Principles of Operation of Weather Satellite

Prepared By

Dr. Husham Jawad Ahmad

Communication and Computer Engineering Department

- Abstract

WEATHER SATELLITES are robotic spacecraft that observe changes in terrestrial weather patterns. Their forecasting sharply reduces deaths from hurricanes and other violent weather. The first weather satellite, TIROS I, was launched in 1960 and functioned only eighty-nine days. TIROS (an acronym for Television and Infrared Observation Satellite) recorded television images of cloud patterns below, enabling meteorologists to track the movement of weather patterns and fronts. Weather satellites have since grown much more durable and can register more data, including wind speeds, atmospheric and surface temperatures, water temperatures, wave heights, and height of the polar ice caps. The U.S. government operates separate weather satellite programs for civilians and the military.

Contents

The physical basis for meteorological satellites

(1) The electromagnetic spectrum

- The electromagnetic spectrum
- Basic quantities
- Radiation interacting with the atmosphere

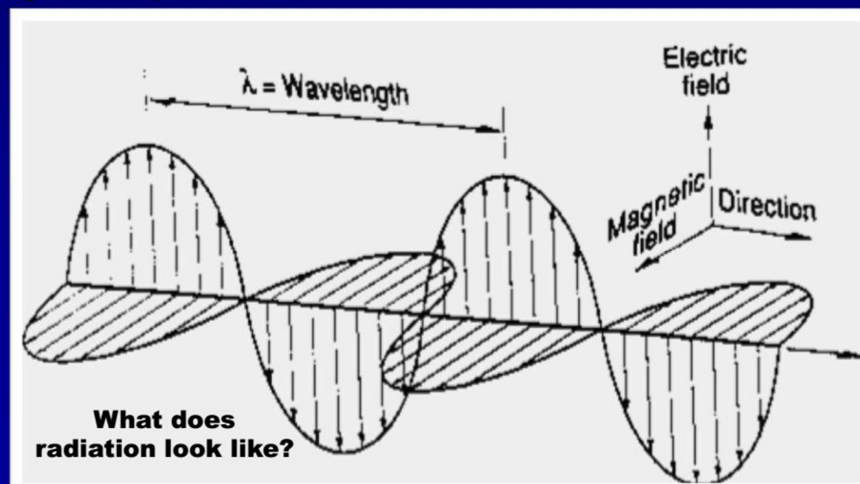
(2) Meteorological Satellites

- Designing a meteorological satellite
- Satellite platforms and orbits
- Satellite instruments and channels
- Data types

(3) The GOES-R Satellites

Electromagnetic Energy (Radiation)

- All objects at temperatures above absolute zero emit radiation which moves through space, or a medium, in the form of waves with electric and magnetic fields.
- Radiation usually has a broad range of wavelengths that travel through a vacuum at the "speed of light" (c).
- The range of all possible wavelengths is described by the *electromagnetic spectrum*.

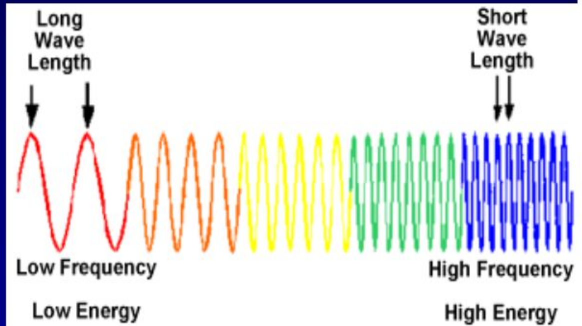


Basic Relationships and Units

wavelength

$\lambda = c/f$ Units of micrometers (10^{-6} m, μm, "microns"), Used for visible and infrared radiation

Wavelength (λ) = the distance between successive maxima in electric field strength (peak to peak)



(NOTE: Frequency refers to number of crests of waves of same wavelength that pass by a point in one second.)

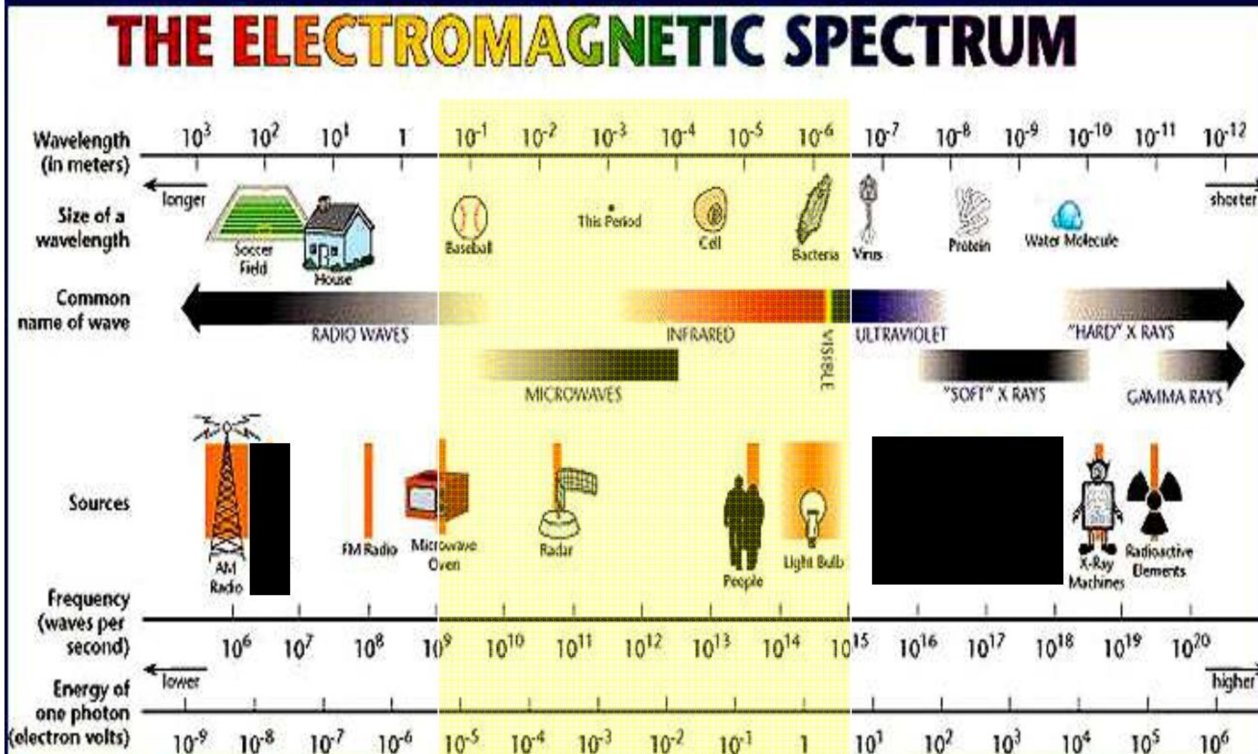
frequency

$f = c/\lambda$ Units of cycles (number of waves) per second, or hertz (Hz)

Frequency (f) = the number of waves passing a given point per unit time

Often used to describe microwaves (gigahertz, GHz = 10^9 Hz) and radio waves (megahertz, MHz = 10^6 Hz)

Meteorology primarily involves radiation within the visible, infrared, and microwave/radio portions of the electromagnetic spectrum (wavelengths from about 0.5 μm to about 12 cm).



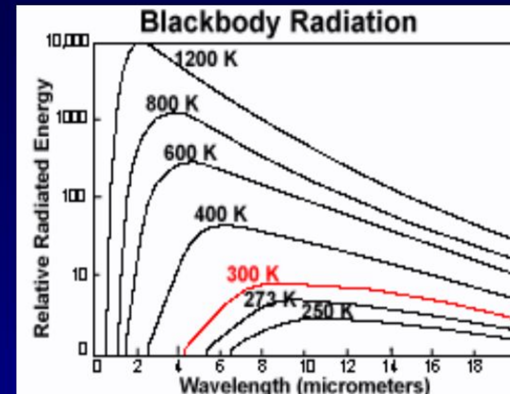
Planck Function

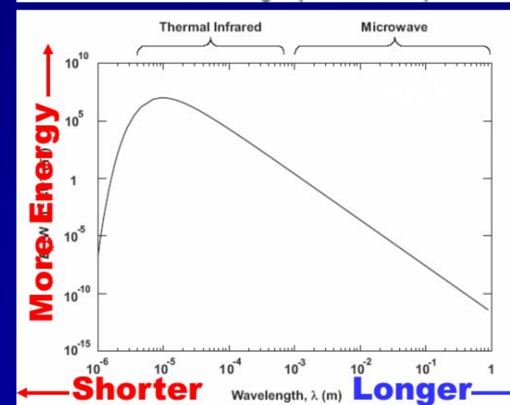
Tells you the amount of energy a blackbody object radiates at a particular wavelength, given its temperature

(A **blackbody**, an idealized radiator, emits its maximum possible radiation at all wavelengths; not all objects do this)

Hotter objects:

- Emit more energy
- Emit most of their radiation at shorter wavelengths and higher frequencies





Wien's Displacement Law

The wavelength of peak emission (λ_m) for a blackbody object is:

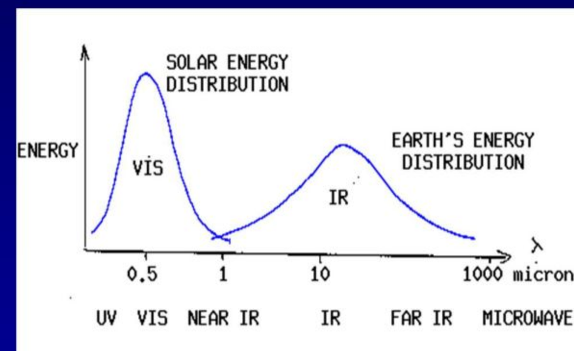
$\lambda_m = 2897 / T$

Where:

λ_m has units of μm

T is the temperature of the object in degrees Kelvin (K)

Example: The very hot Sun emits radiation concentrated at shorter wavelengths, while the much cooler earth-atmosphere system emits radiation concentrated at longer wavelengths.



