How we will View the Earth in 2025

Keynote Address to the
Remote Sensing and Photogrammetry Society
Annual Conference
Greenwich, UK

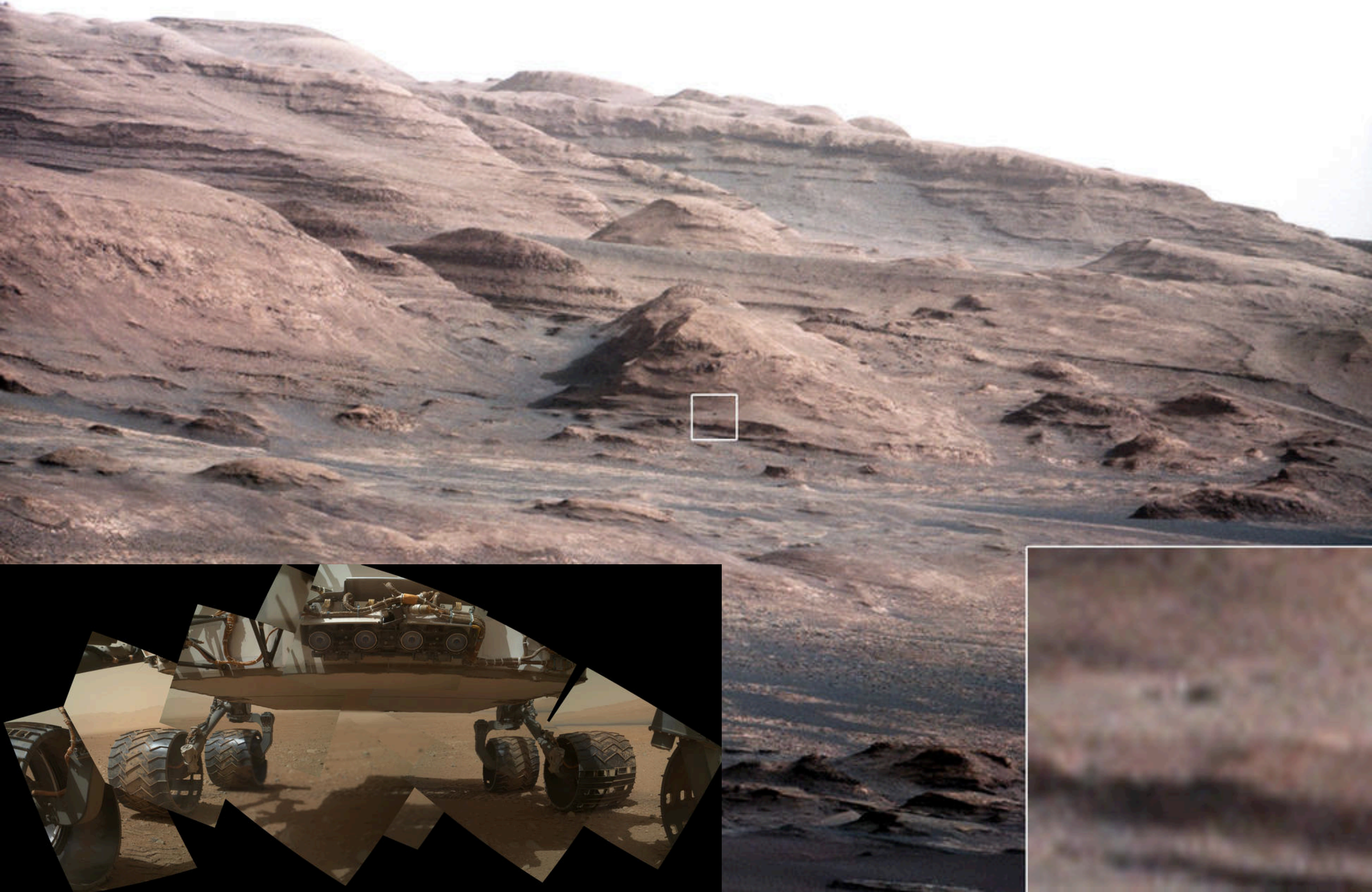
Tony Freeman

September, 2012

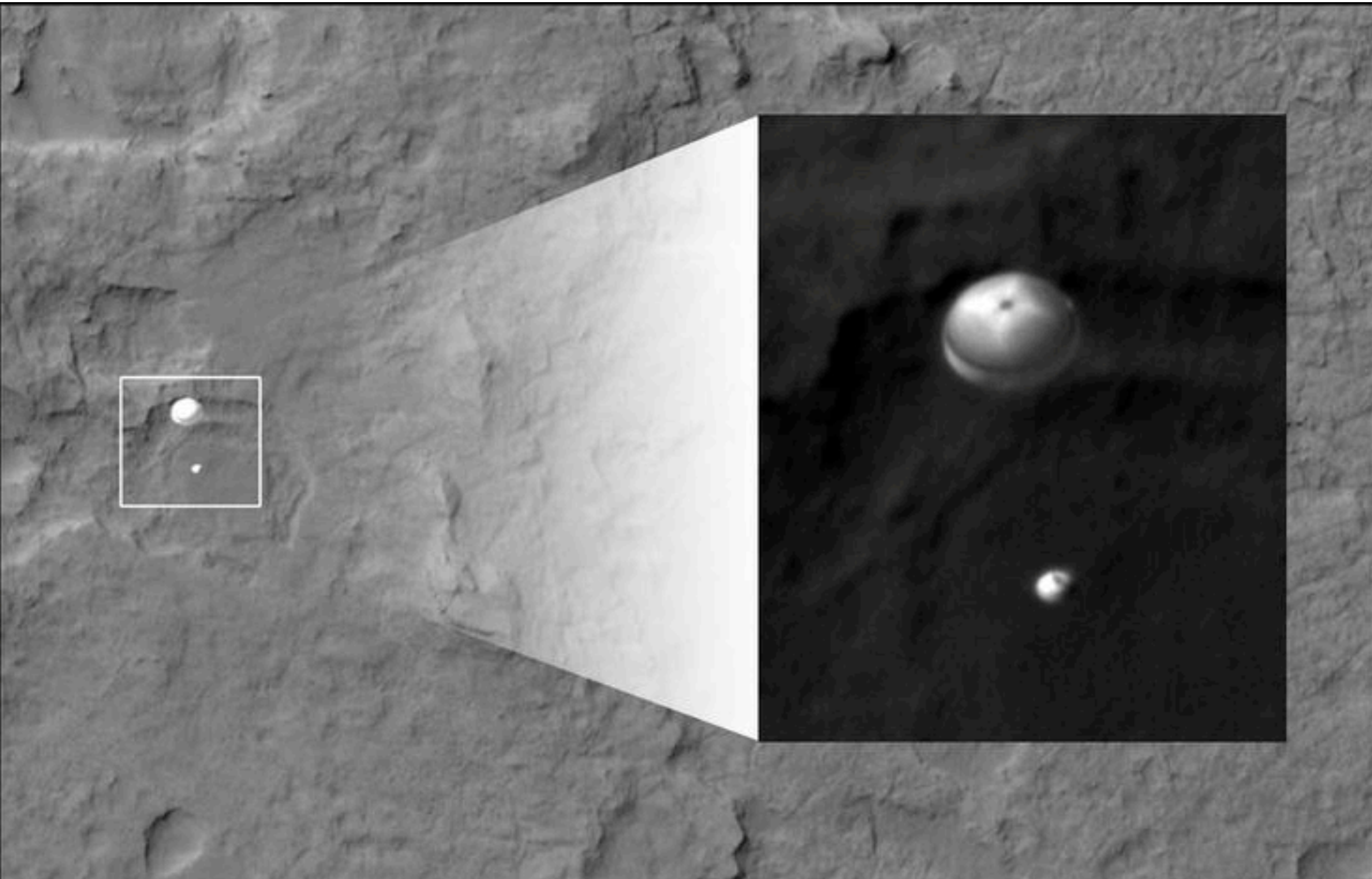
