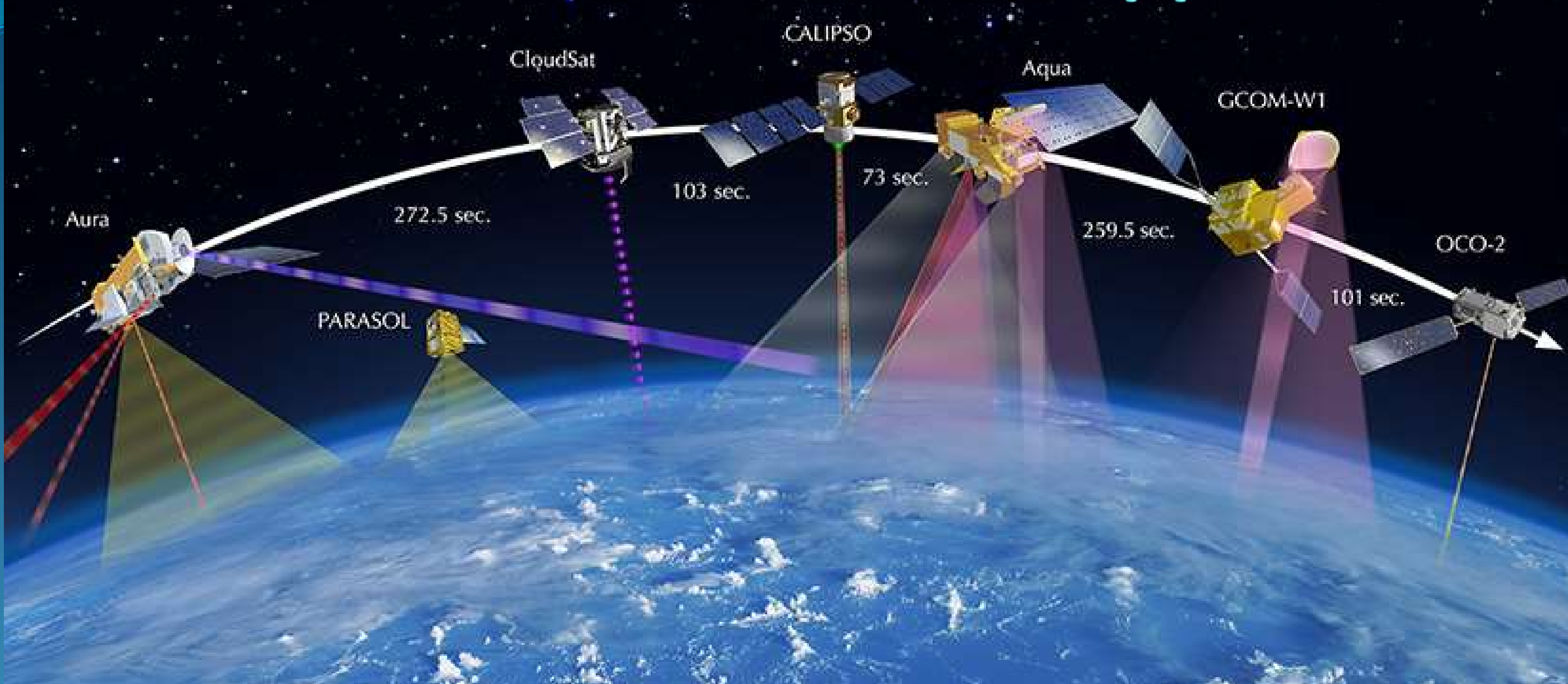
# MET 611 – Satellite Data Applications



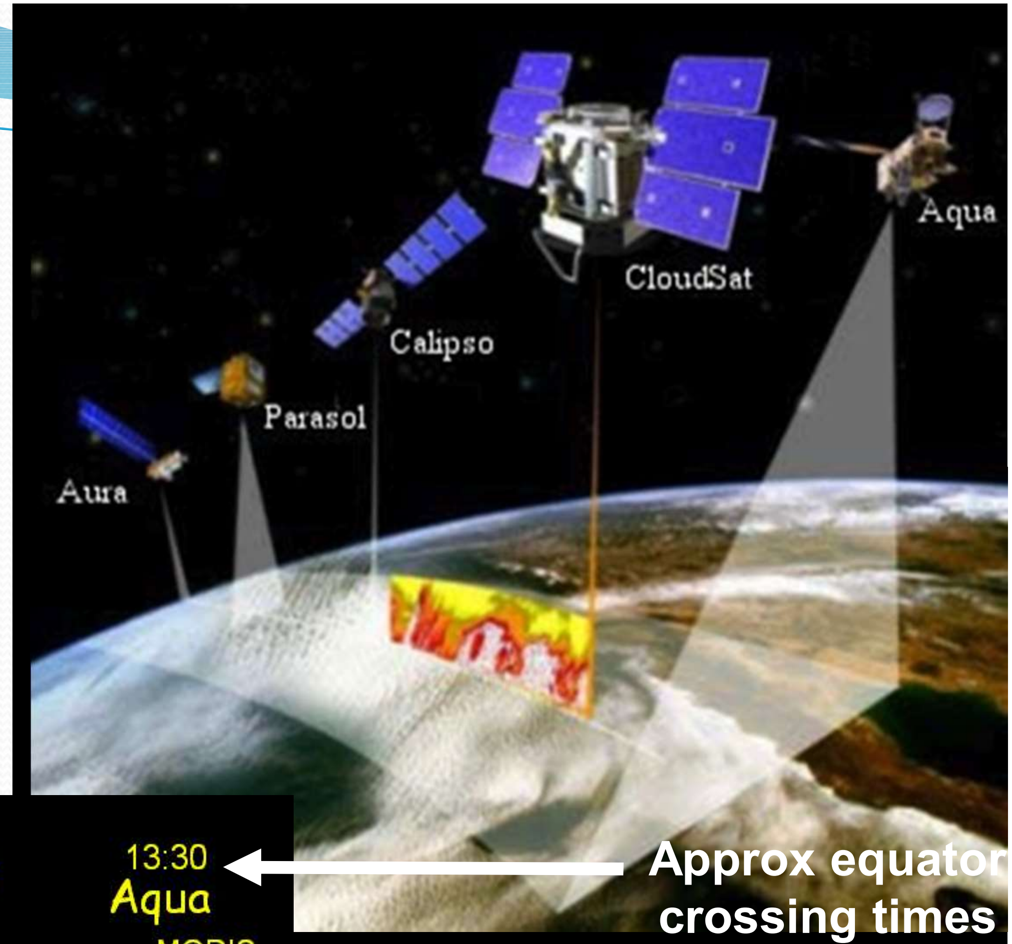

## CloudSat Introduction

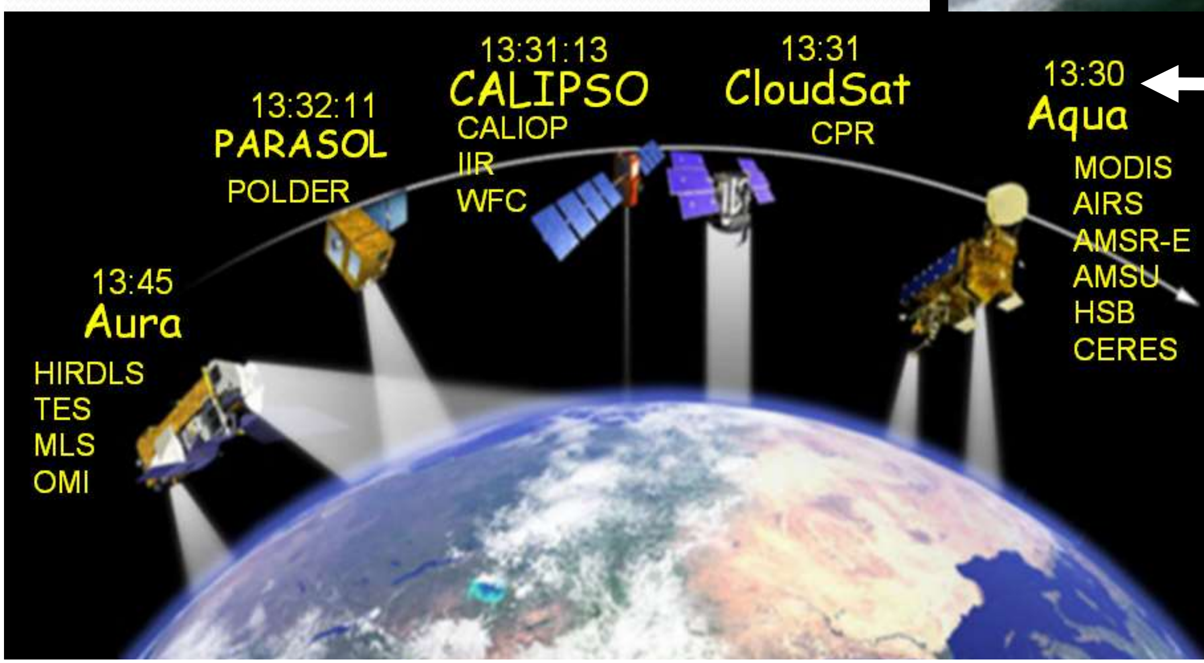
Jennifer D. S. Griswold

# A-Train

- The Afternoon or "A-Train" Satellite constellation presently consists of 5 satellites:
  - NASA Aqua
  - NASA Aura
  - PARASOL
  - CloudSat
  - CALIPSO

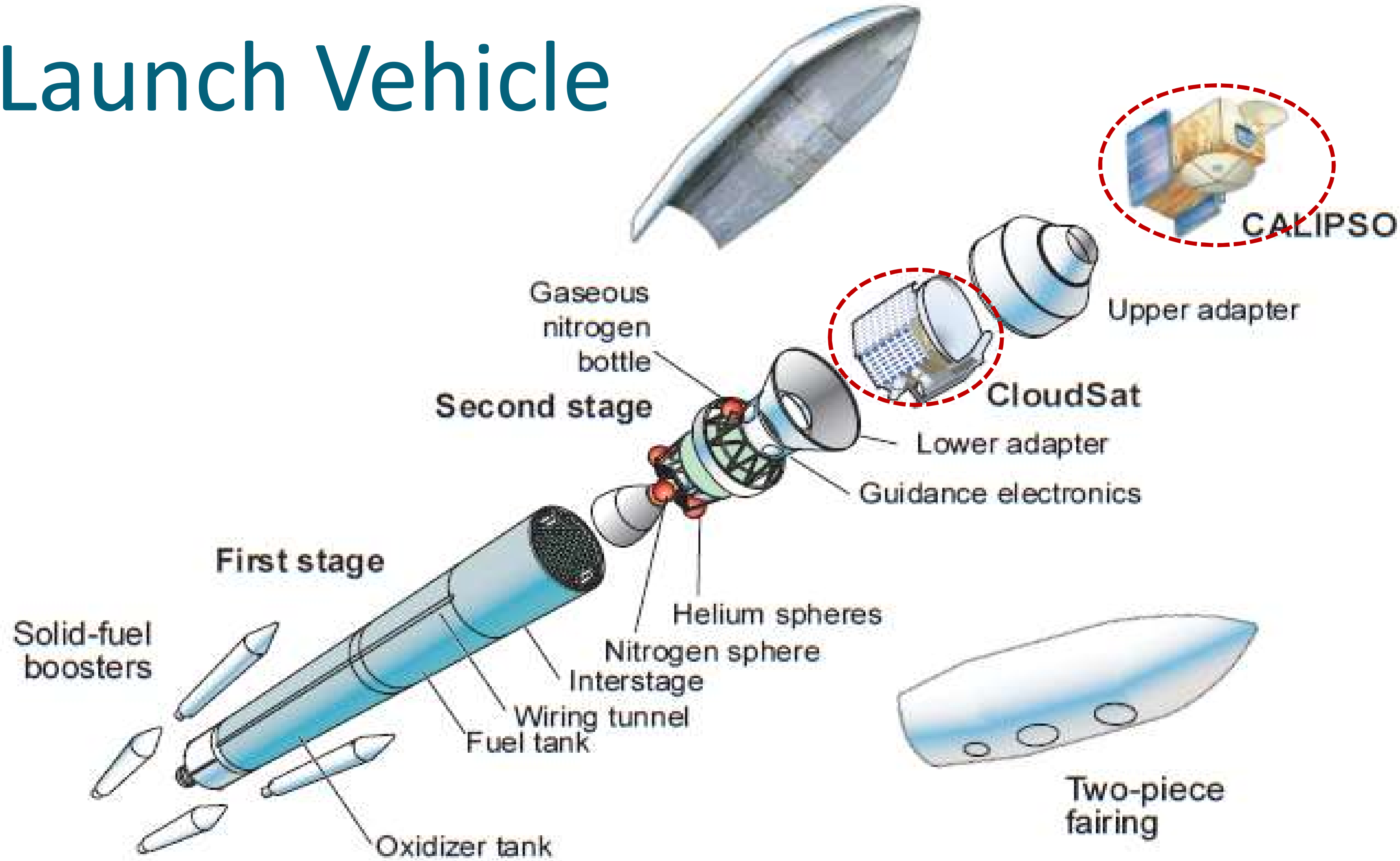
*Inserted behind Aqua in 2006* (CloudSat, CALIPSO)




- **CALIPSO** and **CloudSat** fly in formation enabling an even greater understanding of our climate system from the broad array of sensors on the same orbit.

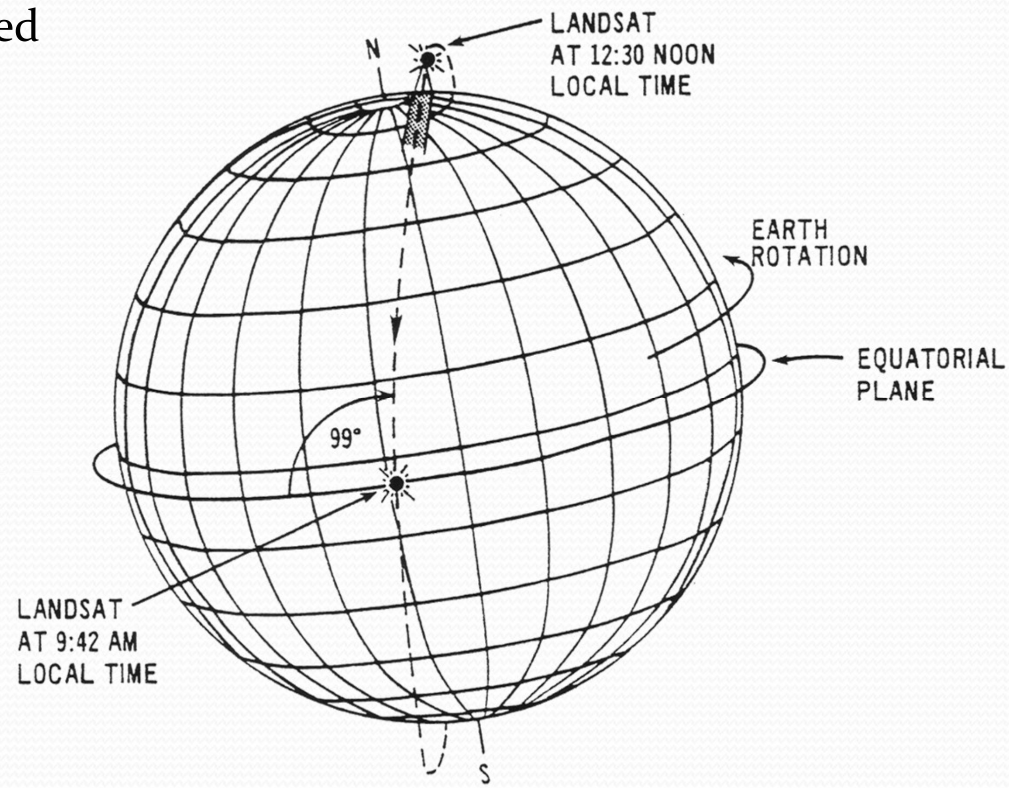
# Launch Vehicle




*Delta II launch vehicle*

# A-Train Orbit

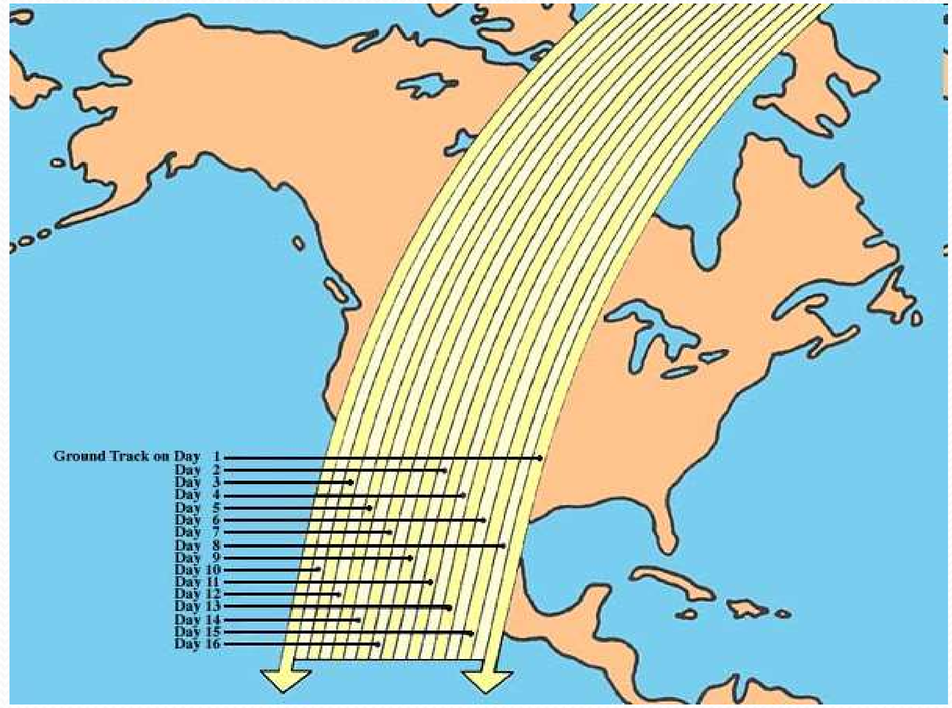
- The satellites in the A-Train are maintained in orbit to match the World Reference System 2 (WRS -2) reference grid used by Landsat