Radiation Interacting with the Atmosphere

Radiation passing in any direction through the earth's atmosphere is subject to 4 processes:

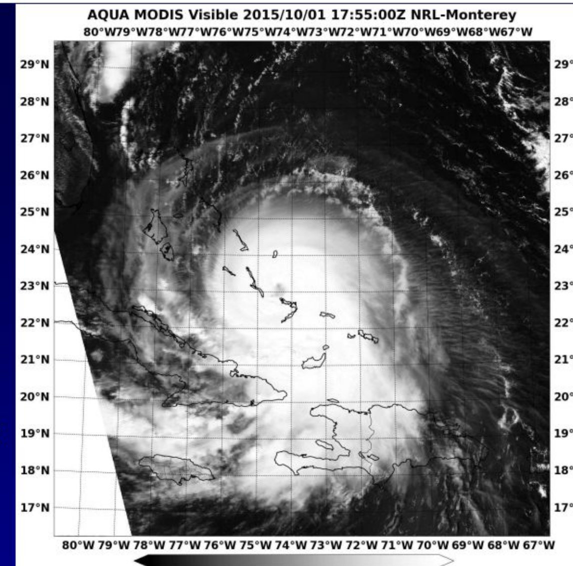
- reflection
- scattering
- absorption
- emission

These processes behave differently at various wavelengths, and they determine how remote sensing instruments work.

Reflection

Radiation sent back in the direction from which it came

- Reflection occurs more readily as the wavelength decreases and/or size of the reflecting object increases.
- <u>Albedo</u> is the fraction of the incident sunlight that is reflected.
- Clouds are the primary reflectors of radiation in the atmosphere.
- Thick clouds reflect about twice as much visible radiation as thin clouds.
- Fresh white snow reflects about 75-95% of solar radiation; water reflects about 10%.



Hurricane Joaquin (20015) Visible imagery using reflected sunlight – water/ice clouds appear bright while land/water appear dark

Scattering

Radiation diverted in various directions

- In general, occurs when radiation strikes an object with a size similar to its wavelength.

- The amount and direction of scattering depends on the ratio between particle size and radiation wavelength.

Why is the sky blue?

Why are clouds white?

Examples of Scattering

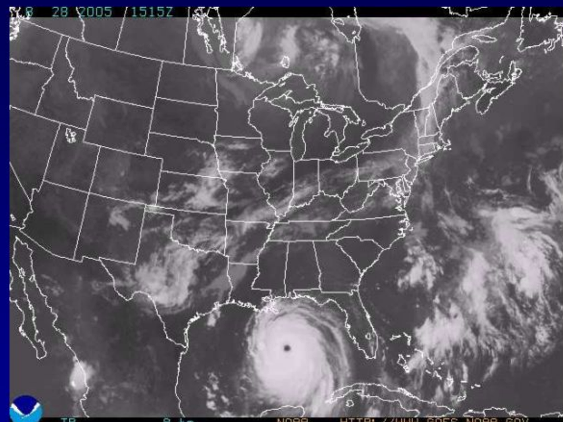
- Air molecules and very small particles (aerosols) tend to scatter the sun's visible radiation
  - Rayleigh scattering: Air molecules scatter mostly shorter-wavelength blue light (causes blue sky)
  - Mie scattering: Water droplets, pollen, dust, smoke scatter all visible wavelengths (cumulus clouds appear white); occurs when particles causing the scattering are larger than wavelengths of radiation striking them
  - Non-selective scattering: occurs in lower part of atmosphere, when particles >> incident radiation. E.g., haze

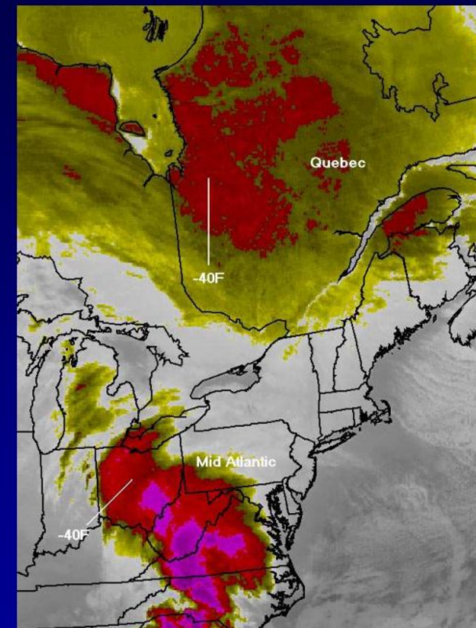
Ice particles in tall thunderstorms tend to scatter certain wavelengths of the earth's microwave radiation

Absorption and Emission

- All objects absorb and emit radiation, with the amounts depending on the object's characteristics such as temperature, color, moisture, and texture.
- If an object absorbs more energy than it emits, it warms.
- An blackbody object absorbs and emits all possible radiation and has emissivity = 1 – no reflection or transmission.
- Many objects do not emit all possible radiation at certain wavelengths.
    - For example, oceans have low emissivity at microwave wavelengths.
- Absorption varies with respect to wavelength, and each atmospheric element characteristically absorbs in specific wavelength intervals called absorption bands.
    - For example, ozone in the upper atmosphere absorbs *only* ultraviolet radiation.

Infrared Imagery

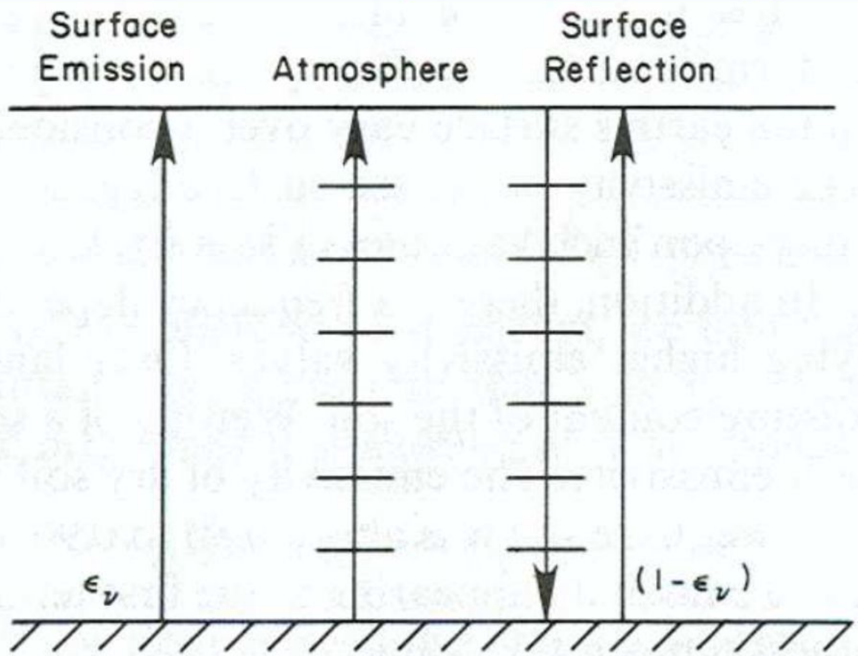




Standard infrared imagery uses wavelengths with low atmospheric absorption – "window" channels (e. g. 10.7 μm)

The Radiative Transfer Equation:

Combining the effects of emission, absorption, and reflection (non-scattering example)

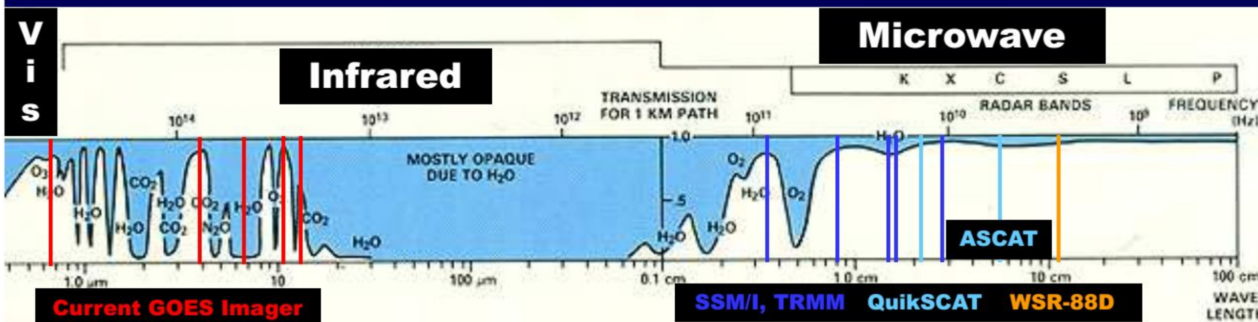


Contribution of brightness temperature at the top of a clear atmosphere.