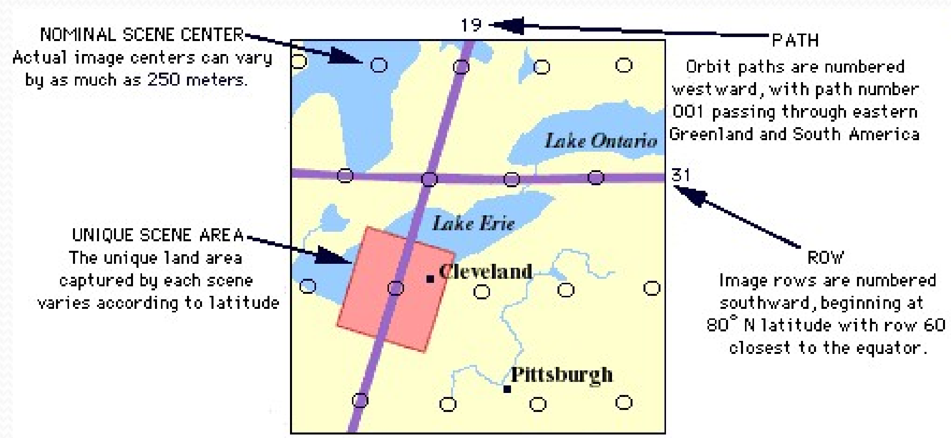



- **CloudSat** and **CALIPSO lag Aqua by 1 to 2 minutes**
- **CloudSat** and **CALIPSO** travel within **10-15 seconds** of each other so that both instrument suites view the same cloud area at nearly the same time.
- Crucial for studying clouds which have **lifetimes often less than 15 minutes**.
- The constellation has a nominal **orbit altitude of 705 km** and inclination of **98 deg**.
- **Aqua leads the A-train** with an equatorial crossing time of about **1:30 pm**

# WRS-2 Reference Grid

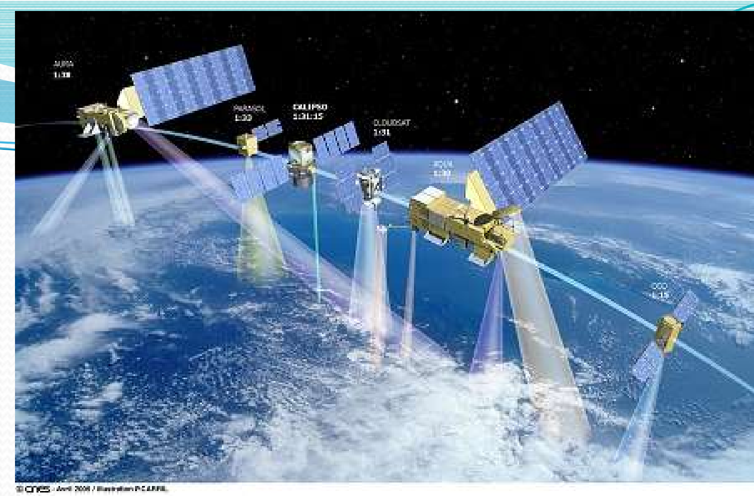
- Developed to facilitate **regular sampling patterns** by remote sensors in the Landsat program
- Landsat-7 and Terra are "morning" satellites in the same orbit as the A-Train
- Each satellite competes 14.55 orbits per day with a separation of 24.7 degrees longitude between each successive orbit at the equator.
- The orbit tracks at the equator and progresses westward 10.8 degrees on succeeding days, which over a 16-day period produces a uniform WRS grid over the globe. The WRS grid pattern of 233 orbits with separation between orbits at the equator of 172 km
- The aqua satellite is controlled to the WRS grid to within +/- 10 km

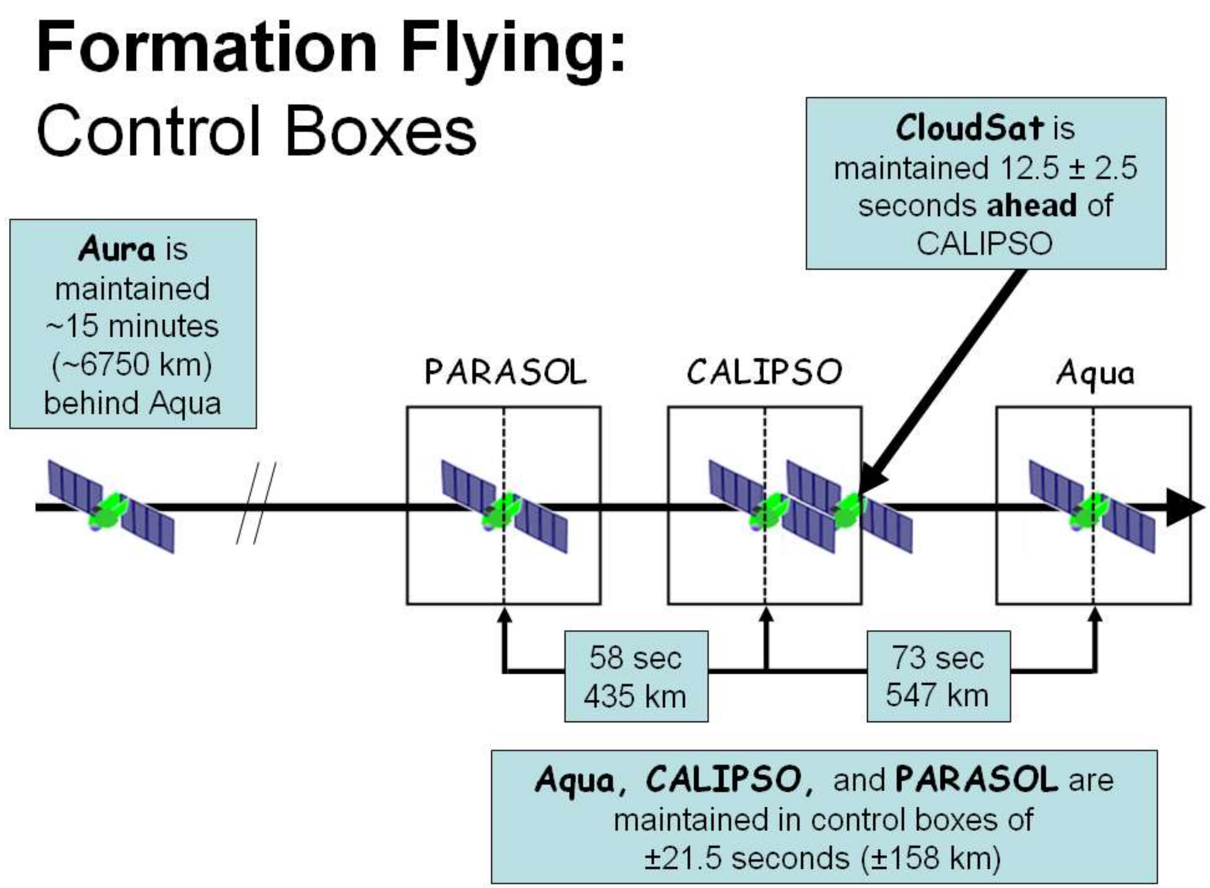


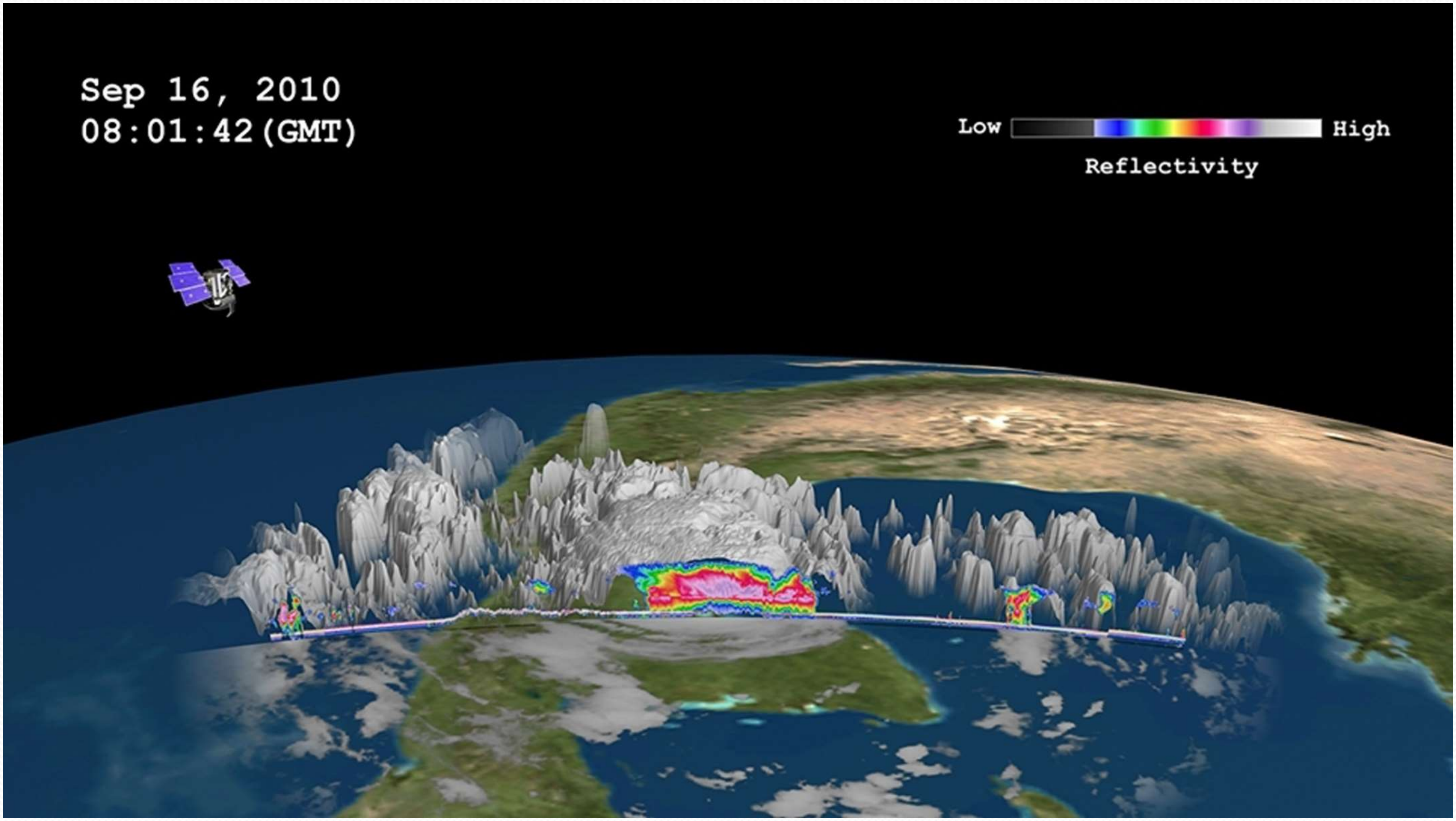
# Formation Flying

- **Control Boxes**
  - Satellites are allowed to drift inside control boxes until they approach the **boundaries of the box**, then **maneuvers** are initiated to adjust the orbit.
- **Staying in "Boxes" is Crucial to:**
  - **maintain the observing times**
  - **geometries of the instruments**
  - **avoid collisions**
    - which would produce a debris field that would threaten the entire formation.





# CloudSat



# CloudSat

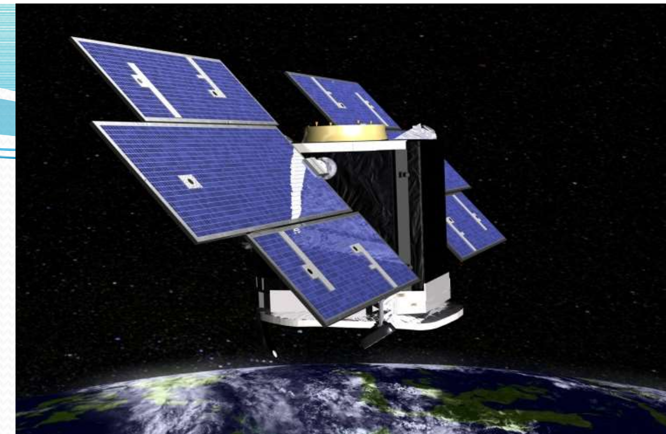
- 1999 selected as a NASA mission, launched **April 28, 2006**

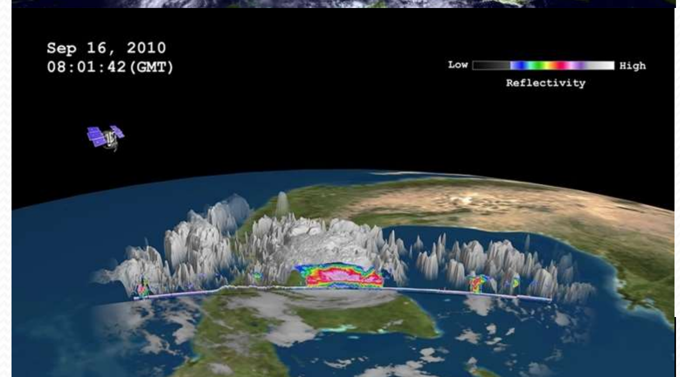
- To Study:
  - Cloud Abundance
  - Distribution
  - Structure
  - Radiative Properties

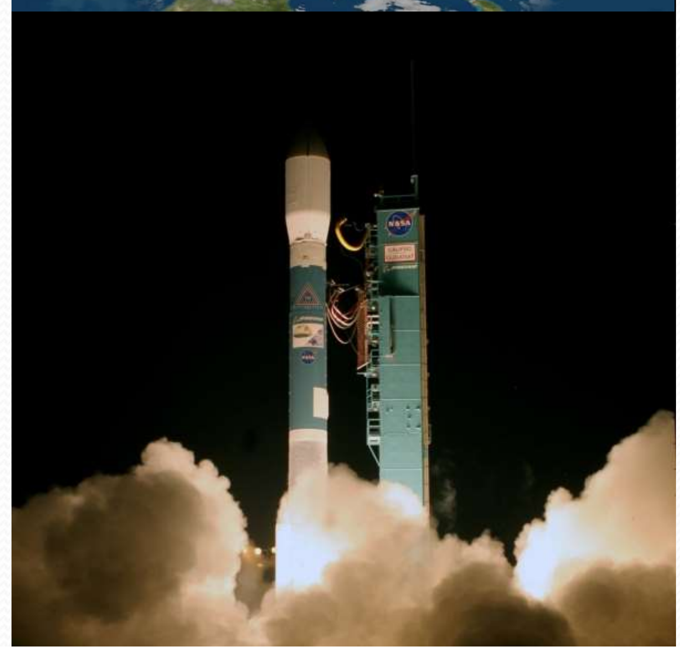
- first satellite-based **mm-wavelength cloud radar**

- more than **1000 times more sensitive** than existing weather radars.
  - 485 m vertical resolution
  - 1.4 km antenna 3 dB footprint

- detection of much smaller particles of liquid water and ice that constitute the large cloud masses