Parts of the Radiative Transfer System

- The Sun
- The atmospheric constituents:
  - Water vapor (varies greatly in space and time)
  - Liquid water and ice (clouds; also vary greatly)
  - Carbon dioxide (well-mixed)
- The major wavelength bands of interest:
  - Atmospheric infrared “window” (emissions from the earth)
  - Water vapor infrared absorption region
  - Shortwave infrared region
  - Visible region (reflection)
  - Microwave region (can pass through clouds but not rain)
- Surfaces:
  - Land
  - Ocean
  - Clouds

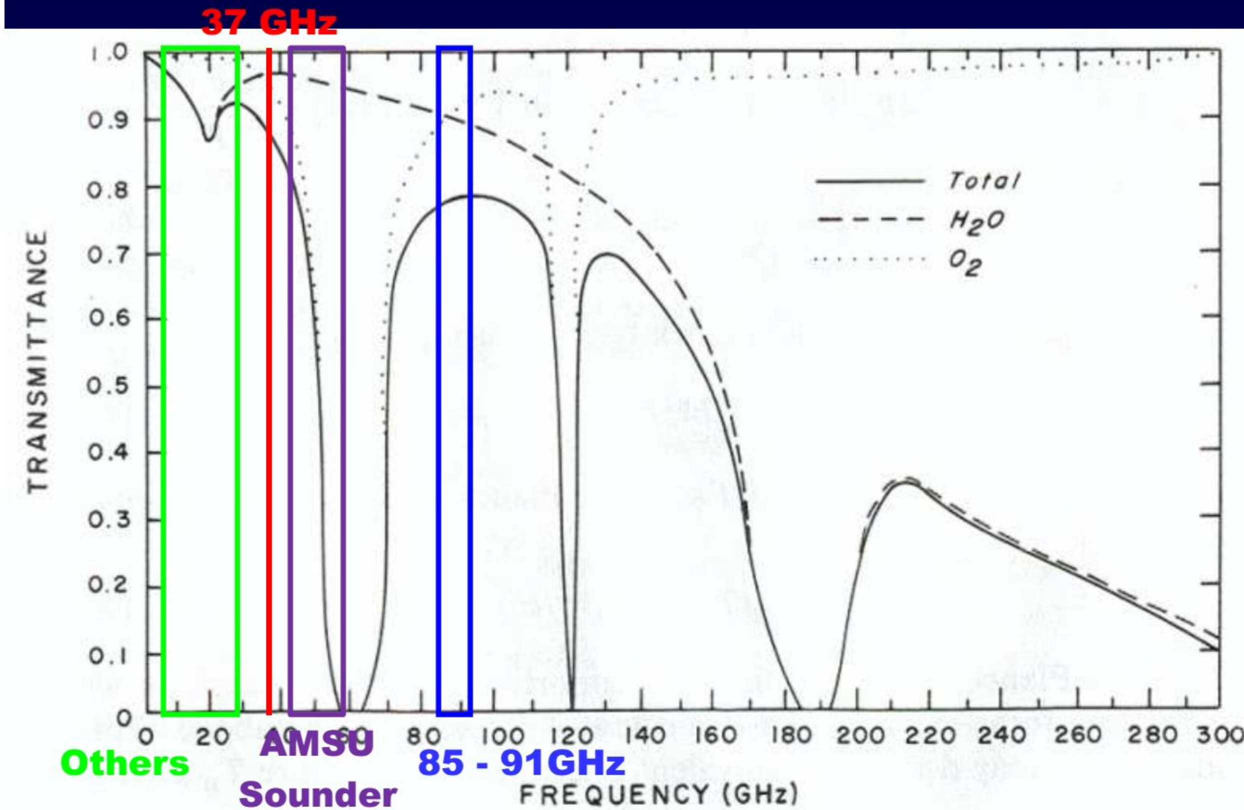
Atmospheric Absorption/Emission Spectrum



Longer wavelength

Higher frequency

Microwave Transmittance



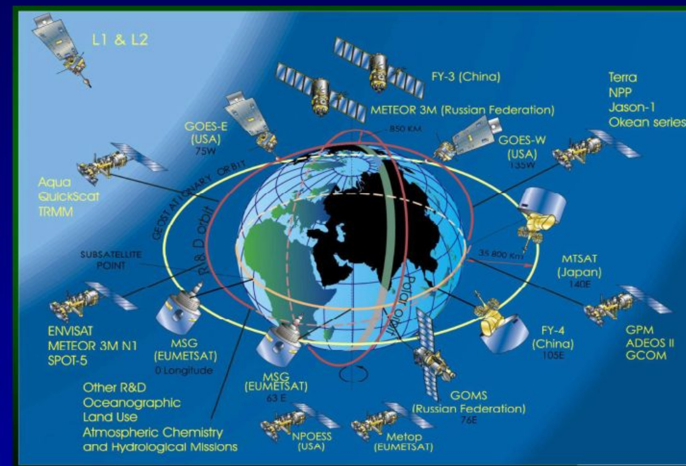
Measuring Electromagnetic Energy

- **Passive Instruments:**
  - Receive radiation leaving the earth-atmosphere system
  - Measure solar radiation reflected by earth/atmosphere targets
  - 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

Remote Sensing Satellites

- These "look" down from a great height and can thus see more detail depending on the height above the Earth's surface.
- Remote sensing can be thought of as how to obtain information about an object of interest without being in physical contact with it.
- Satellite instruments can be designed to observe many types of atmospheric, oceanic, and land-surface phenomena based on the instrument frequencies chosen.



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

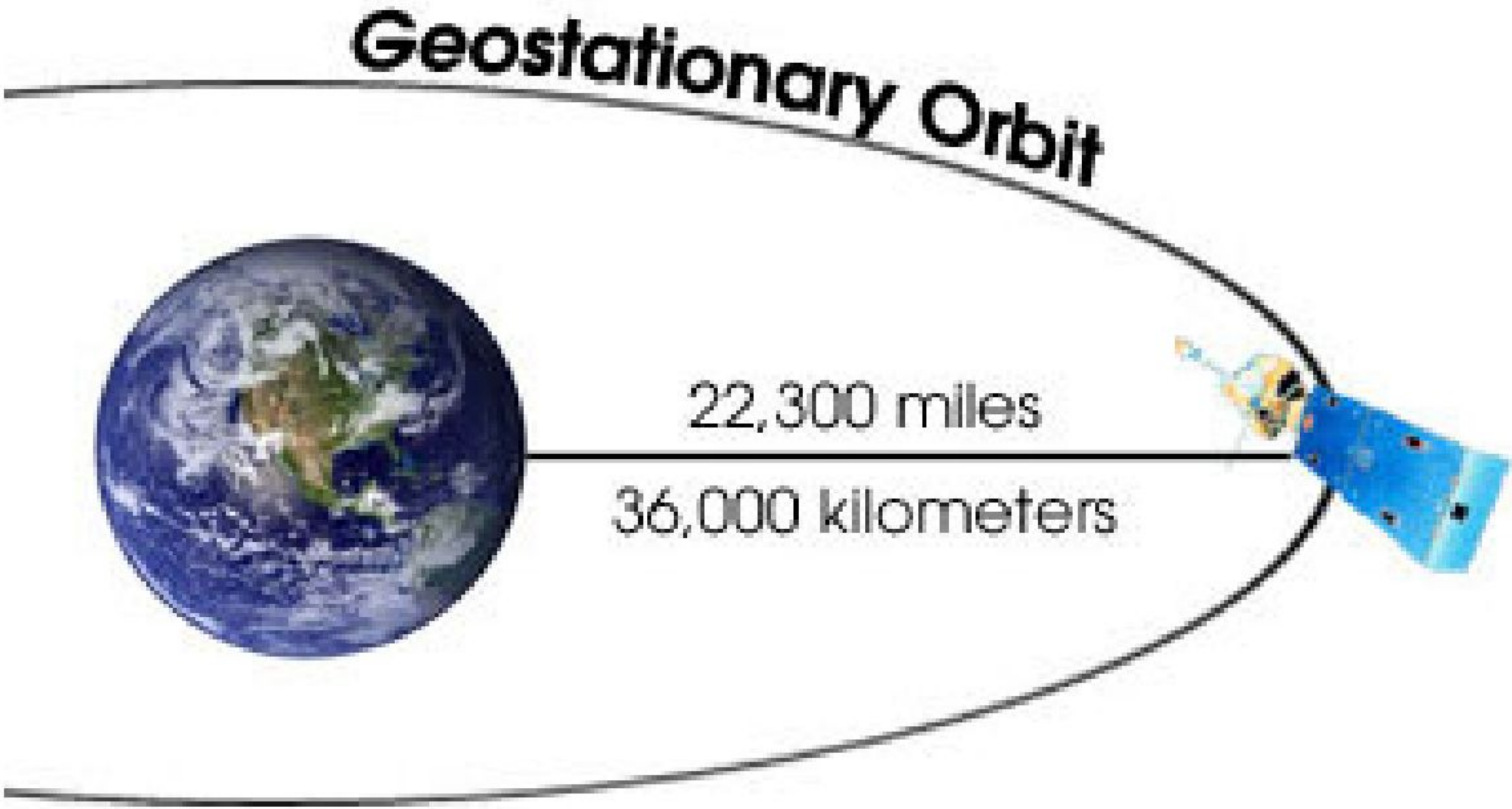
- Low earth orbit (LEO) satellites
  - Good for microwave (active and passive), visible, and infrared
  - Lower altitude orbit, but not over same spot on earth
  - Finer spatial resolution
  - Views each area only twice per day (except near poles)
  - Limited spatial coverage (narrow swaths of data)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

Weather Satellites and Weather Forecasting

★ Geostationary Orbiting Environmental Satellites (GOES)
provide continuous images of the same area on Earth 24 hours a day.

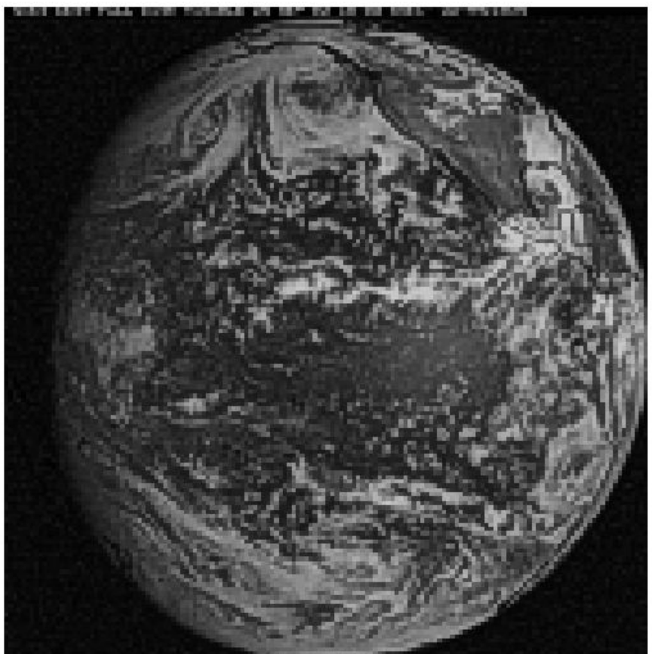
★ They **hover over a single point above the Earth's equator** at an altitude of about 36,000 kilometers (22,300 miles).

Weather Satellites and Weather Forecasting

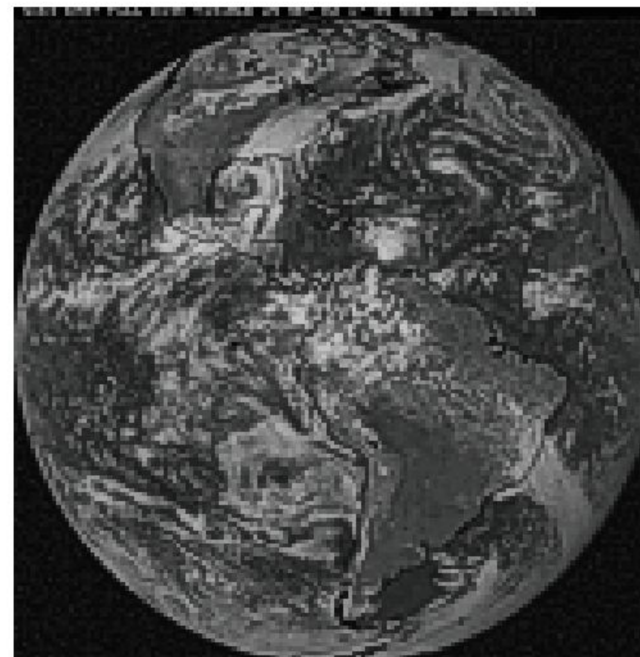


The United States operates two GOES weather satellites, one over the East Coast and one over the West Coast. They have overlapping coverage in the central United States.

GOES West

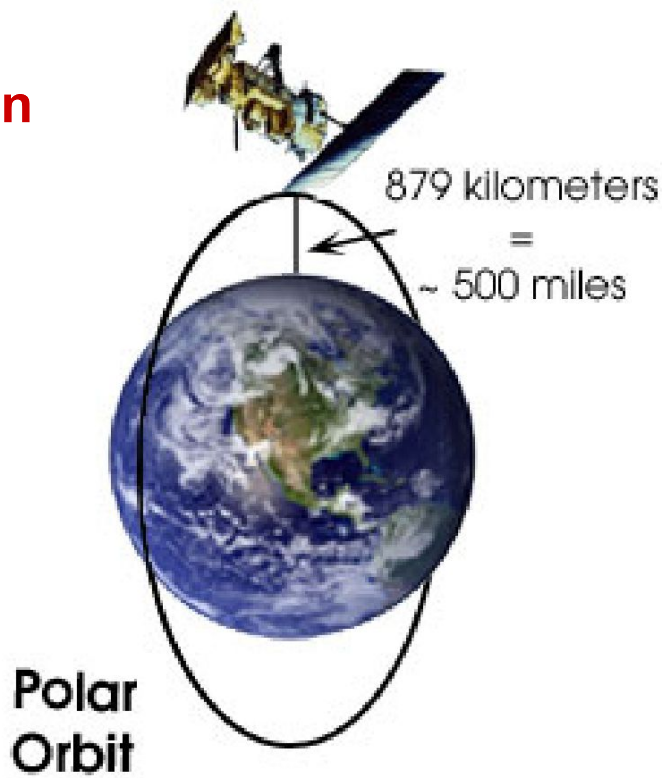


GOES East



Polar Orbiting Environmental Satellites (POES) Polar orbiting satellites travel in a circular orbit from pole to pole, much closer to the Earth than GOES.

In this way, a polar orbiting satellite can �see� the entire planet twice in a 24 hour period.



While they aren't as useful to watching the weather as GOES, they are extremely valuable because they provide such fantastic detail of storms, volcanoes, mudslides, wildfires and other natural events on Earth.

GEO vs. LEO Orbital Altitiude Comparison

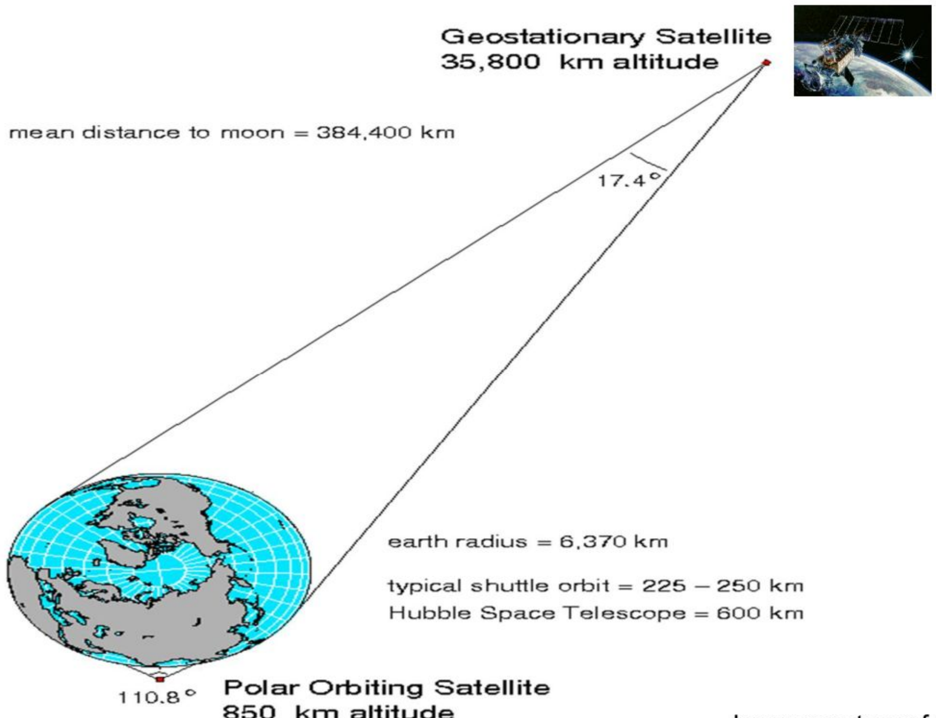
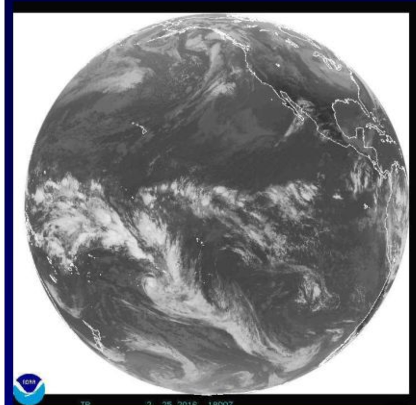
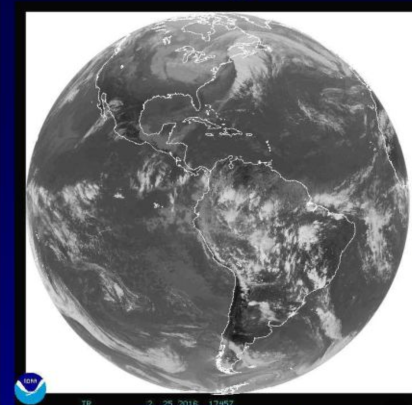


Image courtesy of http://www.nrlmry.navy.mil

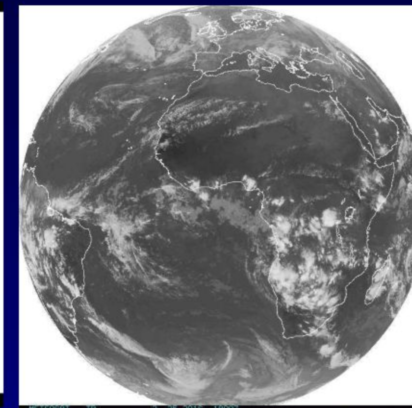
Geostationary Satellites



GOES-15 135° W

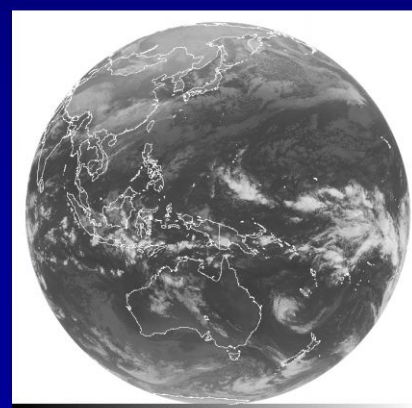


GOES-13 75° W



METEOSAT-10 0°

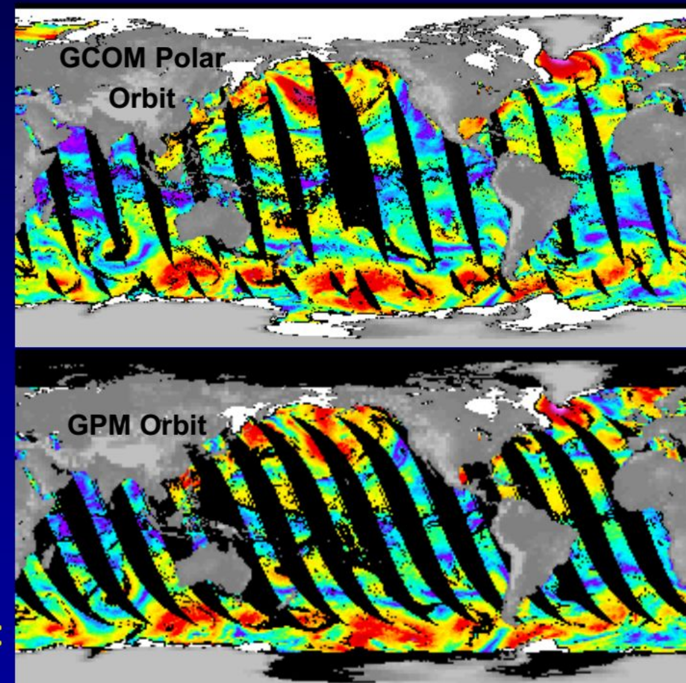
HIMAWARI-8
141° E



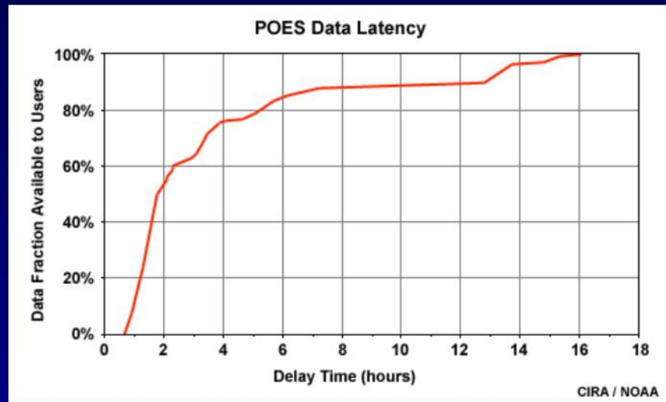
METEOSAT-7
57.5° E

Low Earth Orbiting Satellites

- Generally fly 300-1000 miles (500-1600 km) above the surface
- Many such satellite travel over the Earth almost from pole to pole – polar orbit.
- Polar orbiting satellites are usually <u>sun-synchronous</u> (the satellite crosses the Equator at the same local time every day).
- Sun-synchronous satellites make about 14 orbits of the Earth a day.
- There are other specialized low earth orbits such as that of the Global Precipitation Mission satellite.