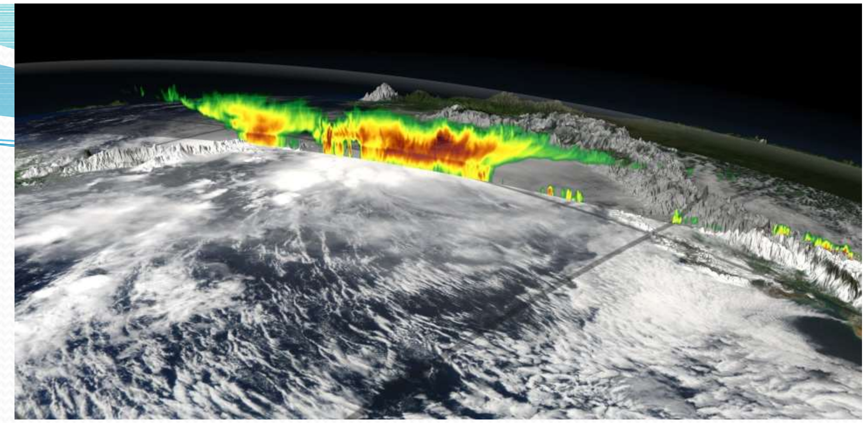



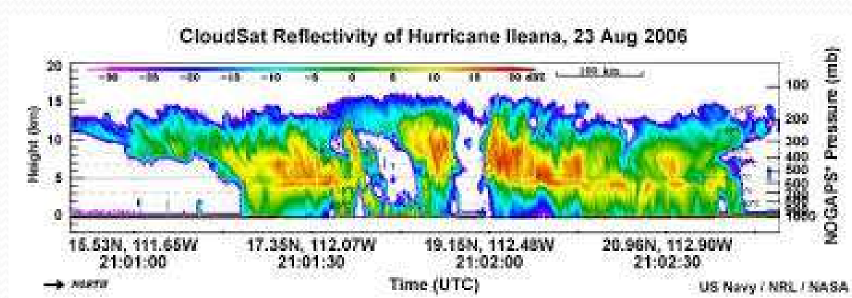
# Mission Objectives

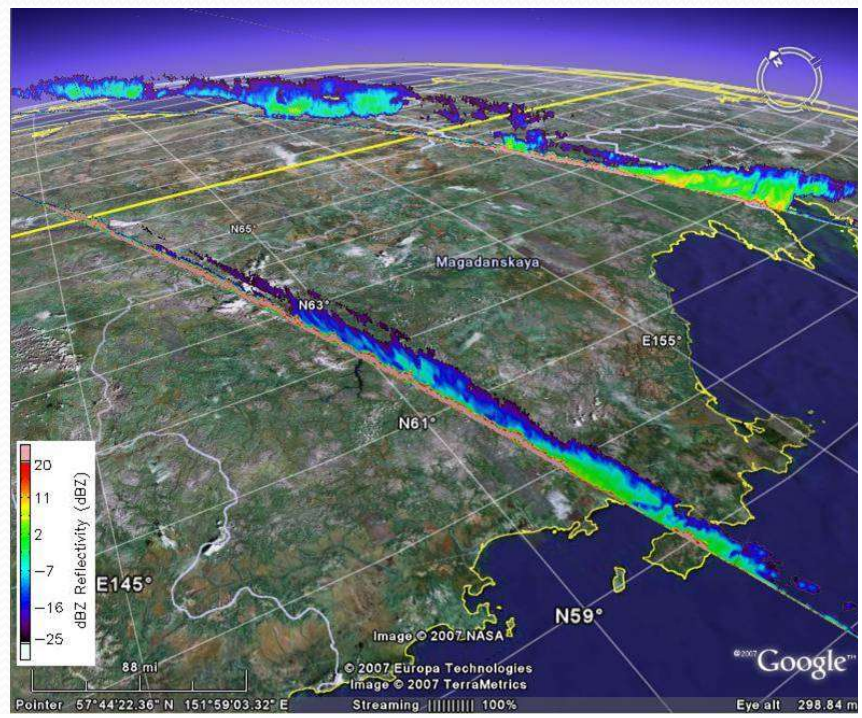
- **Why CloudSat?**
  - Unique in its ability to sense condensed **cloud particles** while coincidently detecting **precipitation**!
  - It has a number of important goals in its mission, including:
    1. Improve the way clouds are parameterized in global models
    2. Quantitatively evaluate the relationship between the vertical profiles of cloud liquid water and ice and the radiative heating of the atmosphere and surface
    3. Evaluate cloud properties retrieved from other satellite systems
    4. Contribute to improving our understanding of the indirect effect of aerosols on clouds by investigating the effect of aerosol on cloud and precipitation formation.
  - Other Goals Include
    - improving weather prediction  and water resource management
    - help mitigate natural hazards
    - develop critical space-born technologies
    - designed to clarify the relationship between clouds and climate
    - It contributes to the better understanding of cloud-climate feedback problem

# Science Questions

- How much water and ice is the cloud expected to contain?
- How much of that water is likely to turn into precipitation?
- What fraction of the globe's cloud cover produces precipitation that reaches the ground?
- Can we quantitatively evaluate the representation of clouds and cloud processes in global atmospheric circulation models, leading to improvements in both weather forecasting and climate predication?
- Can we quantitatively evaluate the relationship between the vertical profiles of cloud liquid water and ice content and the radiative heating by clouds?





# CloudSat Operations

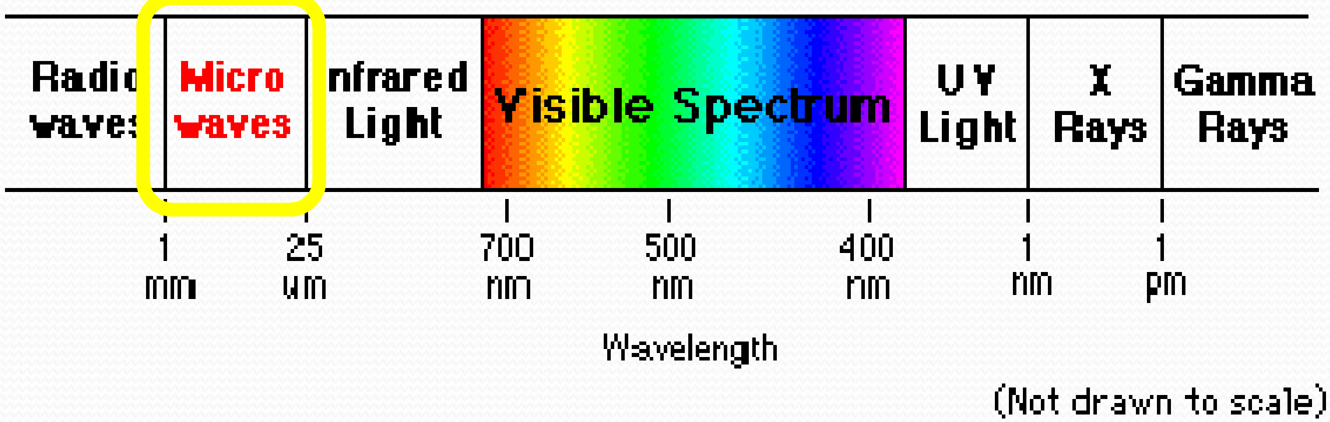
- CloudSat uses **advanced radar** to "**slice**" through clouds, **(Active Sensor scenario)**

- It uses **millimeter wave radar** that operate at wavelengths of approximately **3 to 8 mm (or frequency of 94 or 35 GHz)**

**Table 1.** Cloud Profiling Radar Instrument and Performance Parameters

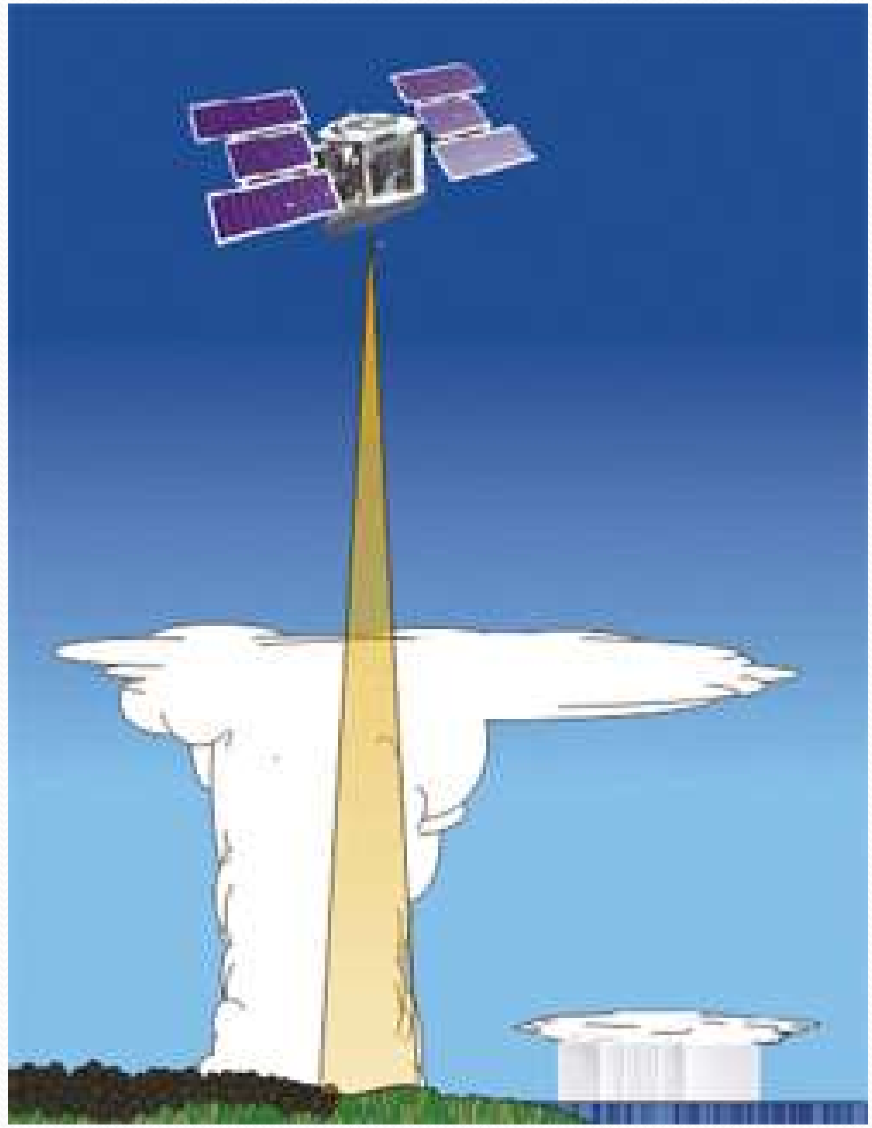
| Parameter | Proposed Performance |
|---|---|
| Frequency | 94.05 GHz |
| Altitude | 705 – 730 km |
| Range resolution (6 dB) | 485 m |
| Cross-track resolution | 1.4 km |
| Along-track resolution | 1.8 km |
| Pulse width | 3.3 $\mu s$ |
| Peak power (measured) | 32.6 dB |
| PRF | 3700 – 4300 Hz |
| Antenna diameter | 1.85 m |
| Antenna gain | 63.1 dBi |
| Antenna sidelobes | $-50$ dB @ $\theta > 7°$ |
| Integration time (single-beam) | 0.16 s |
| Data window | 30 km |
| Minimum detected reflectivity (measured) | $-30$ dBZ |

(Stephens et al. 2008)

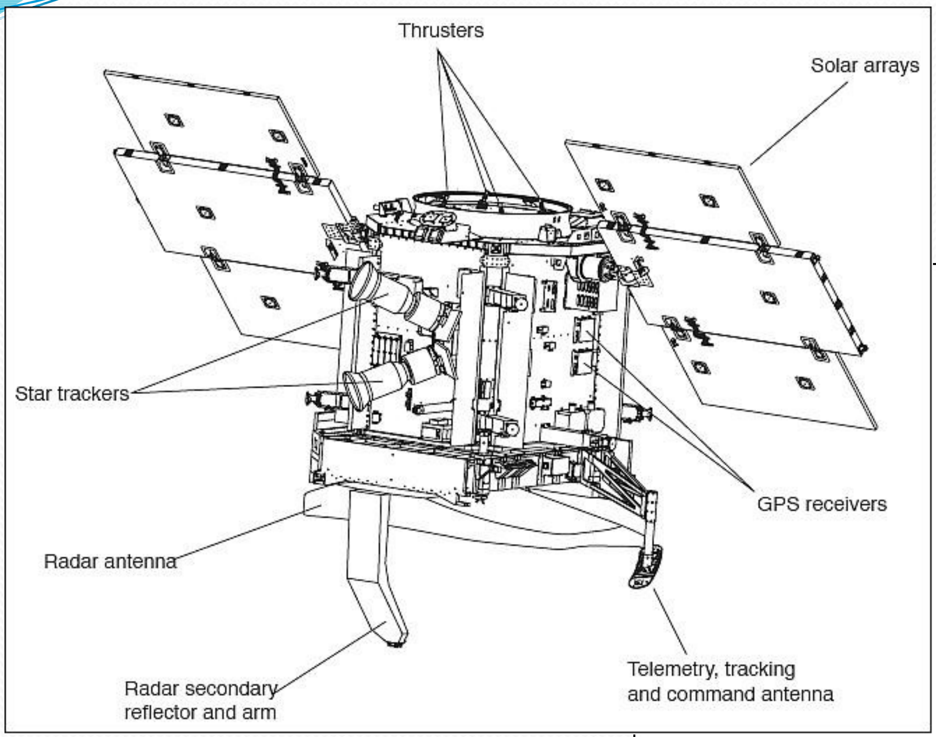


# CloudSat Operations

- **Cloud Profiling Radar (CPR)**
  - CPR is **94 GHz**
  - Developed jointly by NASA's JPL and the Canadian Space Agency
- **Why 94 GHz Radar Frequency?**
  - 3.1 mm wavelength
  - ***Compromise:***
    - Sensitivity
    - Antenna Gain
    - Atmospheric Transmission
    - Radar Transmitting Efficiency
  - Sensitivity and Antenna Gain **increase with frequency**
  - Atmospheric Transmission and Transmitter Efficiency **decrease with frequency**

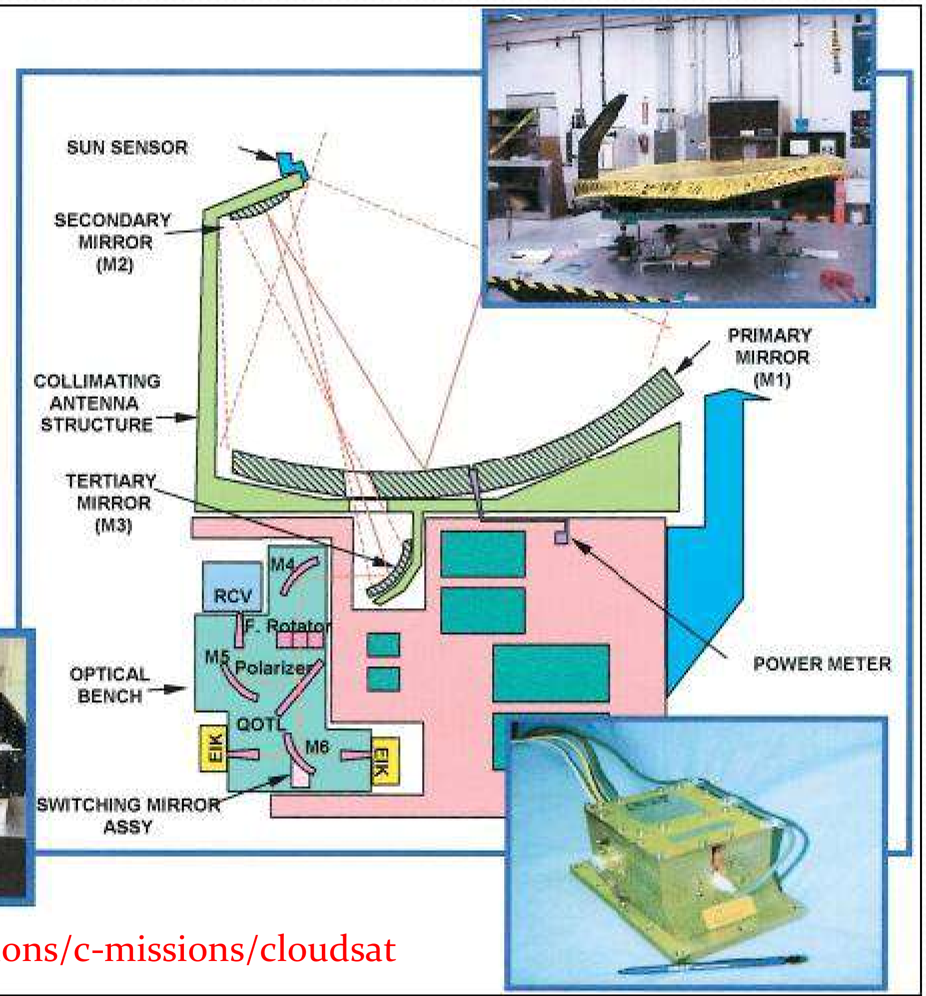


# CloudSat CPR




- The design of the CPR consists of the following subsystems:
  - **RFES (Radio Frequency Electronics Subsystem)**
    - The RFES consists of an up-converter which generates a pulsed signal and up-converts it to 94 GHz.
  - **HPA (High Power Amplifier)**
    - The signal is amplified to about 200 mW by a state-of-the-art MMIC power amplifier.
  - **Antenna Subsystem (Quasi-Optical Transmission Line)**
  - **DSS (Digital Subsystem)**

- The receiver portion of the RFES down-converts the signal to an IF (Intermediate Frequency).
- The IF signal is detected using a logarithmic amplifier (high dynamic range).
- The receiver noise level is critical in achieving the required sensitivity.




https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cloudsat

# CPR Profile Data

(Stephens et al. 2008)

- Range-resolved radar cross section per unit volume, $\eta$, at a specific range $r$:

$$\eta = \frac{P_{rec}(4\pi)^3 r^2 L_a}{P_t \lambda^2 G_{rec} G^2 \Omega \Delta}$$

- $\eta$ = range-resolved radar cross section per unit volume
- $P_{rec}$ =output power of the receiver
- $P_t$ = transmitted power
- $\lambda$ = wavelength
- $G_{rec}$ = the receiver gain
- $G$ = the antenna gain
- $r$ = range to the atmospheric target
- $\Omega$ = integral of the normalized two-way antenna pattern
- $\Delta$ = integral of the received waveform shape
- $L_a$ = the two-way atmospheric loss

Absolute calibration requires precise knowledge of:

$r$, $\lambda$, $G_{rec}$, $\Omega$, $\Delta$, $P_{rec}$, and $P_t$

Expected Accuracy of 2dBZ!