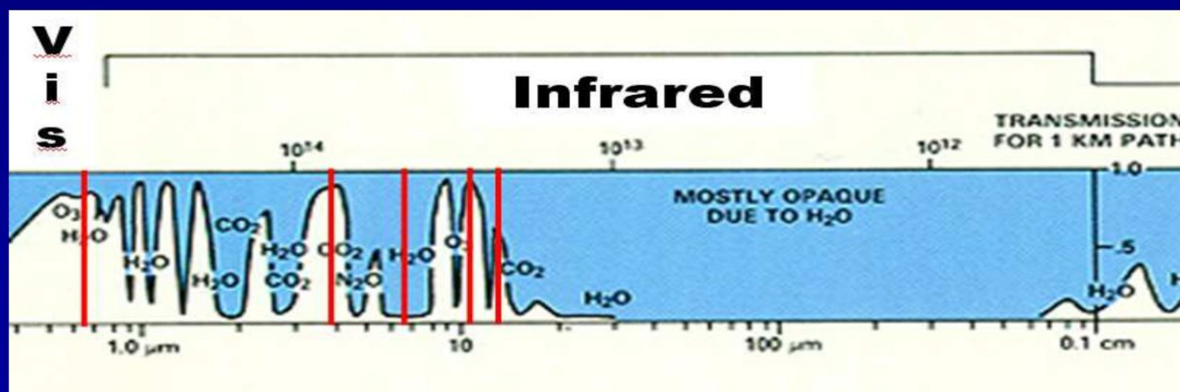
Data Latency Issue



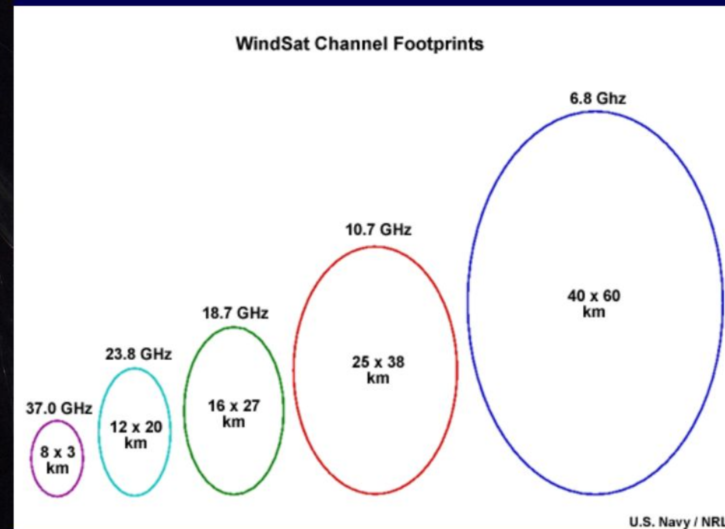
• LEO satellites are not continuously in view of data receiving stations. They can only download data when they are in range of those stations, which leads to delays in data transmission and processing.

GOES-13/14/15 Imager Channels

Channel 1	Channel 2	Channel 3	Channel 4	Channel 5
0.65 µm 1 km	3.9 µm 4 km	6.5 µm 4 km	10.7 µm 4 km	13.3 µm 4 km
Visible	Shortwave IR	Water Vapor (IR)	IR Window	CO_2 (IR)



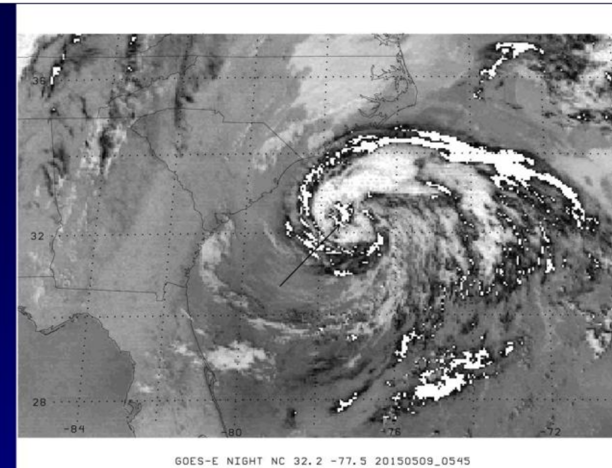
The WindSat Microwave Imager

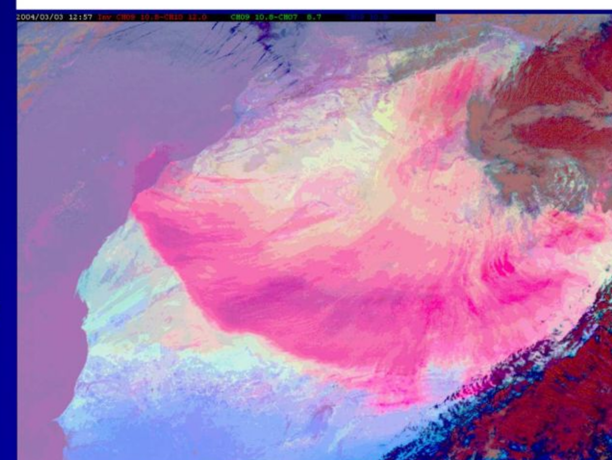


The footprint (pixel) size of the imager increases with decreasing frequency.

Multi-spectral Imagery

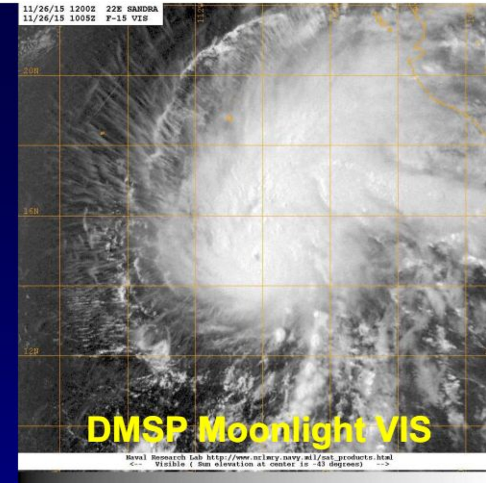
- Combinations of channels can show important features that a single channel cannot, such as enhanced convection or aerosols.
- Taking advantage of radiative properties can maximize image amount of information in an image.
- Nighttime visible is an example, along with the EUMETSAT dust imagery.

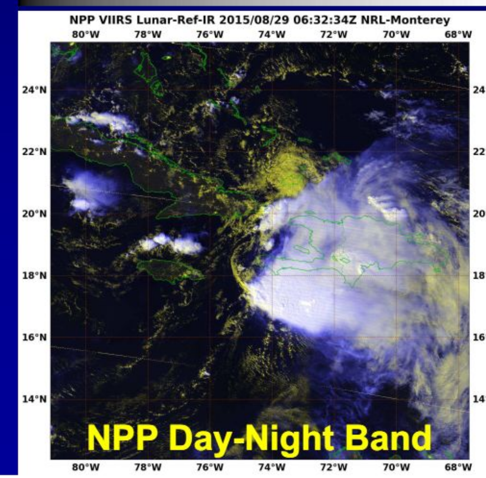




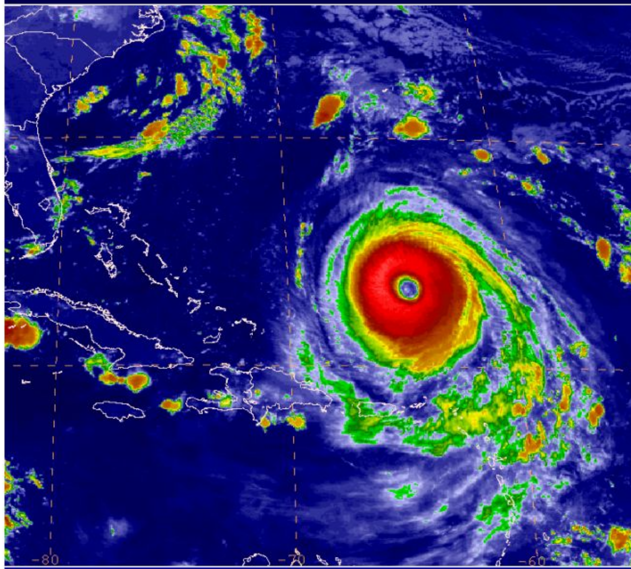
Day-Night Band Imagery

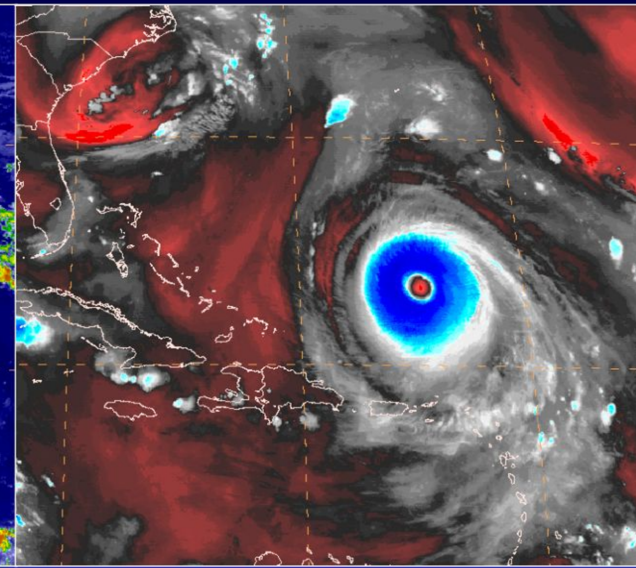
- DMSP and NPP satellites have the ability to take visible images by reflected moonlight.
- This allows the resolution of visible imagery at night, which is useful for diagnosing the structure of tropical cyclones and other weather systems.





Are we looking at levels or layers?





Conventional IR 10.7 µm

More of a level quantity.

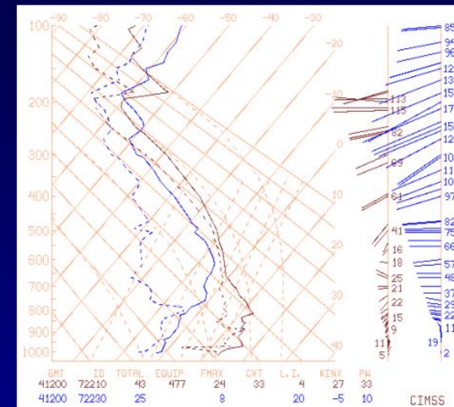
Water Vapor IR 6.5 µm

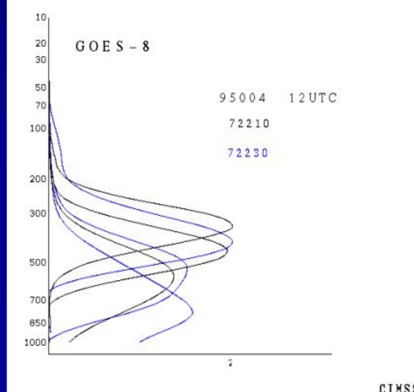
More of a layer quantity.

GOES-12 0600 UTC 14 Sep 2003

Weighting Functions

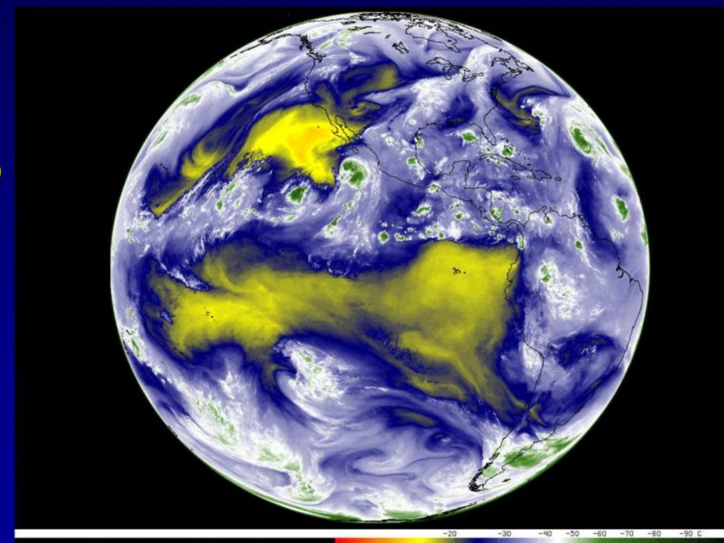
- ***Weighting function***, the derivative of transmittance with respect to height, specifies the relative contribution that each atmospheric layer makes to the radiation emitted to space.
- Therefore determines those regions of the atmosphere, which are sensed from space at a particular wavelength λ.
- Since water vapor concentrations are highly variable, weighting functions will also vary by location.
- A good choice of λ on a satellite instrument can allow for atmospheric vertical profiling or "sounding".





Water Vapor Imagery

- 6.5 µm channel is sensitive to water vapor in the mid to upper troposphere (generally 200-500 mb).
- Other channels are sensitive to vapor at other levels – 7.3 µm channel on METEOSAT-8/10 is most sensitive near 500 mb.
- Water vapor imagery can reveal features that don't generate visible clouds.
- Animation can reveal steering flows, shearing winds, or outflow for tropical cyclones.



Types of Satellite Data

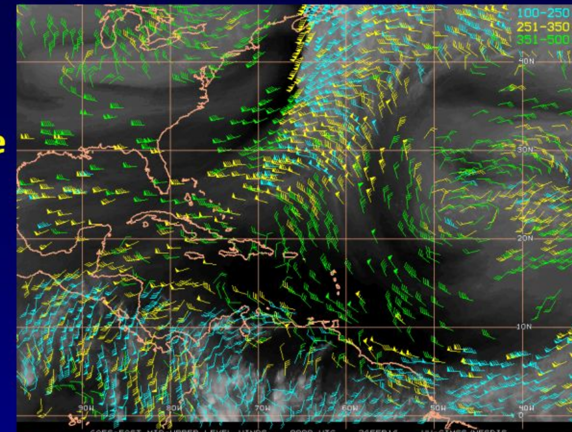
- **Imagery: Visible (VIS), Infrared (IR), Water Vapor (WV), Shortwave Infrared (SWIR), Microwave (MW), Multispectral – most meteorological satellites**
- **Satellite Atmospheric Winds: from multiple images (VIS, IR, WV) - geostationary satellites, some LEO satellites near the poles**
- **Sea Surface Temperatures (IR, MW) - GOES, NOAA, GPM, GCOM, METOP, NPP**
- **Ocean Surface Wind Speeds (MW) * - DMSP, GPM, GCOM, Coriolis, METOP, ISS**
- **Precipitation Estimates (IR, MW) * - geostationary satellites, GPM (including the Precipitation Radar), GCOM, DMSP, METOP**

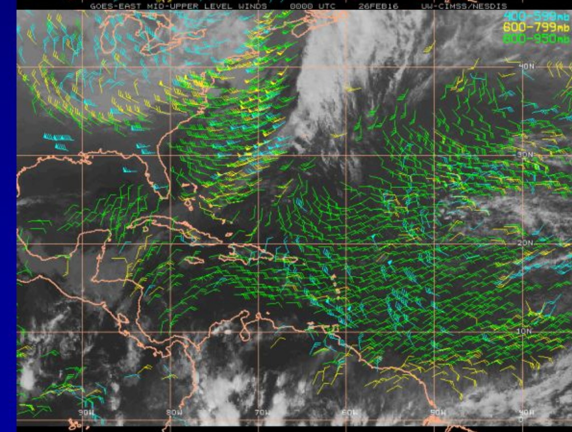
Types of Satellite Data

- Tropical Cyclone Intensity Estimates (VIS, IR, MW) * - geostationary satellites, NOAA (Advanced Microwave sounding Unit or AMSU), DMSP (SSM/IS), GPM, GCOM, METOP, NPP (ATMS)
- Satellite Vertical Soundings (IR, WV, MW) - GOES, NOAA, DMSP, METOP, Aqua, NPP
- Ocean Wave Heights (Jason2, Jason 3, Cryosat, Altika)
- Oceanic Heat Content (Jason2, Jason 3, Cryosat, Altika)

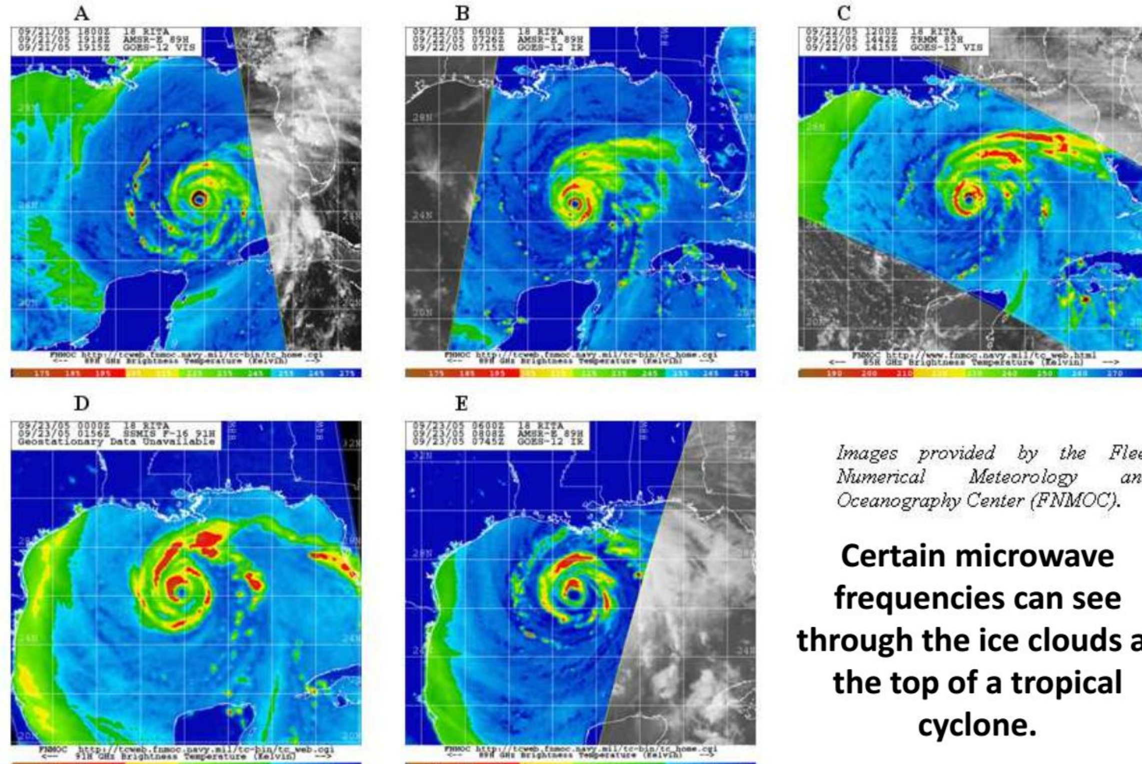
Satellite-derived winds

- Satellite winds are computed from the displacement of targets on two successive geostationary images.
- Targets can include clouds in visible or infrared imagery and features in water vapor imagery.
- Temperature of cloud or water vapor feature is used for height assignment.
- Satellite winds can show tropical cyclone steering, shearing, and outflow patterns, but cannot be made below the central cirrus canopy of a TC.
- Satellite winds are used for analysis as well as to initialize numerical weather prediction models.
- Reference: Velden et al., BAMS, 1997