# CPR Profile Data

(Stephens et al. 2008)

- The quantity, $\eta$, is converted to the equivalent (attenuated) range resolved reflectivity factor:

$$Z_e = \eta \frac{\lambda^4 10^{18}}{\pi^5 |K_w|^2}$$

- $Z_e$ = range-resolved reflectivity factor
- $\eta$ = range-resolved radar cross section per unit volume
- $\lambda$ = wavelength
- $|K_w|$ = set to 0.75 representative of water at 10°C

# CloudSat Operations -Radar

- Radar reflectivity (Z) of a cloud is dependent on the Number (N) and size (D) of reflectors (Roughly Z= [$mm^6/m^3$])
  - **Rain, Snow, Graupel, hail**

$$Z = \int_0^{Dmax} N_0 e^{-\Lambda D} D^6 dD$$

- Z is also expressed in dBZ to account for the very large and very small values attributed to the different size reflectors

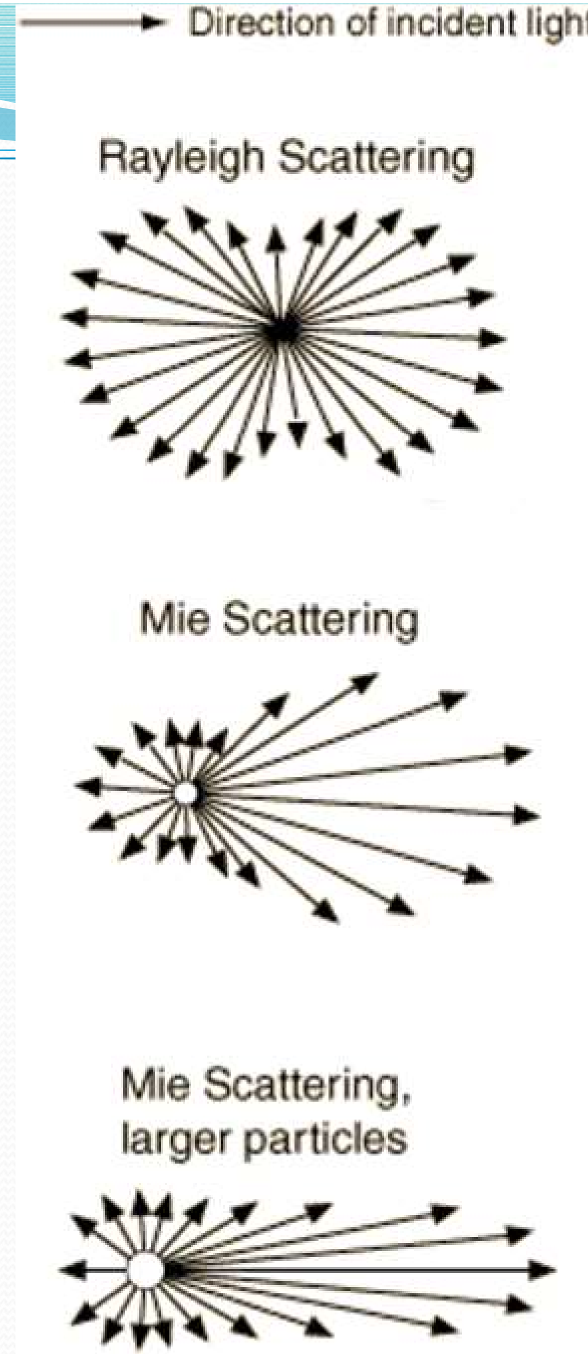
$$dBZ \propto 10 \log_{10} \frac{Z}{Z_0}$$

- Can be converted to rainfall rates:

$$\frac{\text{mm}}{\text{hr}} = \left( \frac{10^{(dBZ/10)}}{200} \right)^{\frac{5}{8}}$$

# Radar in Space

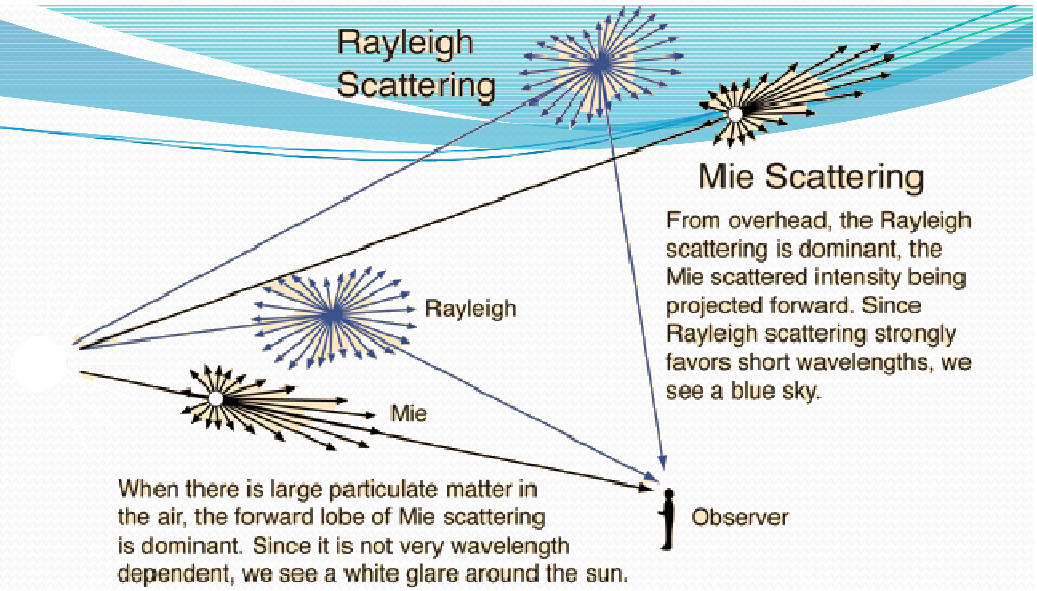
- While TRMM has been a successful precipitation radar, its 17-18 dBZ minimum detectable signal does not allow views of light precipitation and/or clouds (except some anvils) due to wavelength and sensitivity
- Going to a higher frequency increases sensitivity to smaller particles ($D^6$)
- However, Mie effects are more likely to occur, so there is some tradeoff
- W-Band (mm-wave) is an attractive option, since it is sensitive to many large cloud particles
- It has been demonstrated as an excellent airborne (Wyoming King Air) and ground-based platform, in combination with lidar, to estimate IWC and LWC in clouds

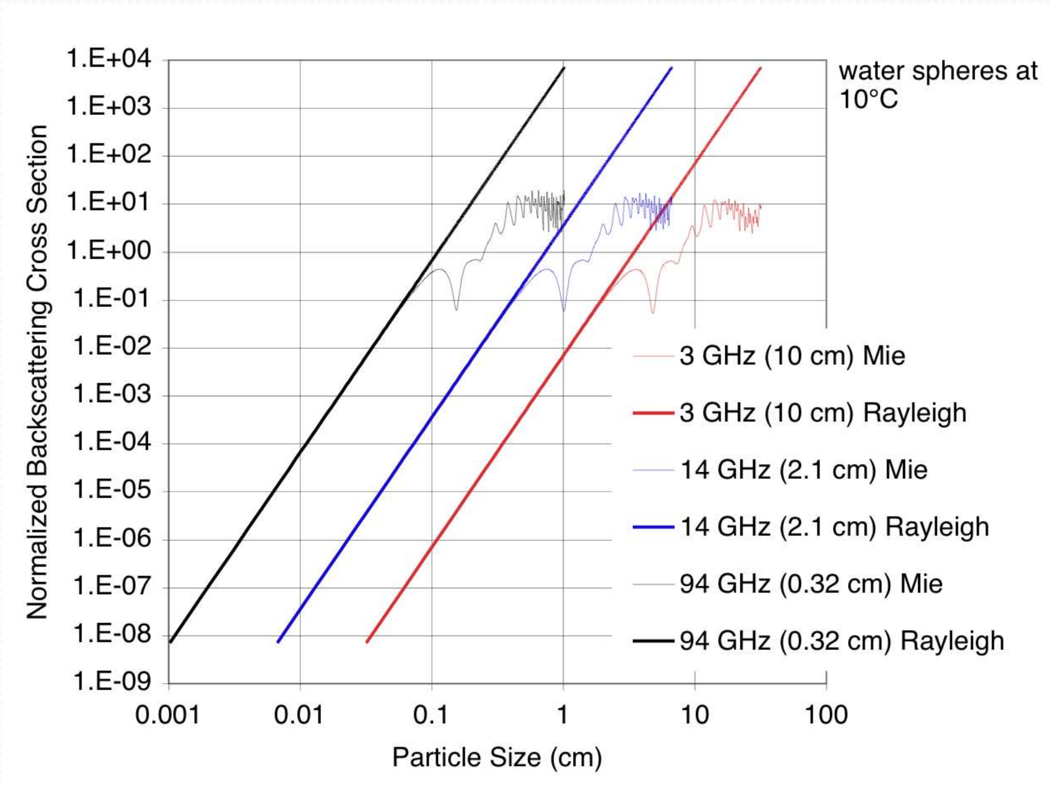


# Radar in Space

- Radar energy becomes more susceptible to Mie scattering as wavelength gets shorter or particles get larger (cutoff at x = $\pi$*D/$\lambda$ - from geometric optics)

- above this cutoff, Rayleigh assumption breaks down and backscattered energy (in this case, *Z*) is reduced



# Attenuation

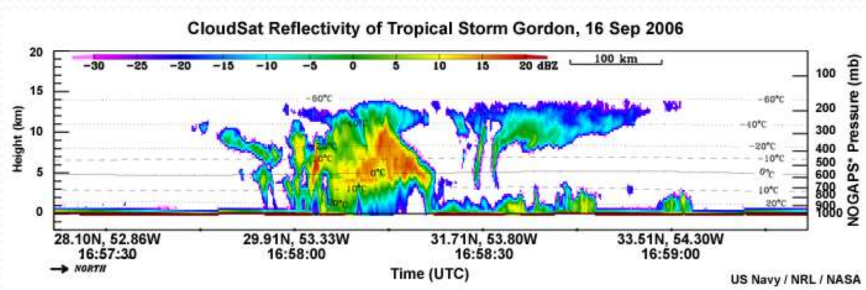
- Depending on wavelength and the concentration of molecules, cloud particles, and precipitation-sized particles, power loss due to attenuation can be very significant.

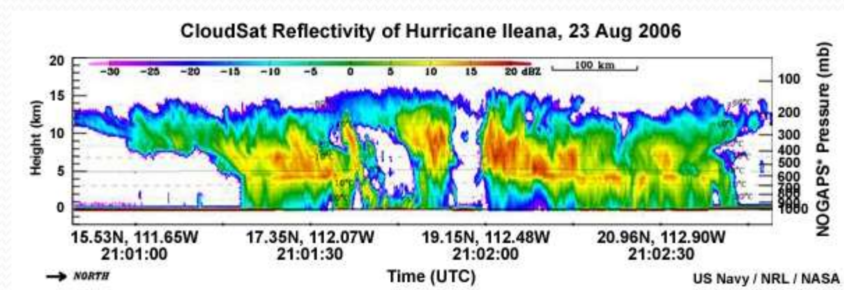
- This power loss of either the transmitted power moving out to the target, or the backscattered power returning from the target is a result of both:

Power loss → Absorption

Power loss → Scattering (by particles along the path)

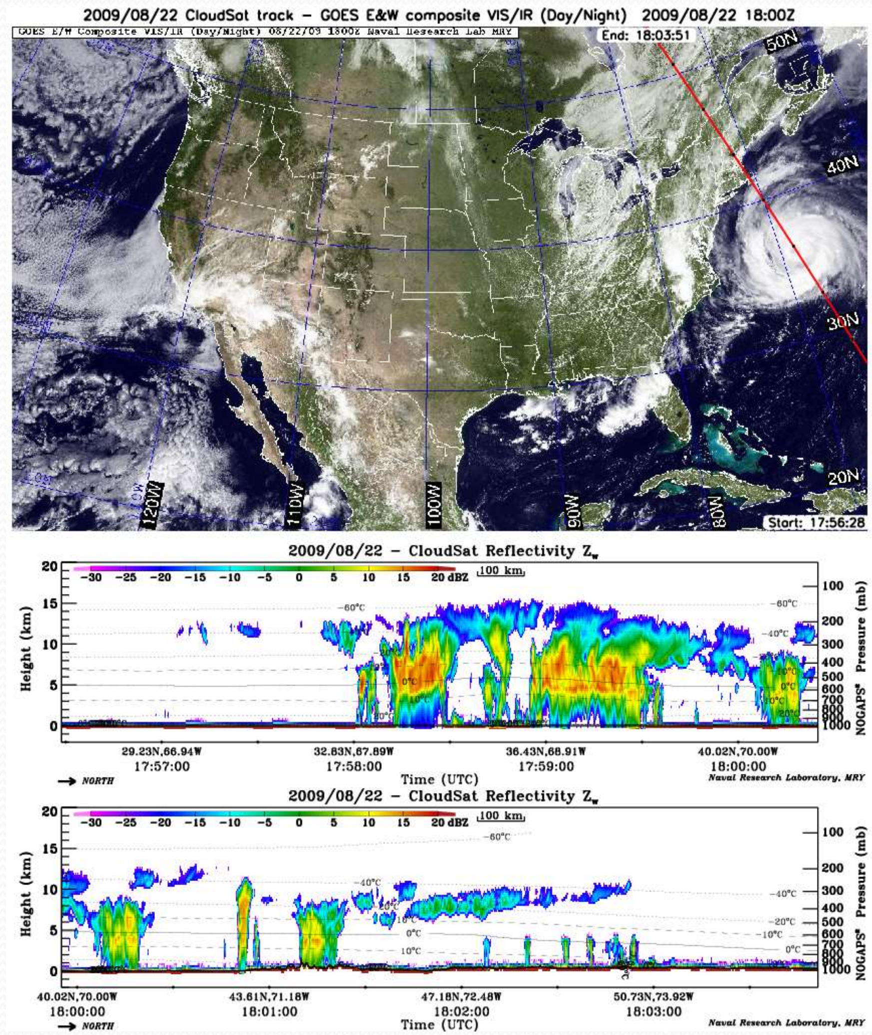
- Attenuation From:
  - **Gases**
    - At radar wavelengths attenuation by gases is associated with **absorption only**
    - **Scattering is negligible at radar wavelengths**
    - Attenuation can be very substantial at wavelengths near 1 cm over long path lengths near the Earth's surface.
  - **Cloud Particles & Precipitation**
    - Attenuation by cloud and precipitation particles can be due to both **absorption** and **scattering**. **Attenuation will therefore be dependent upon particle size, shape, and composition.**



# CloudSat Operations -Radar

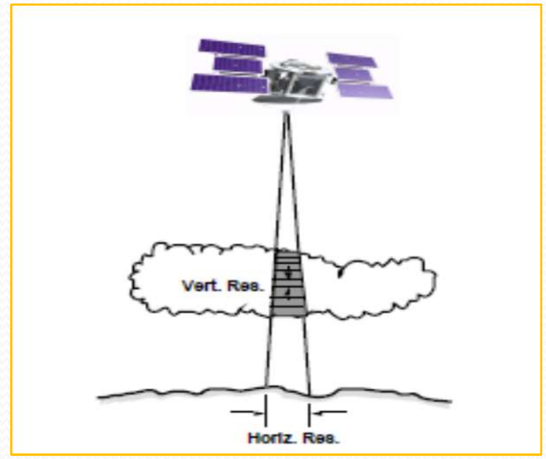
- **What does dBZ stand for?**
  - **dB = "decibel"**
    - Unit used to express differences in relative power or intensity
  - **Z** = **Reflectivity Factor**
    - amount of transmitted energy that is reflected back to the radar receiver
- <u>In General:</u>
  - **The higher the dB value the larger the object detected (Ex: large rain drops)**
  - Values of dBZ < 15 usually indicate very light precipitation that evaporates before reaching the ground
- **Original requirements on CPR**
  - Sensitivity defined by a minimum detectable reflecitvity factor of around **-30 dBZ (actual ~30-31 dBZ)**
    - Due to the fact that clouds are weak scatterers of microwave radiation

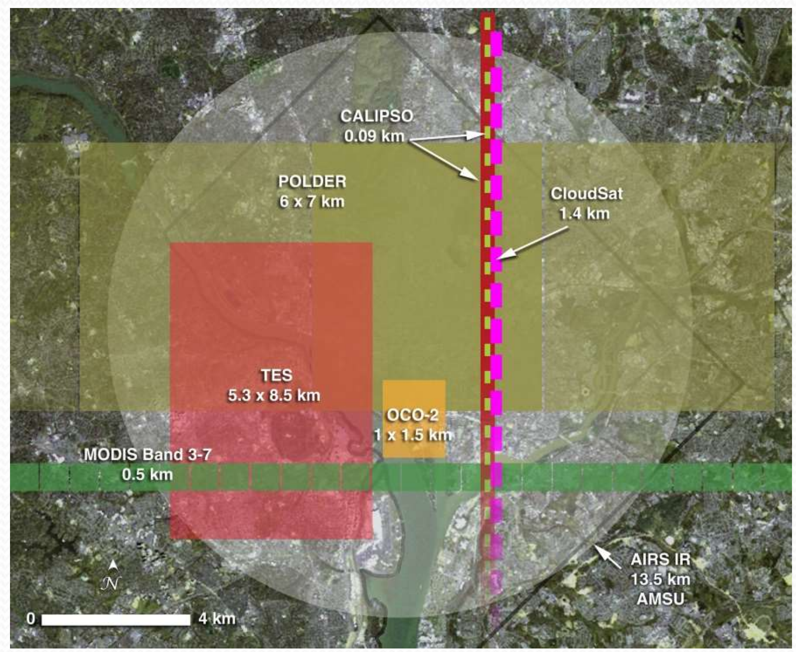



Hurricane Bill

# Other CPR Properties

- **Radar Sampling** takes place at 625  kHZ
- **Burst Rate** 0.16 s/burst
  - The interval to create a CloudSat "ray" or Profile
- **Pulse Repetition Frequency (PRF)** 3400-4300
  - (4300 pule/sec) * (0.16 s/burst) = 688 pulse/burst
- CloudSat antenna has a diameter of 1.85 m
  - **Footprint** = **1.4 km across track area**
    - Is the area covered by a satellite
    - Describes the horizontal spatial resolution
- CloudSat has **125 vertical** bins with approximately
  - **240 m Vertical Spatial Resolution.**