Microwave imagery of TCs

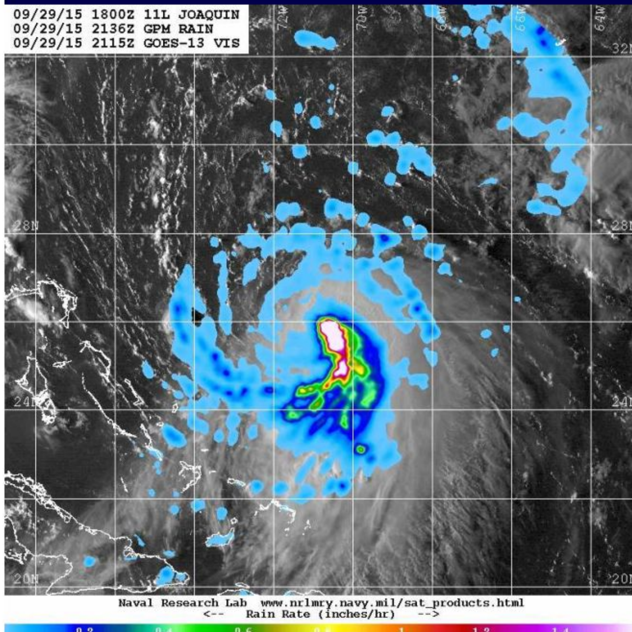


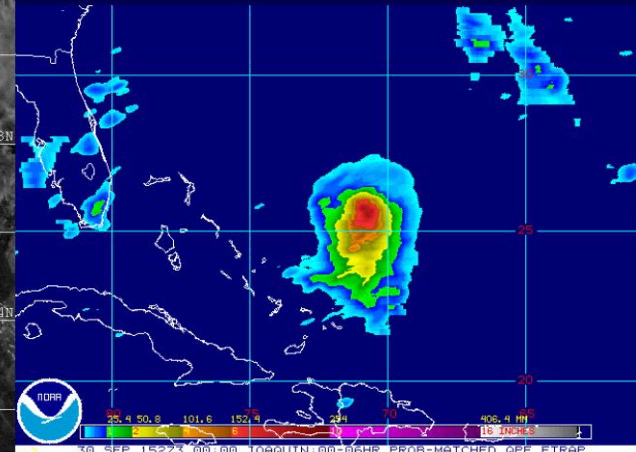
Images provided by the Fleet Numerical Meteorology and Oceanography Center (FNMOC).

Certain microwave frequencies can see through the ice clouds at the top of a tropical cyclone.

Figure 4. Series (in order A-E) of 85-91 GHz passive microwave images of Hurricane Rita during 21-23 September 2005.

Microwave Satellite Rainfall Estimates



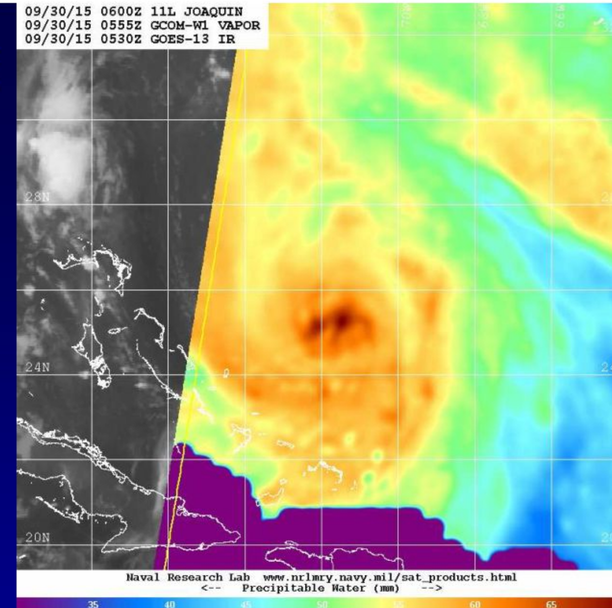


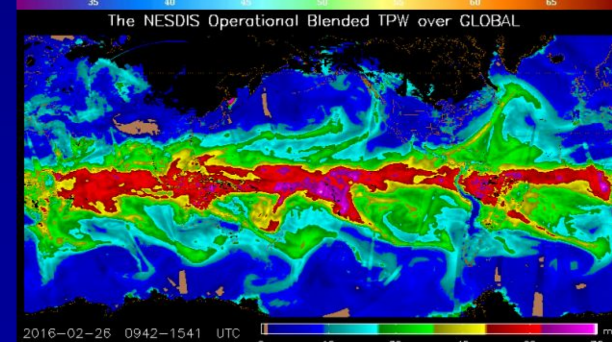
Observed Rainfall Rate **Forecast Precipitation Totals**

The Ensemble Tropical Rainfall Potential (eTRaP) technique is based on extrapolation of microwave convective patterns into the future.

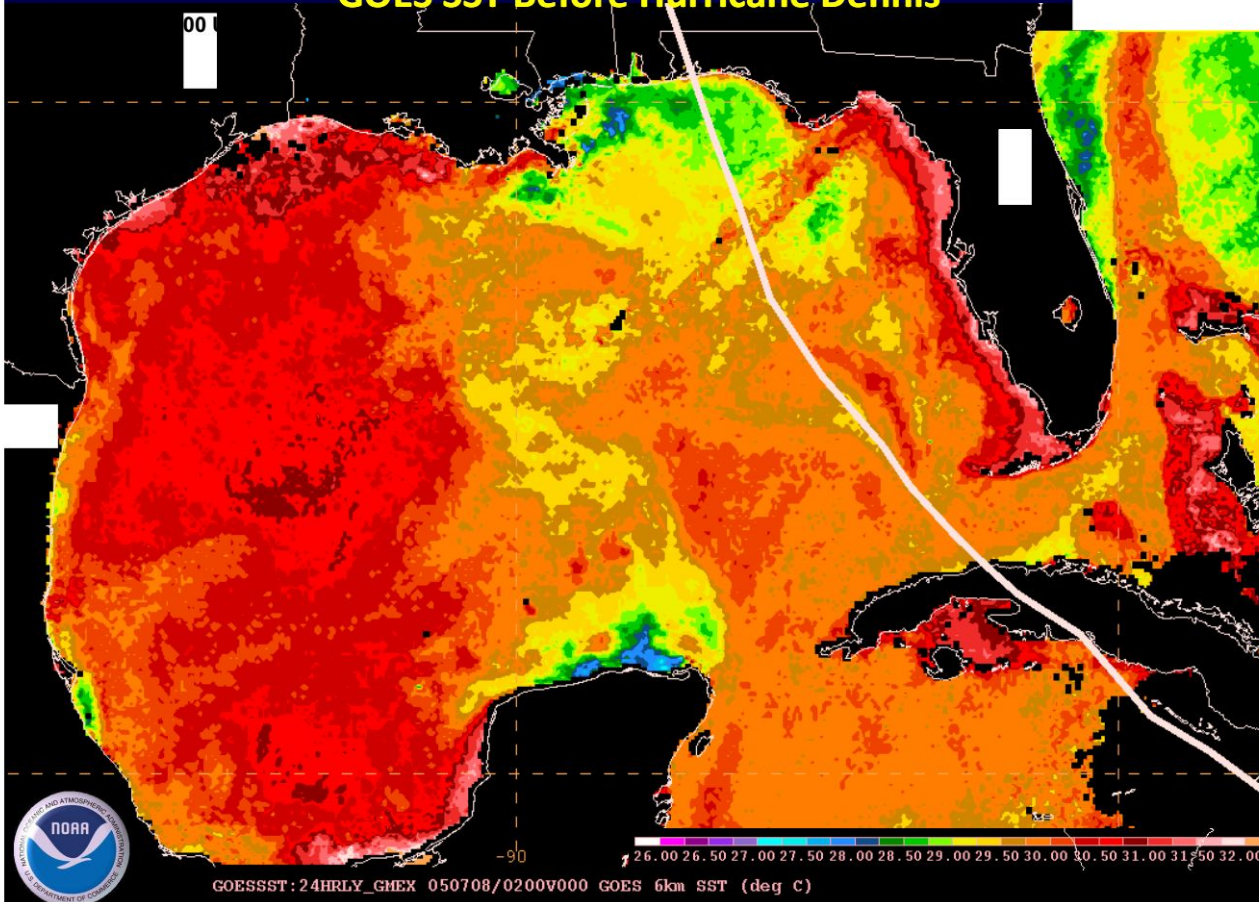
Total Precipitable Water Products

- **Microwave sounders measure moisture, which allows for the determination of the total amount of water and water vapor in a column of atmosphere – the total precipitable water (TPW).**
- **The TPW is used to track moist and dry air masses in weather systems, for determination of cyclone structure, and determination of how much atmospheric moisture is available to become rain.**

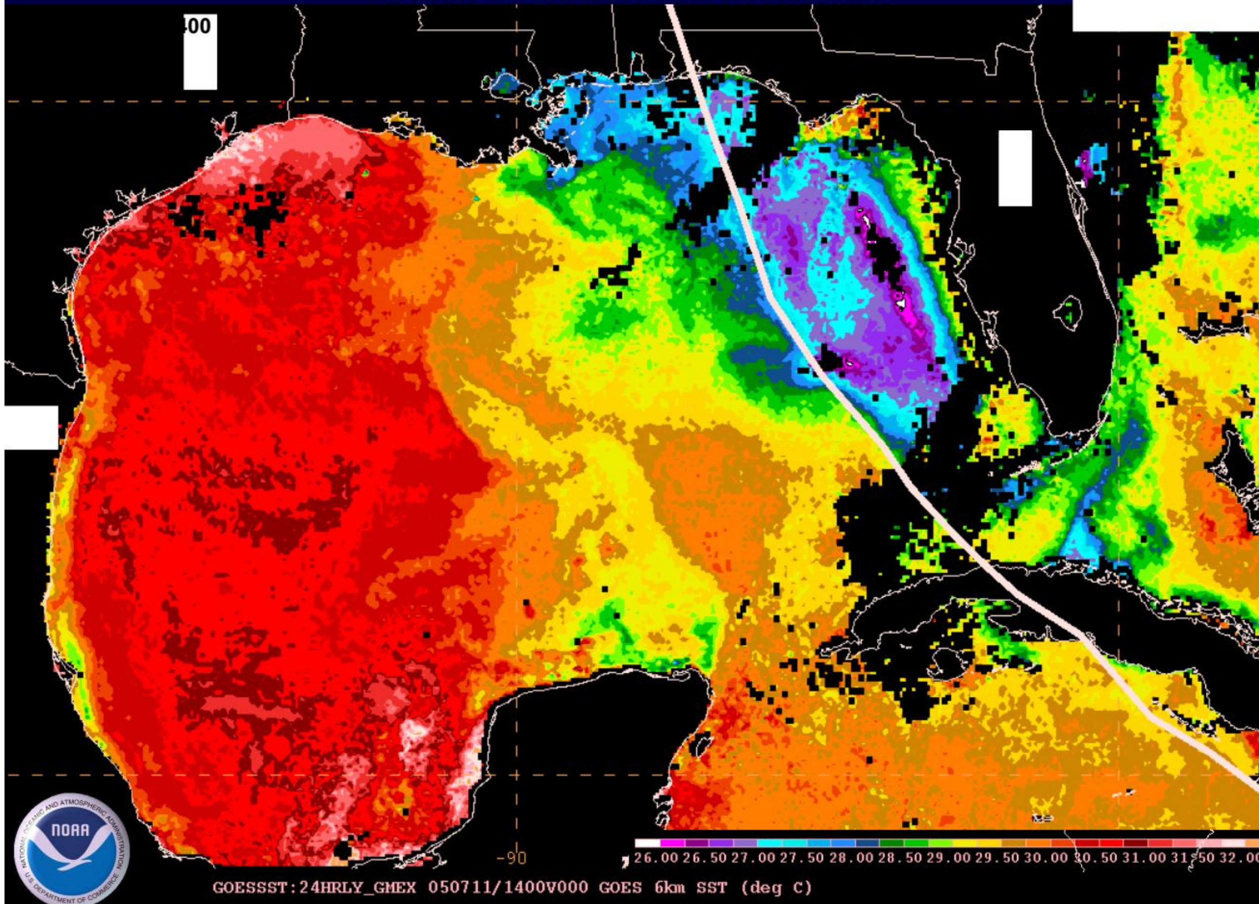




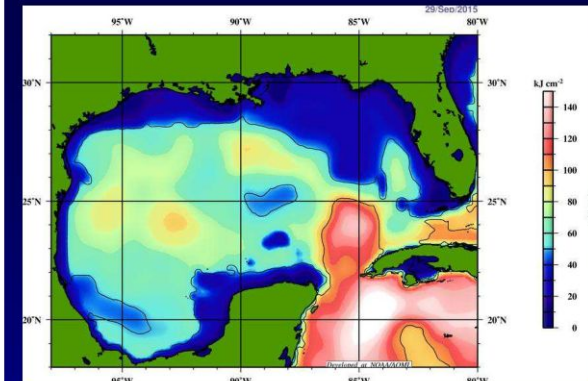
GOES SST Before Hurricane Dennis



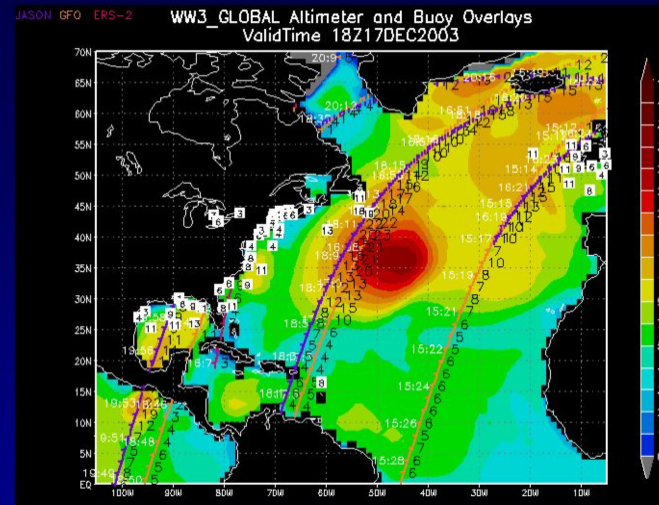
Hurricane Dennis' Cool Wake



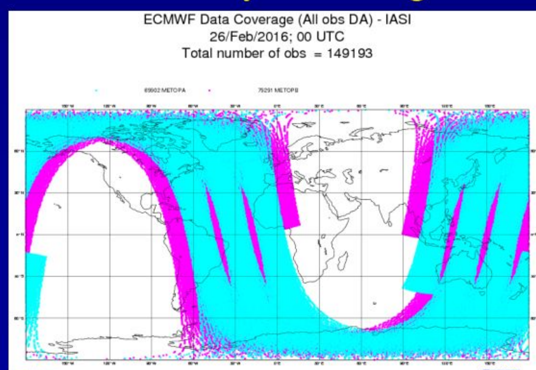
Other useful satellite data



Ocean height and heat content for TC intensity forecasting



Radar altimeter wave heights

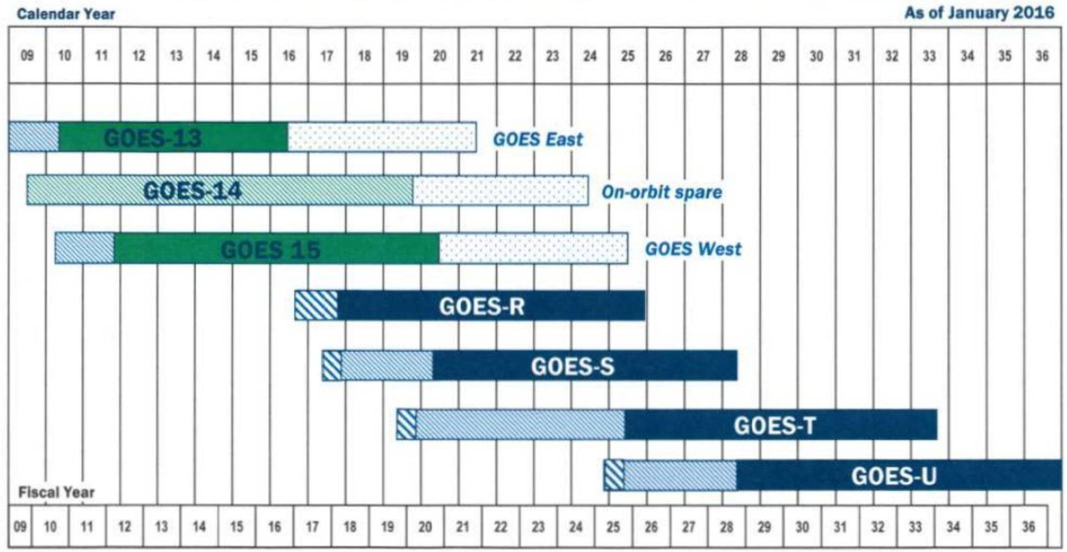


Satellite temperature and moisture soundings for use in numerical models – not used directly at NHC but of vital importance in forecasting

Future Meteorological Satellites

- There are numerous new meteorological satellites being planned around the world.
- Some of the planned improvements are to the ongoing geostationary and polar-orbiting satellite constellations.
- Others are research satellites that will produce data useable for operations.

NOAA Geostationary Satellite Programs
Continuity of Weather Observations

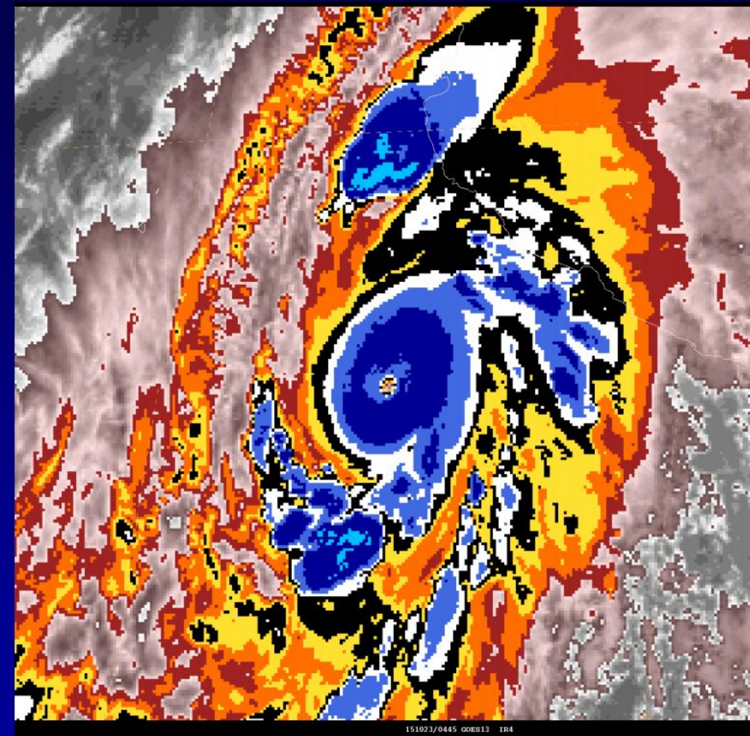


Approved: ______________________

Assistant Administrator for Satellite and Information Services

Conclusions

- Remote sensing satellites use the principles of radiative transfer when designing the instrument type and the portions of the electromagnetic spectrum the instruments use.
- A large part of the TC forecast process is based on data from satellites.
- The GOES-R series of geostationary satellites will create new ways to monitor the tropical cyclone and the nearby environment.



Thank You ….

Questions ?