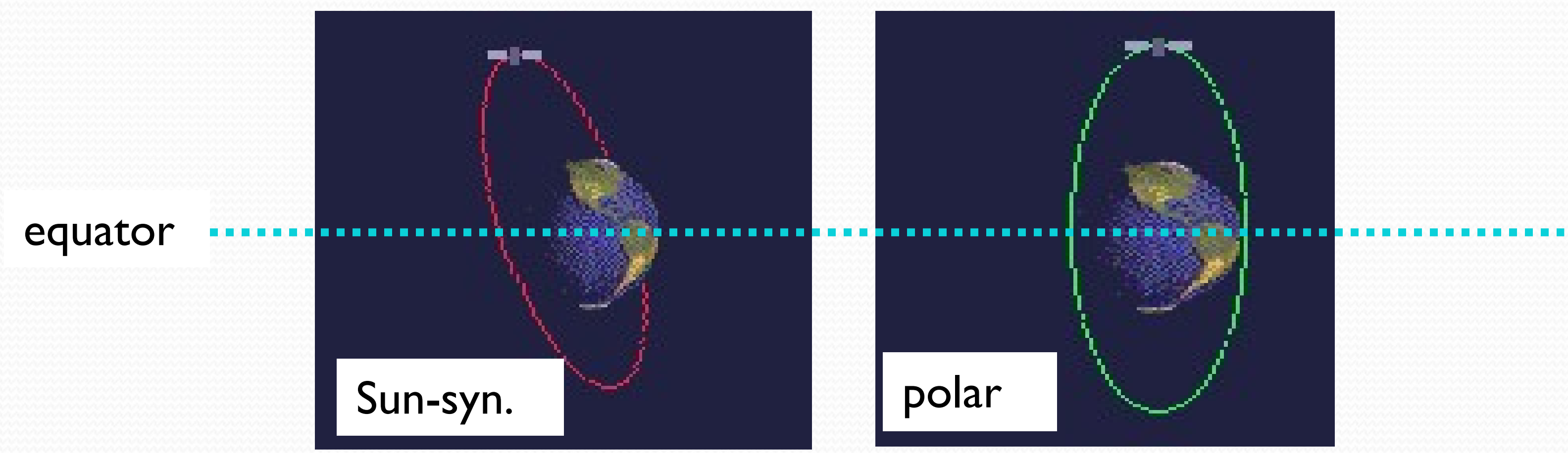


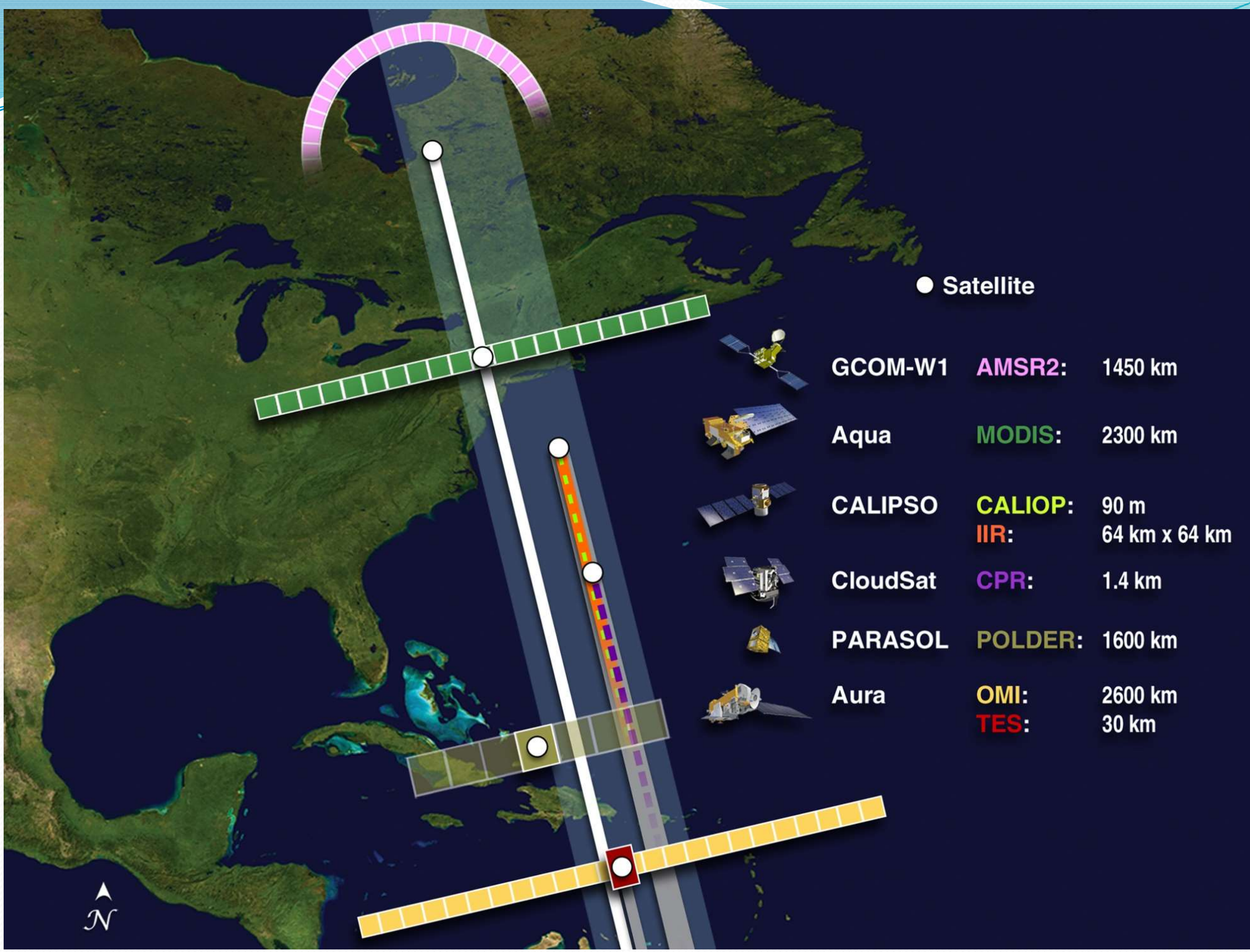



# CloudSat Orbit

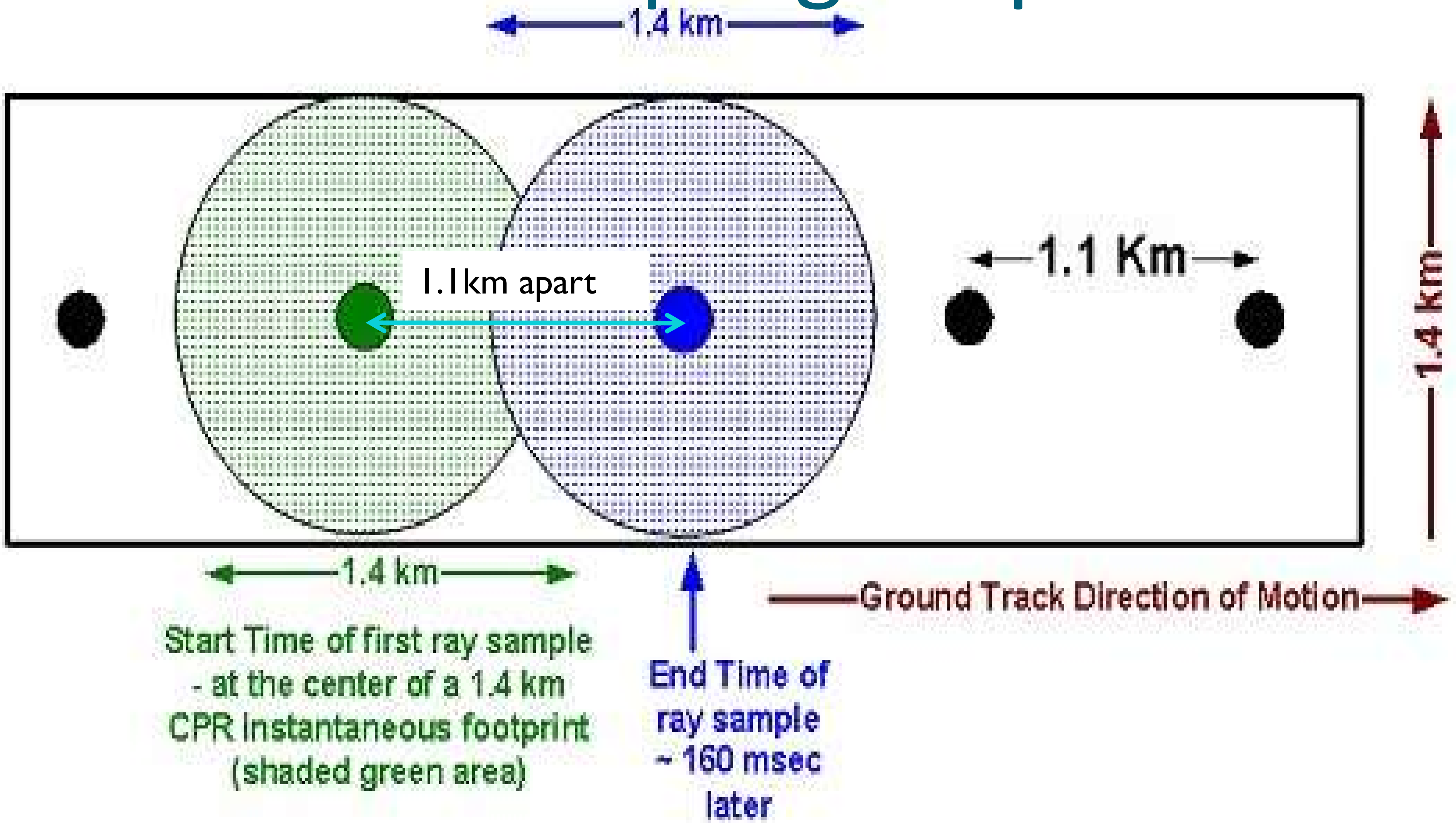
- CPR is flown in a **sun synchronous orbit** at 98 deg inclination angle and altitude raging from 705-230

- Along track velocity of **7 km/s**
  - With the velocity and sample rate of 0.16 sec/profile we determine that:
    - **CPR profile will be generated every 1.1 km along track**



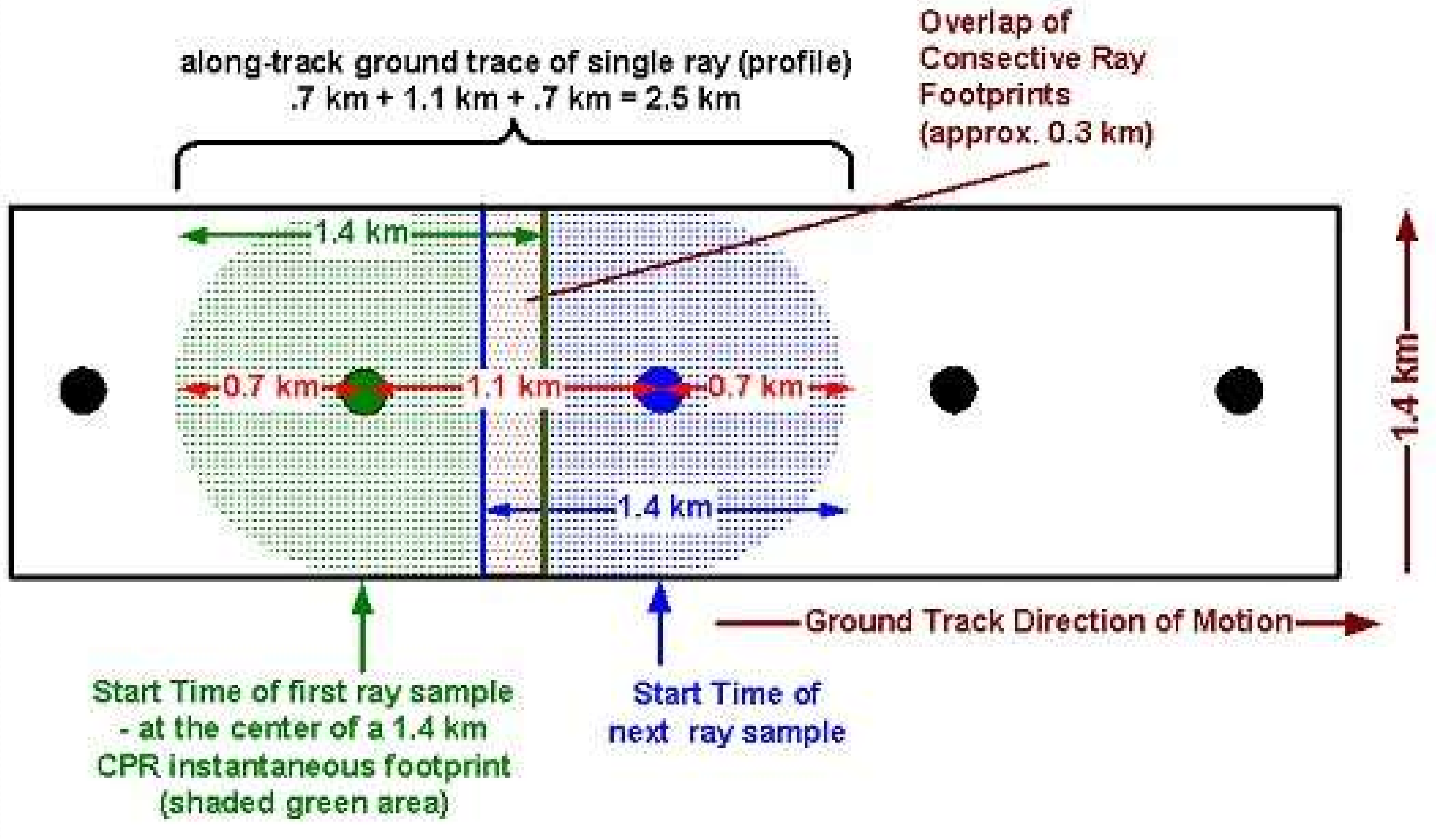

Satellite
GCOM-W1
AMSR2:
1450 km
Aqua
MODIS:
2300 km
CALIPSO
CALIOP:
90 m
IIR:
64 km x 64 km
CloudSat
CPR:
1.4 km
PARASOL
POLDER:
1600 km
Aura
OMI:
2600 km
TES:
30 km
N

# Other CPR Sampling Properties



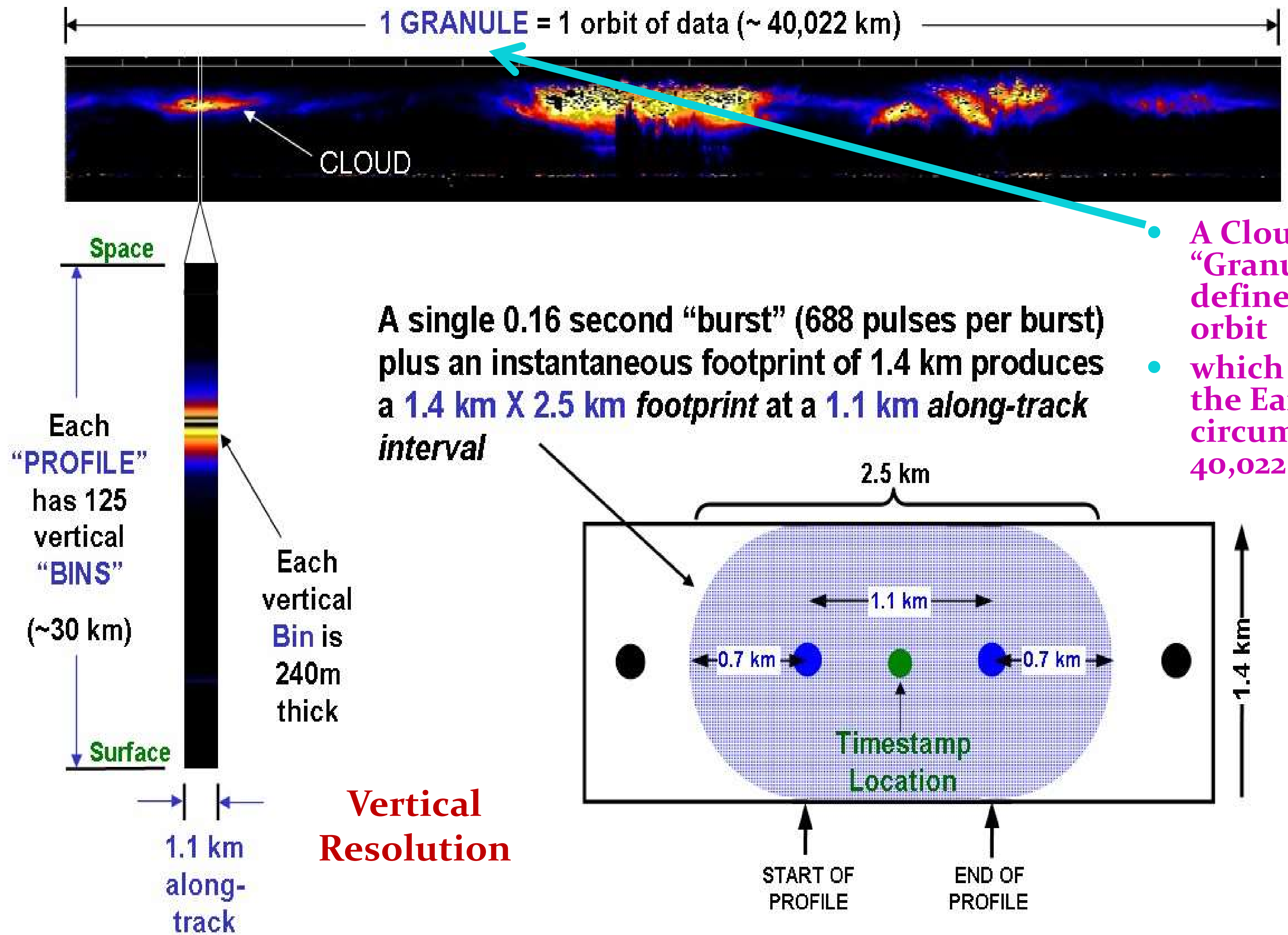

- Instantaneous footprint when satellite travels one sample period of 0.16 seconds

# Other CPR Sampling Properties




- Effect of "sliding" the instantaneous footprint along track for one sample period.

# Other CPR Sampling Properties




**Vertical Resolution**

- A CloudSat Data "Granule" is defined as one orbit
- which is equal to the Earth's circumference, 40,022 km

# CloudSat Data Products

(Stephens et al. 2008)

**Table 2.** Summary of Products

| Standard Product ID | Description | Principal Inputs and Product Size/Day |
|---|---|---|
| 1A-Aux | Auxiliary data for navigation altitude assignments, raw CPR data | Digital Elevation maps, space craft ephemeris |
| 1B-CPR | Calibrated radar reflectivities | Radar power, calibration factors 347 MB |
| 2B-GEOPROF | Cloud geometric profile – includes as mask (with confidence measure), reflectivity (significant echoes), (gas) attenuation correction, and MODIS mask | 1B-CPR, MODIS mask product. 498 MB |
| 2B-GEOPROF-LIDAR | Includes the fraction of a CPR bin filled with clouds as determined by lidar. | 2B-GEOPROF + CALIPSO LIDAR 290 MB |
| 2B-CLDCLASS | 8 classes of cloud type, including precipitation identification and likelihood of mixed phase conditions | Radar and other data (temperature, MODIS) from the constellation 282 MB A version to include lidar information is under development (2B-CLDCLASS-LIDAR)t |
| 2B-TAU | Cloud optical depth by layer, also effective radius (column) | 2B-GEOPROF and MODIS radiances |
| 2B-CWC-RO, 2B-CW-RVOD | Cloud liquid water content (2B-LWC) C loud Ice water content (2B-IWC) | A radar only (RO) version that uses 2B-GEOPROF and temperature, (5291 MB) and a radar-optical depth version (RVOD) that combines 2B-GEOPROF and 2B-TAU |
| 2B-FLXHR | Atmospheric radiative fluxes and heating rates | 2B-GEOPROF, 2B-TAU, 2B-CWC - 1516 MB. A version to include lidar information is under development (2B-FLXHR-LIDAR)t |
| | *Auxiliary Data Products* | |
| MODIS-AUX | MODIS radiances and cloud mask product | Radiances (MOD02) from 23 of the MODIS channels and mask (MOD35) subsetted to 3X5 km about CloudSat. |
| AN-MODIS | MODIS 1B radiances and 2B products subsetted abut the CPR footprint | The data from MODIS-AUX plus selected products from MOD04-05-06 and -07 |
| AN-SSF | CERES single satellite footprint (SDSF) products matched to CPR | Surface and TOA fluxes from the CERES flash flux product |
| AN-state variables | Subset of ECMWF along track of various forecast model state variables, energy fluxes, etc., | The subsetting details are currently under study to constrain data volume sizes |
| | *Enhanced Products* | |
| 2B-rain Precipitation (liquid) | Precipitation incidence, Surface rainrate, profiles of liquid water content in precipitation | 2B-GEOPROF, ECMWF-AUX wind speed and SST, and AMSR-AUX radiances |
| 2B-snow Precipitation (solid) | Preciptation incidence, profiles of snow particle size distribution parameters and snowfall rate | 2B-GEOPROF, ECMWF-AUX temperature |
| 2B-CC-ICE | Profiles of number concentration, particle size and ice water content. | 2B-GEOPOF, 2B-TAU, CALIPSO lidar, MODIS radiances |
| AN-AMSRE | AMSR radiances and level 2 products matched to the CPR | AMSR-E level 2A radiances, rainfall, CWV,LWP SST and wind speed from the AMSR-E ocean product |
| AN-PR | TRMM PR reflectivities and rainfall products matched to CPR reflectivity and rainfall products. | TRMM 1C21 reflectivities, rainfall products 2A21 and 2A25 and CloudSat's 2B-GEOPROF and new rainfall products |
| | *Special Products* | |
| TC-CloudSat | CloudSat profile data mapped into a cyclindrical coordinate relative to storm center location (radial distance from storm, azimuthal direction). MODIS and AMSR-E products matched to CloudSat and also placed into this coordinate system. | 2b-GEOPROF mask, CPR reflectivities, AMR-E wind, water vapor, LWP, rain rates, MODIS cloud top temp, pressure, height and brightness temp, and "best track" storm center, max wind speed, SST, and selected NoGAPS fields |

# CloudSat Data

- **CloudSat's standard data products include:**
  - *calibrated cloud-profiling radar reflectivity data*
  - *cloud geometric profile*
  - *cloud classification*
  - *cloud optical depth by layer*
  - *cloud liquid water content*
  - *cloud ice water content*
  - *atmospheric radiative fluxes* and *heating rates*
  - cloud geometrical profile with lidar input from CALIPSO
  - cloud classification with lidar input from CALIPSO

**http://cloudsat.atmos.colostate.edu/data**

CLOUDSAT

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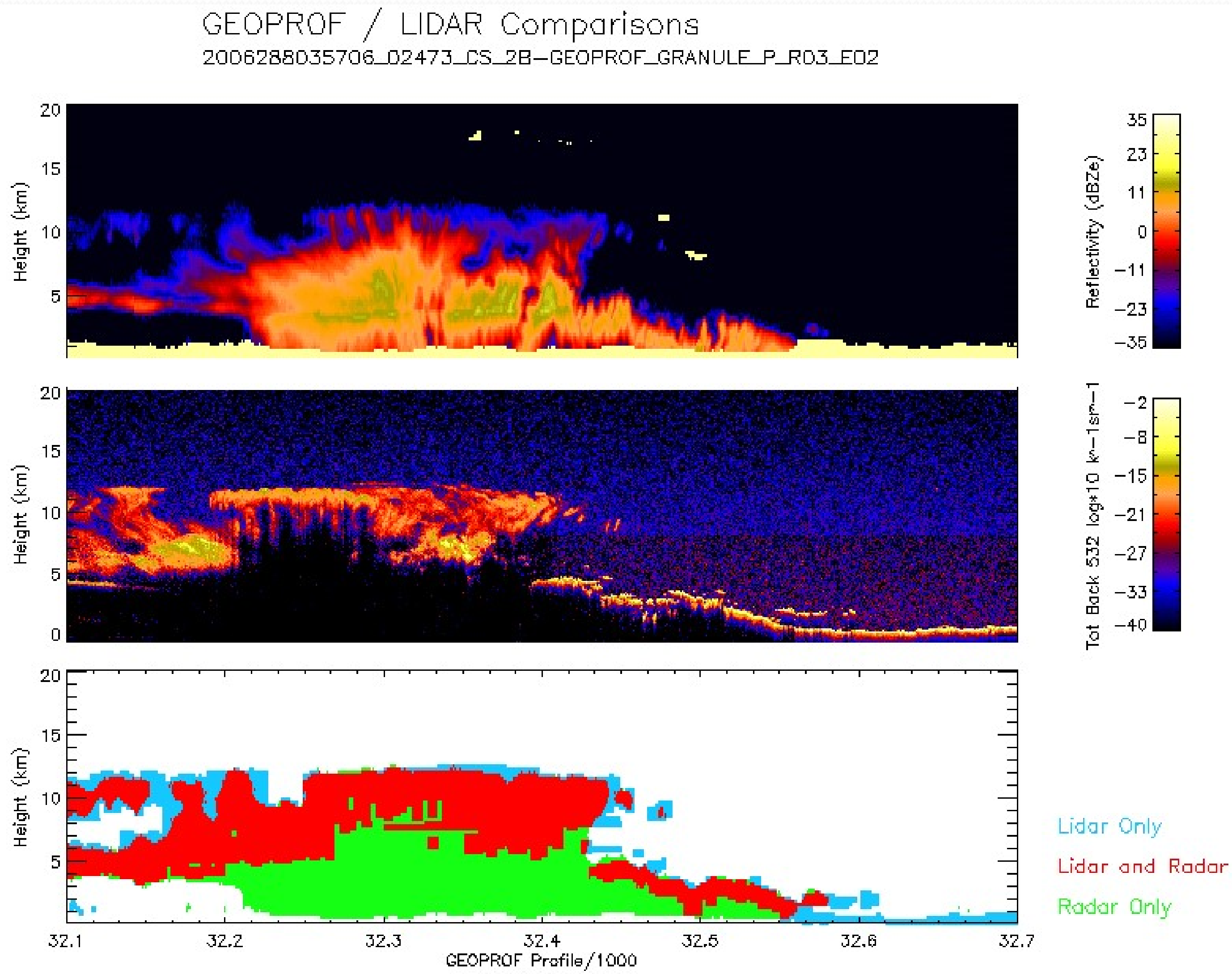
## CloudSat Standard Data Products

CloudSat Standard Data Products are distributed by the CloudSat Data Processing Center, located at the Cooperative Institute for Research in the Atmosphere at Colorado State University in Fort Collins.

Process Description/Interface Control Documents for the Standard Data Products may be obtained here (CloudSat DPC site).

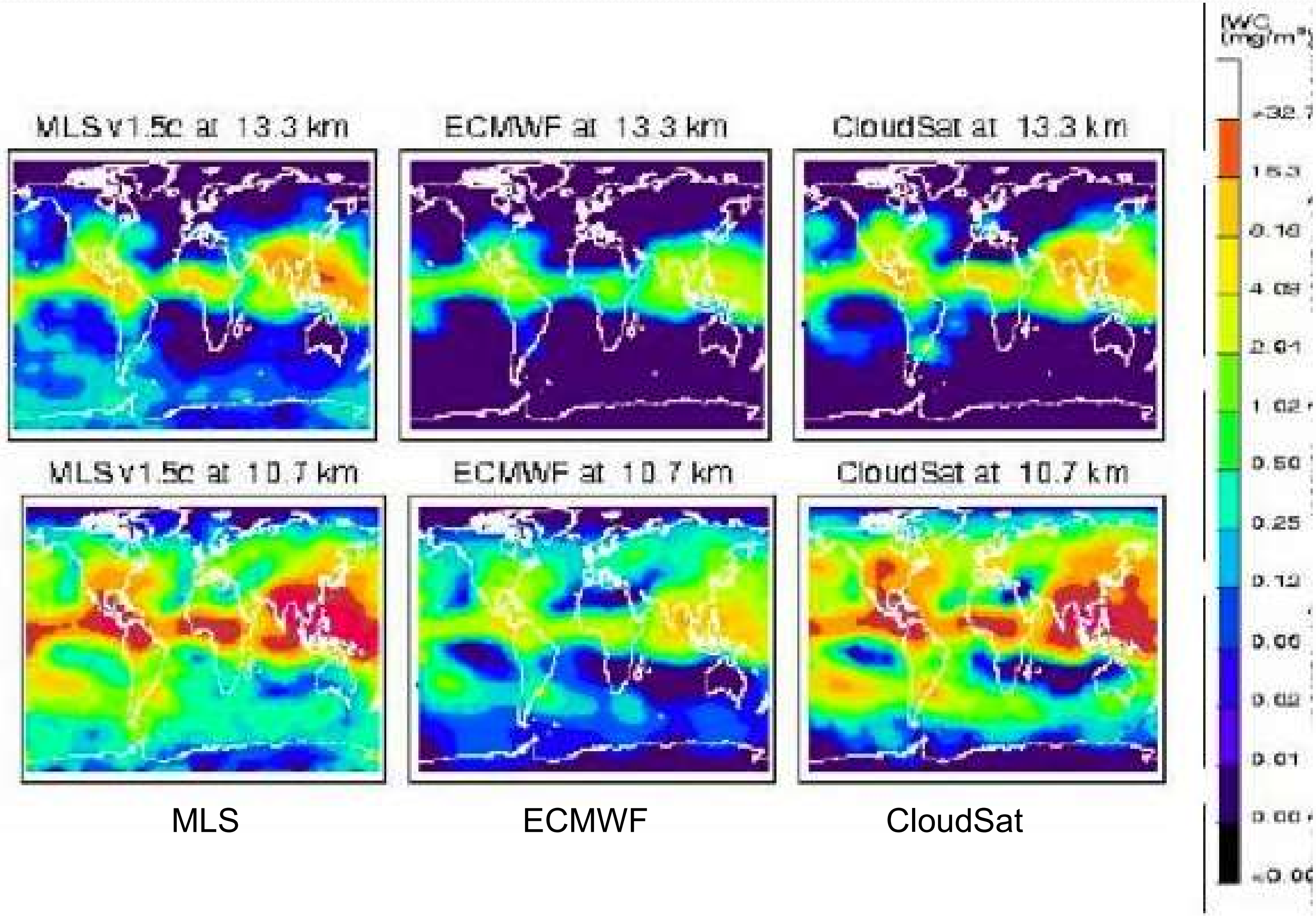
| Product ID | Product Name | Responsible Persons |
|---|---|---|
| 1B-CPR-FL | Radar Backscatter Profiles (First-Look) | Steve Durden |
| 1B-CPR | Radar Backscatter Profiles | Steve Durden |
| 2B-GEOPROF | Cloud Geometrical Profile | Jay Mace |
| 2B-CLDCLASS | Cloud Classification | Zhien Wang |
| 2B-CWC-RO | Cloud Water Content (Radar-only) (includes liquid and ice) | Norm Wood |
| 2B-TAU | Cloud Optical Depth | John Haynes |
| 2B-CWC-RVOD | Cloud Water Content (Radar-Visible Optical Depth) (includes liquid and ice) | Norm Wood |
| 2B-FLXHR | Fluxes and Heating Rates | Tristan L'Ecuyer |
| 2B-GEOPROF-LIDAR | Radar-Lidar Cloud Geometrical Profile | Jay Mace |
| 2B-CLDCLASS-LIDAR | Radar-Lidar Cloud Classification | Zhien Wang |
| 2B-FLXHR-LIDAR | Radar-Lidar Fluxes and Heating Rates | Tristan L'Ecuyer |
| 2C-PRECIP-COLUMN | Column Integrated Precipitation Retrieval | John Haynes |
| 2C-RAIN-PROFILE | Range Resolved Precipitation Retreival | Matt Lebsock |
| 2C-ICE | Ice Microphysical Retrieval | Jay Mace |
| 2C-SNOW-PROFILE | Range Resolved Snowfall Retreival | Norm Wood |
| 2D-CLOUDSAT-TRMM | CloudSat/TRMM Matchups | Kwo-Sen Kuo |
| 2D-CLOUDSAT-TC | CloudSat/Tropical Cyclone Matchups | Natalie Tourville |

# CloudSat Data

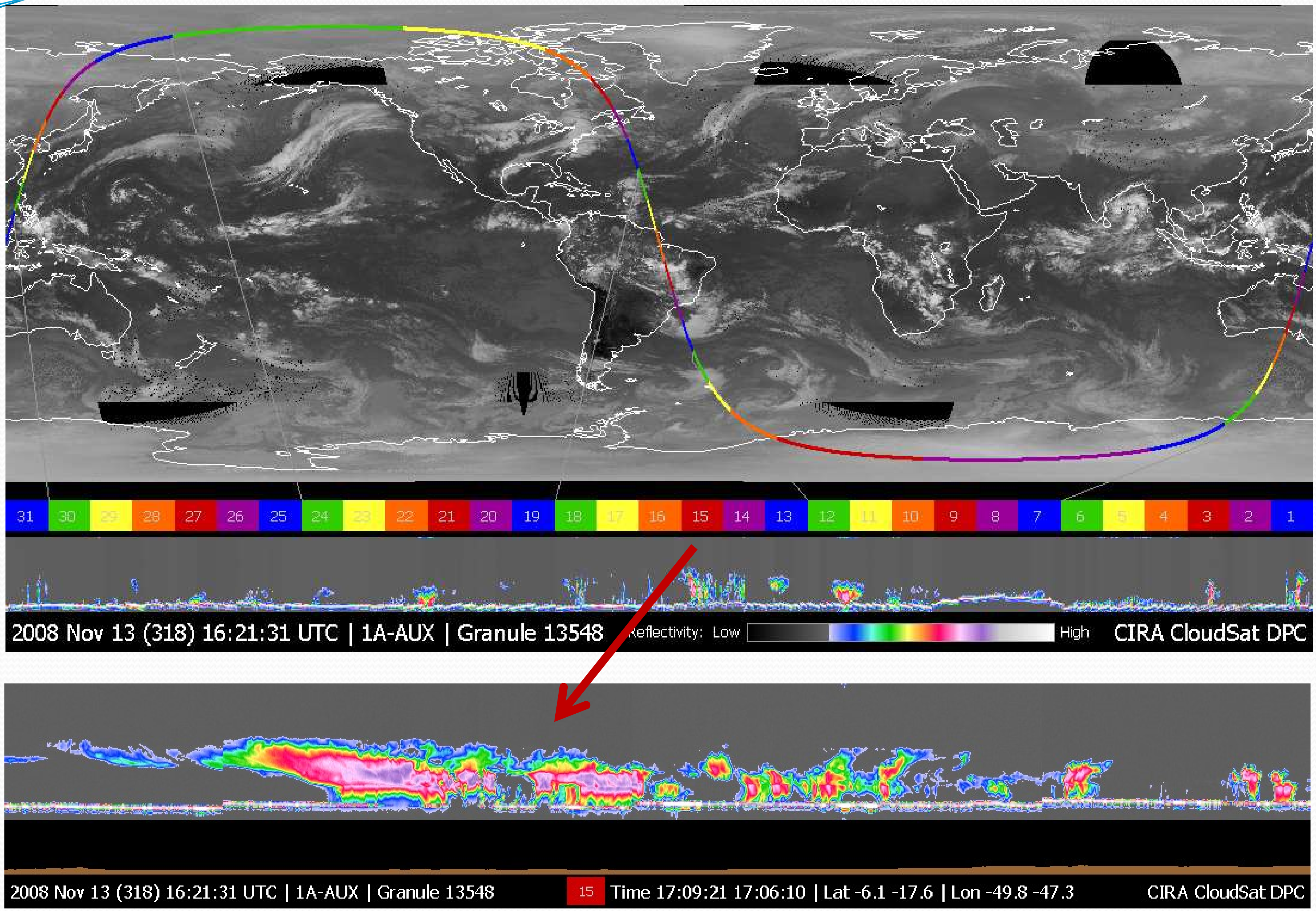



- **Radar/Lidar Combined Product Development**
- Overlap of the **CloudSat footprint and the CALIPSO** footprint, within 15 seconds, is achieved **>90% of the time**.

# A-Train Cloud Ice



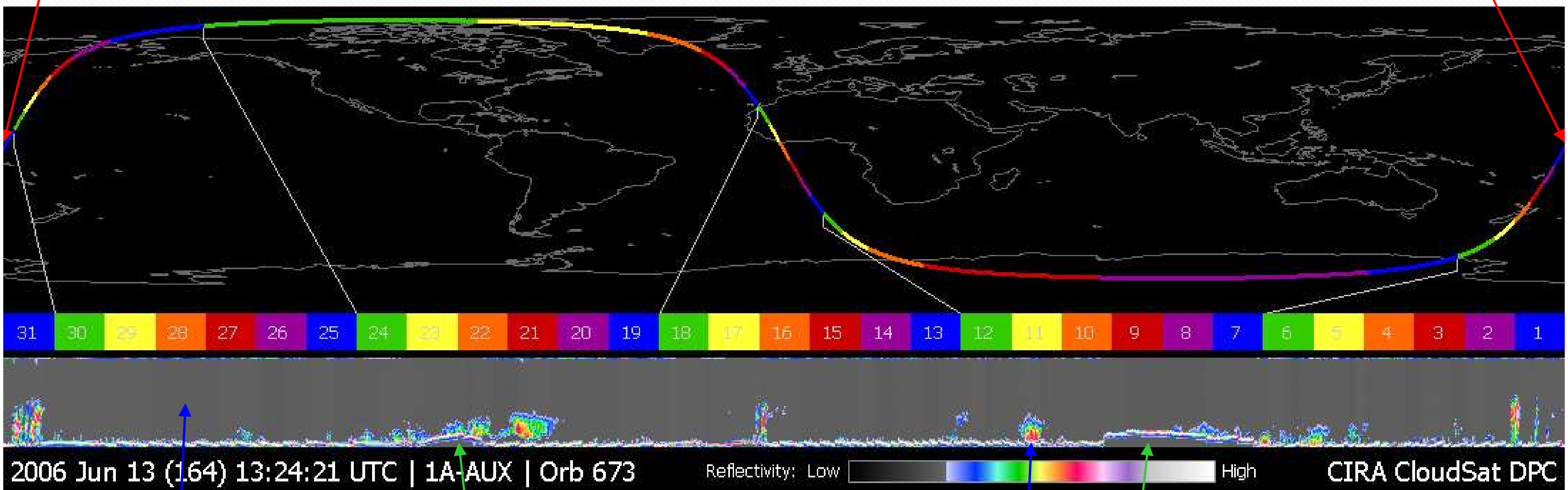
# A CloudSat Granule & Subset



# One orbit: June 13 2006

End of orbit

Start of orbit

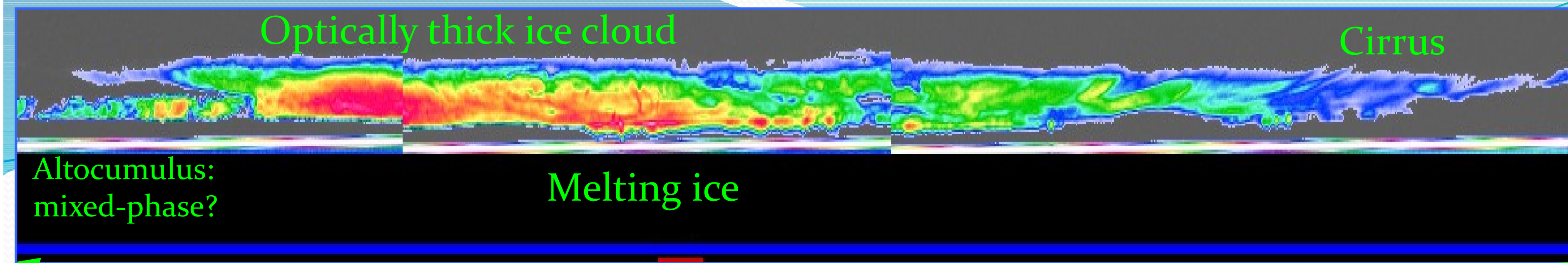



Greenland ice sheet

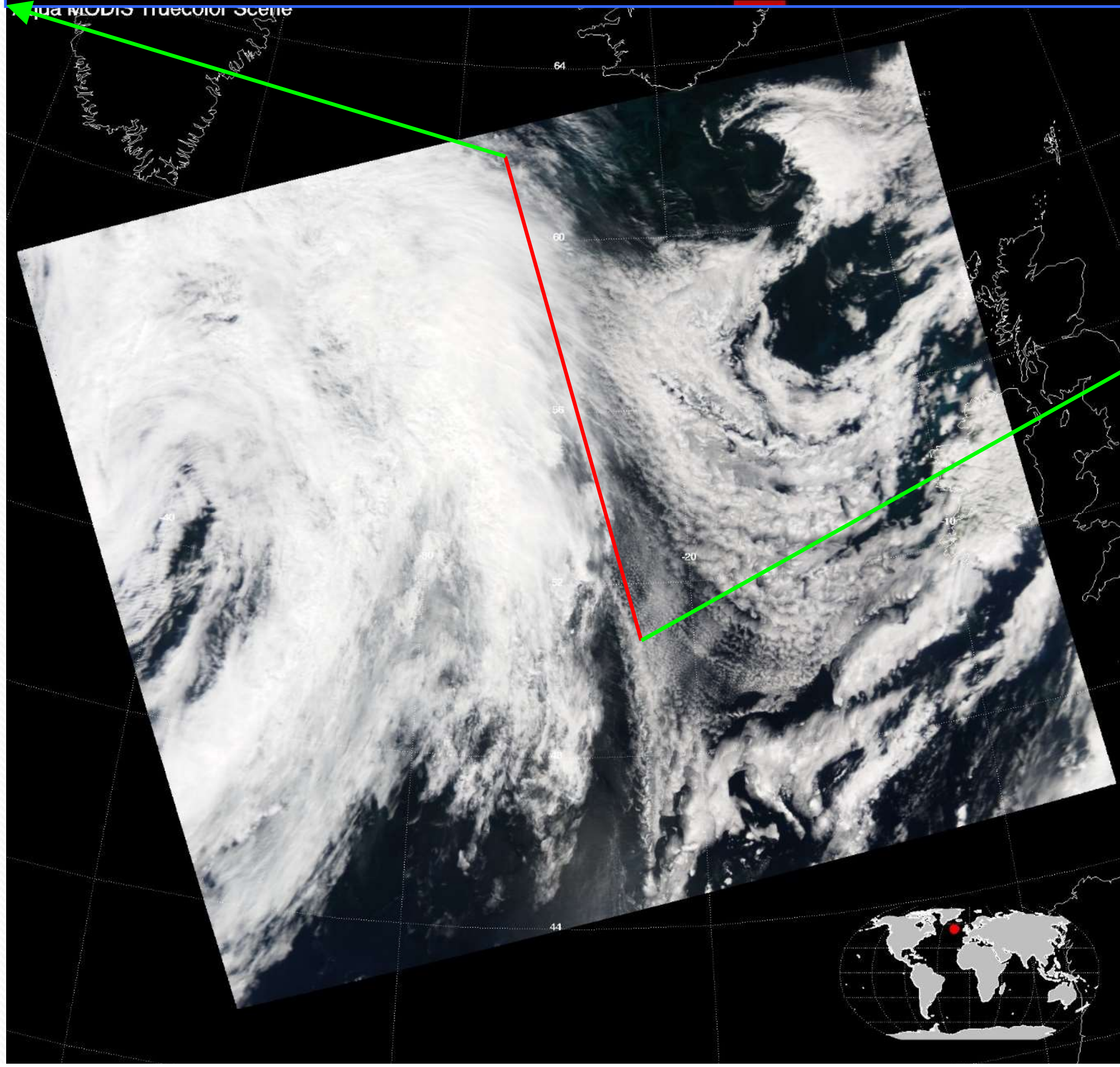
Antarctic ice sheet

30 km of uncalibrated
94-GHz radar
reflectivity factor

Clouds!




CloudSat reflectivity factor

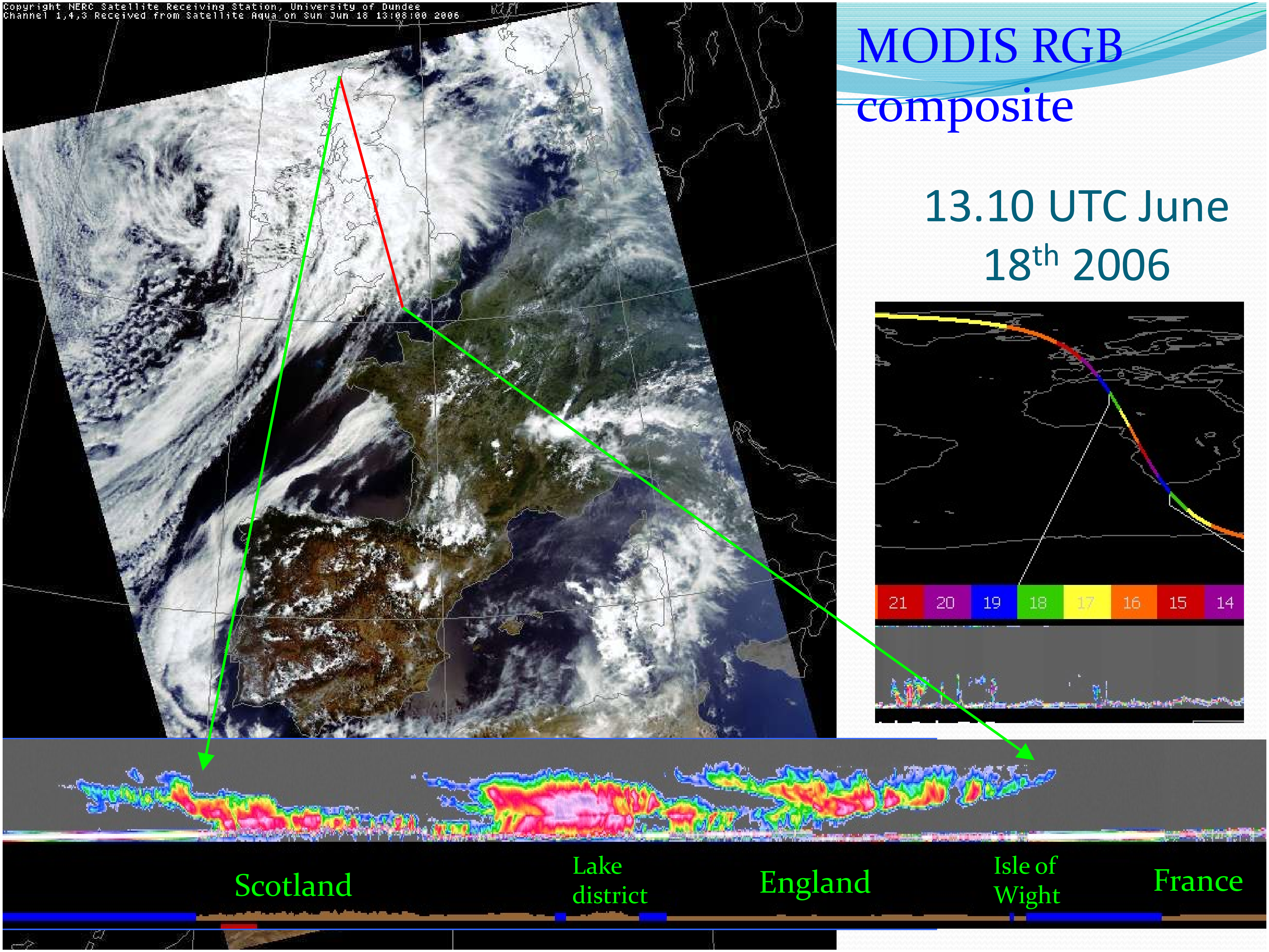


MODIS RGB composite

- 14.30 UTC
  June 13$^{th}$ 2006

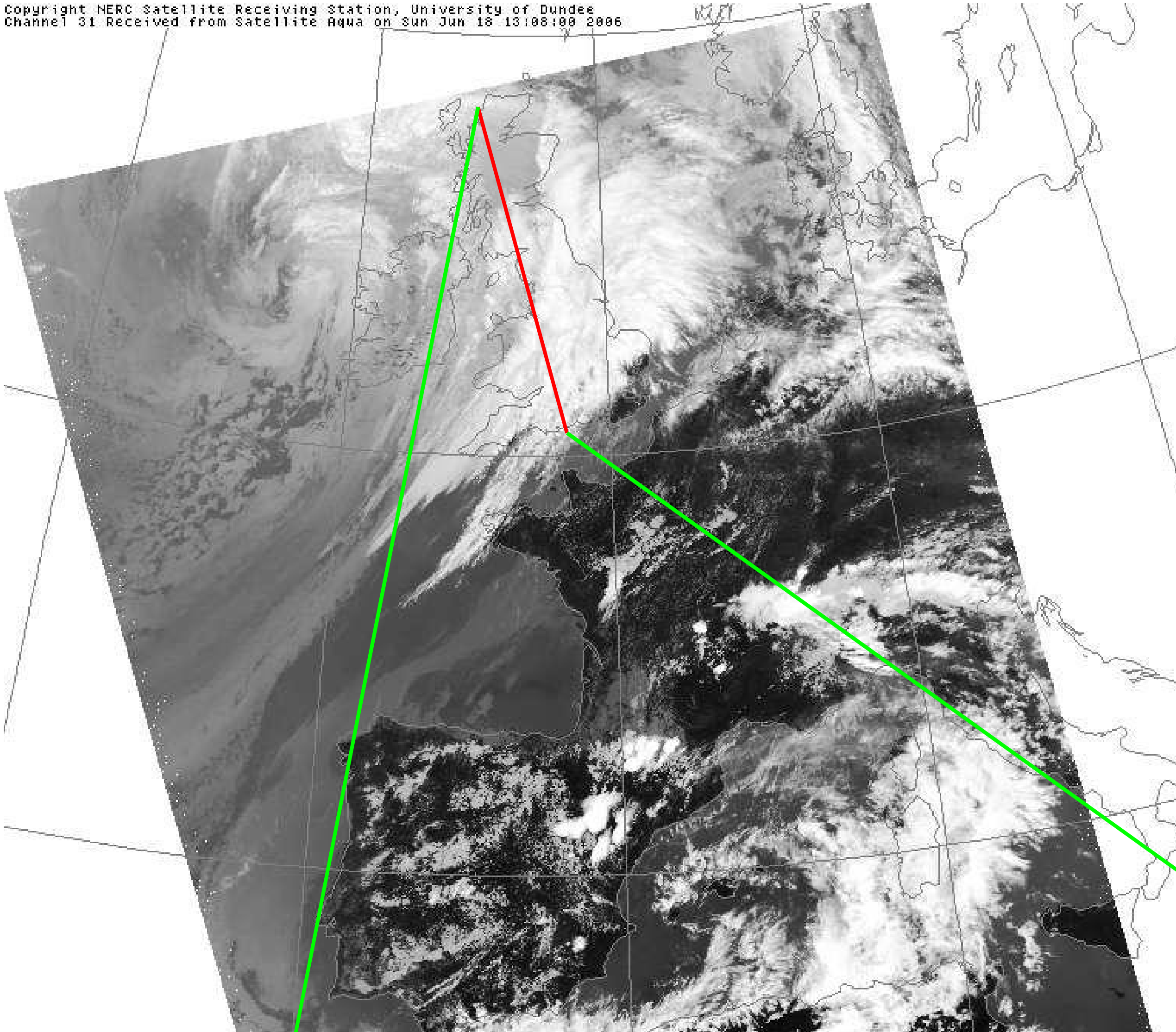
# MODIS RGB composite

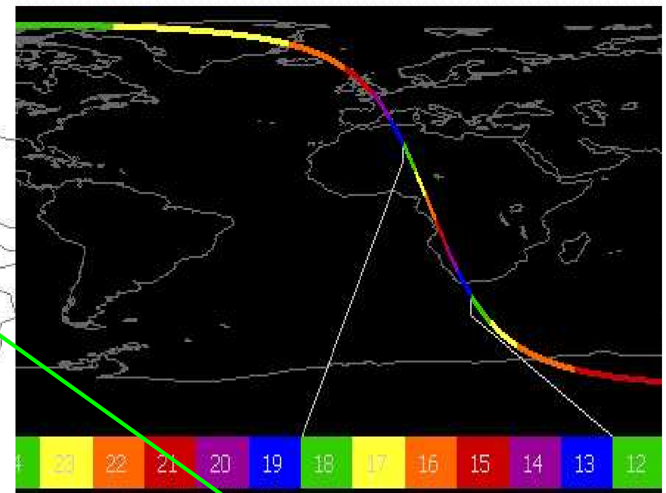
13.10 UTC June 18th 2006

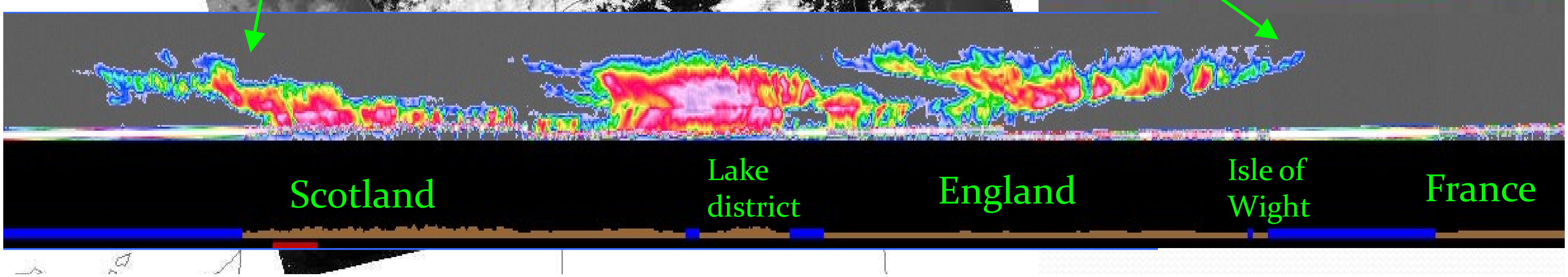


# MODIS Infrared Window

13.10 UTC
June 18$^{th}$
2006

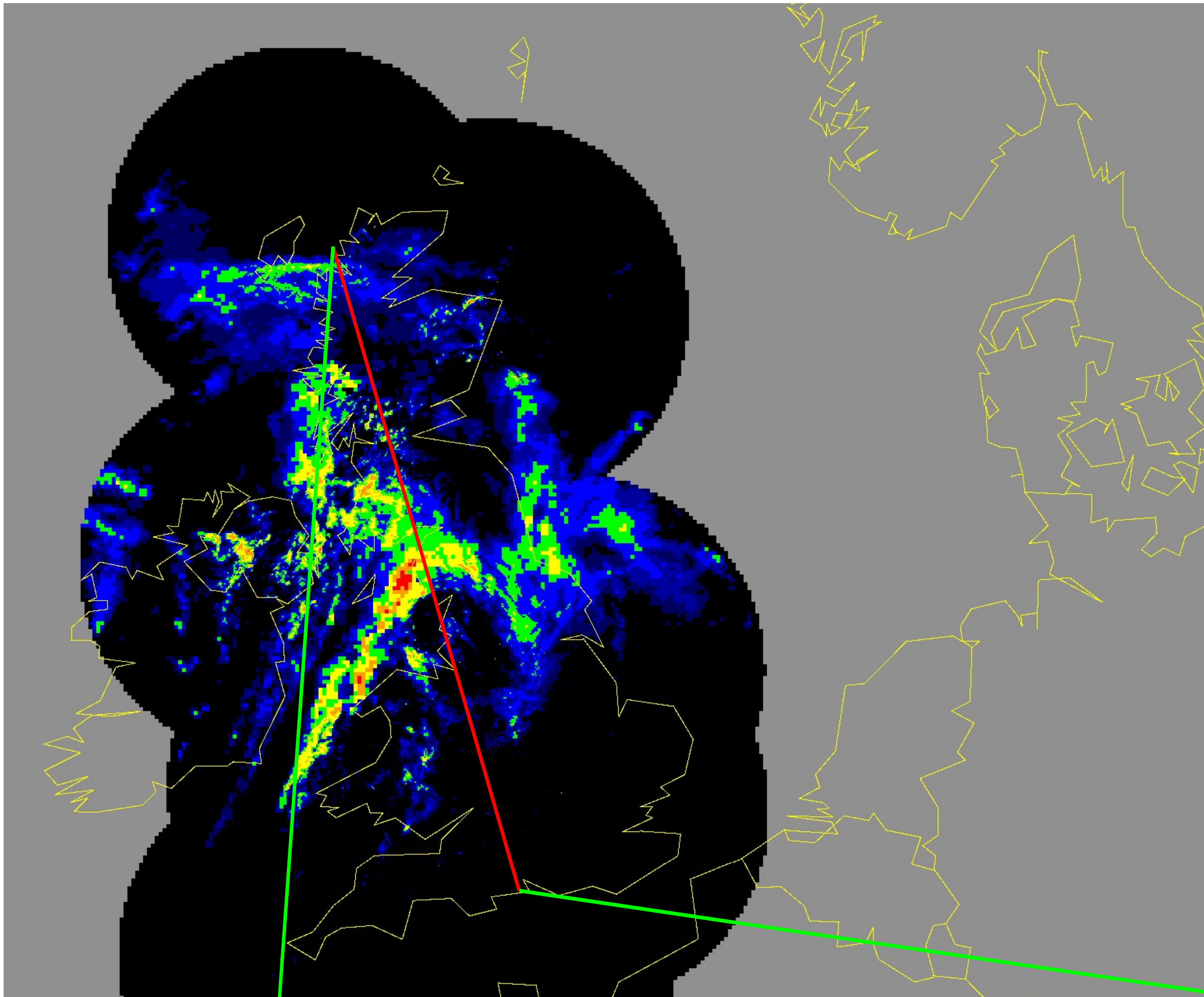


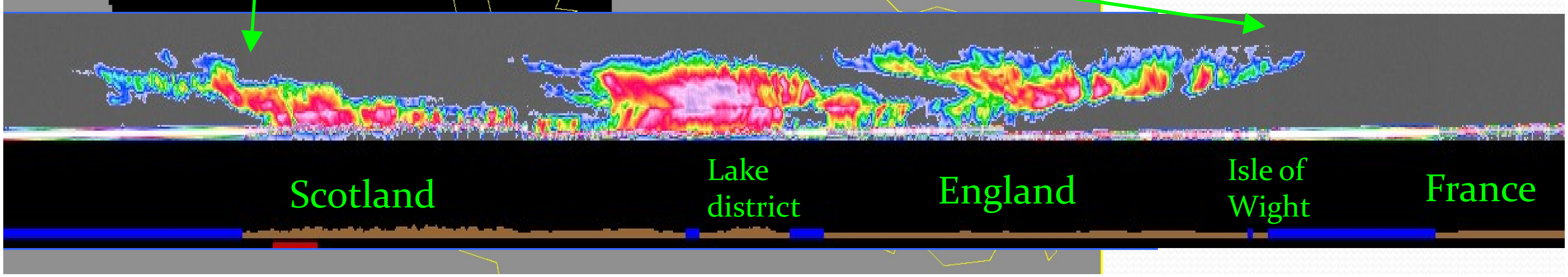



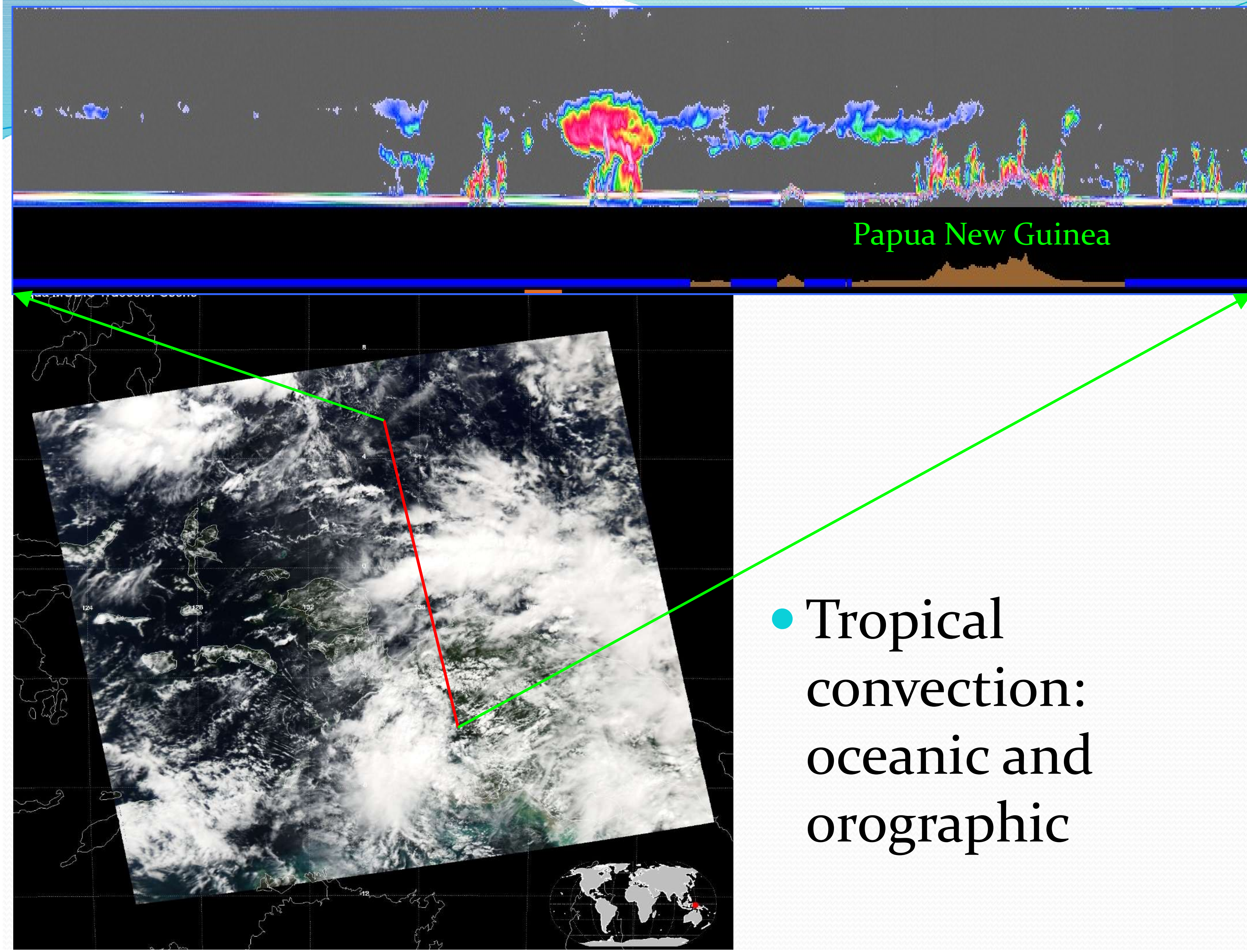



# UK Met Office rain radar network

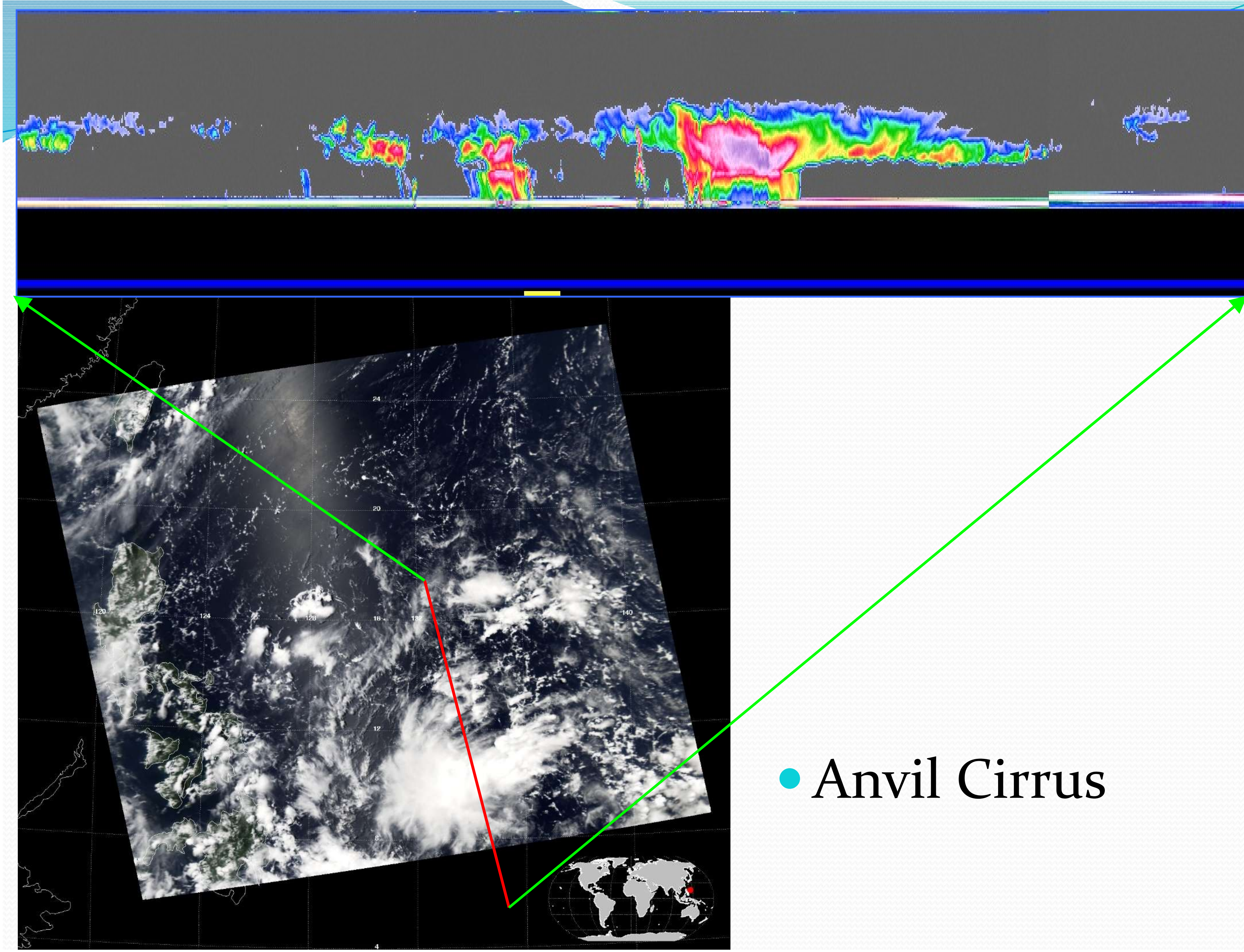
## 13.10 UTC June 18th 2006



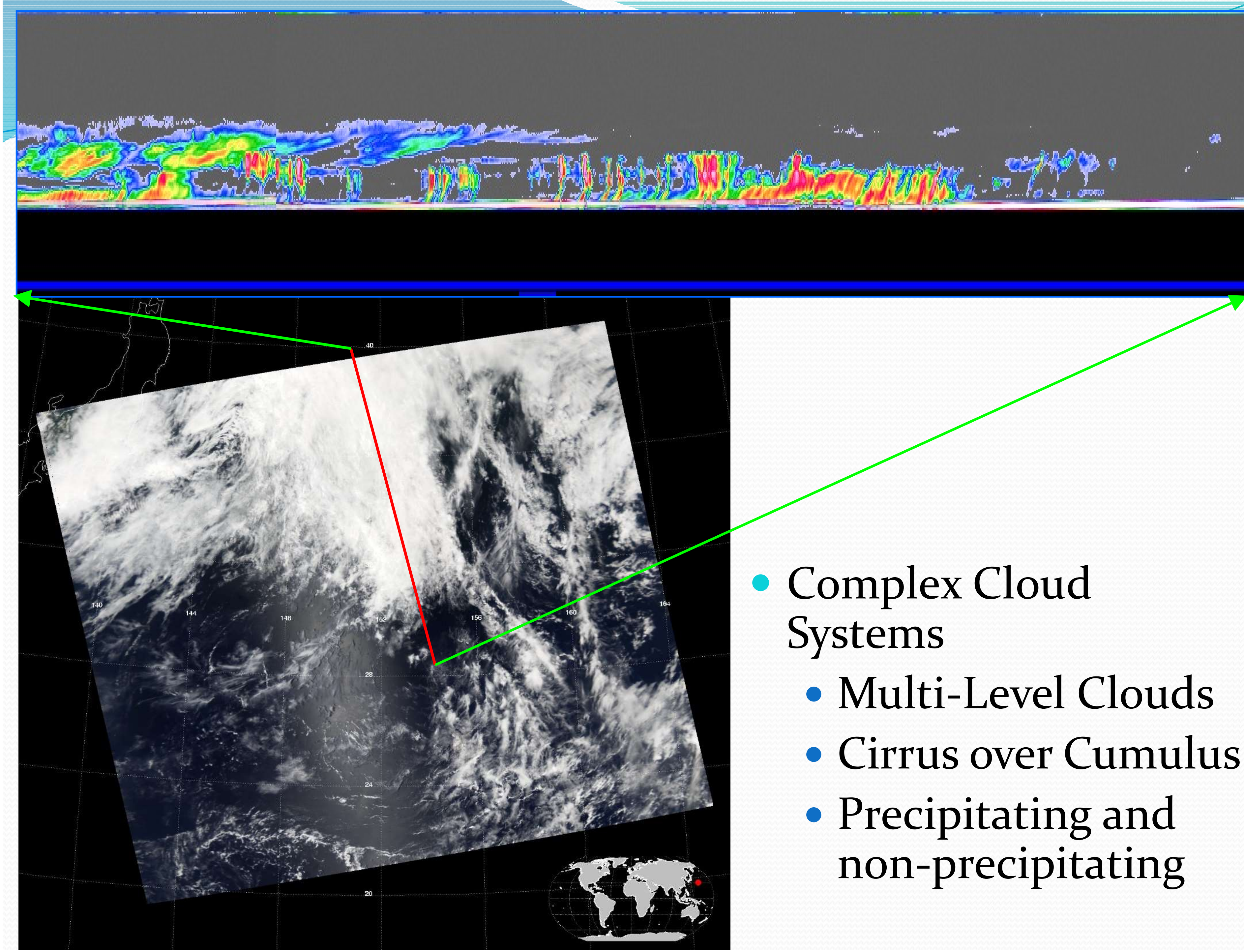





- Tropical convection: oceanic and orographic



- Anvil Cirrus



- Complex Cloud Systems
  - Multi-Level Clouds
  - Cirrus over Cumulus
  - Precipitating and non-precipitating