Overview

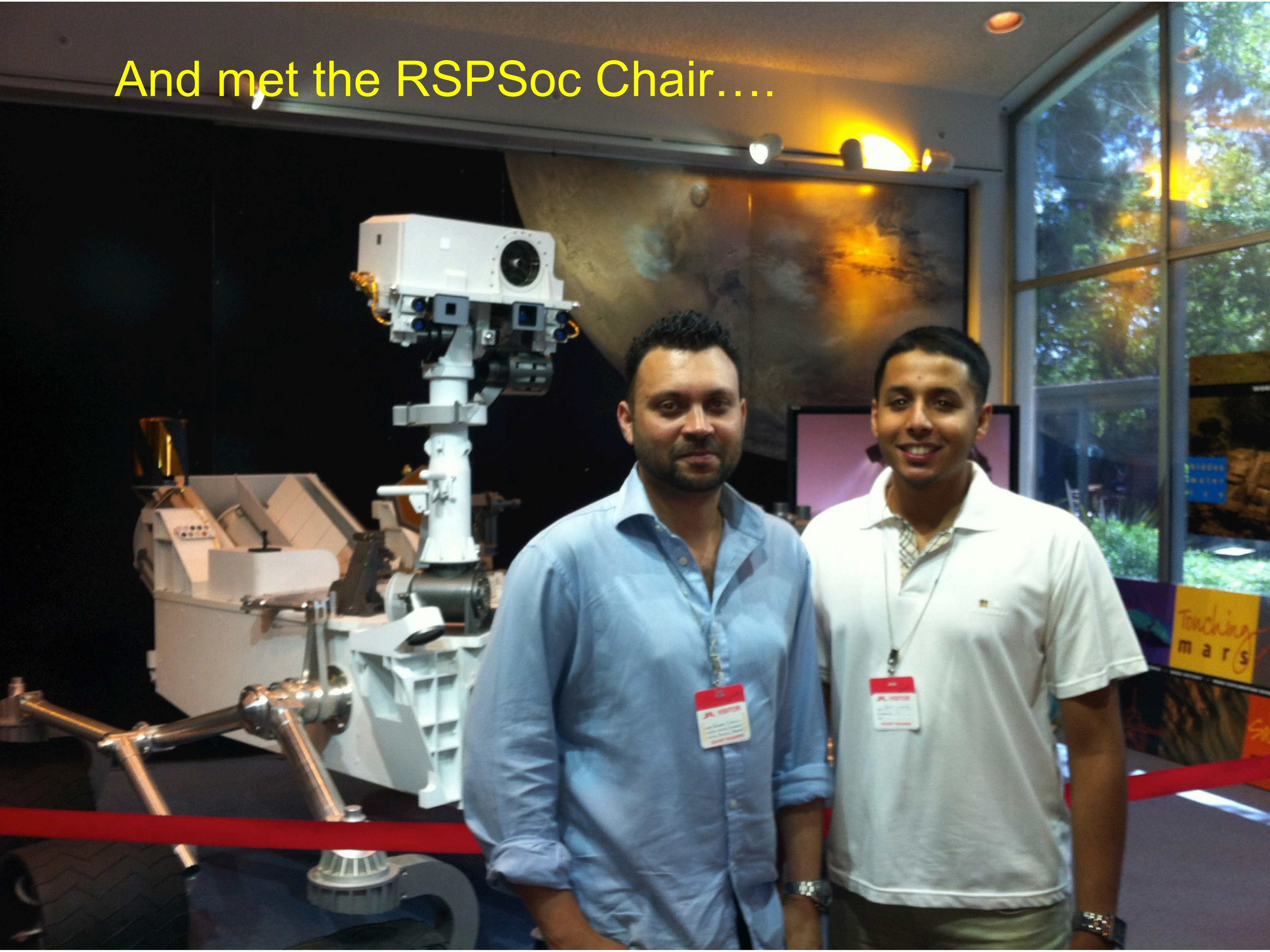
- What it is possible to achieve in 13 years
- The pressing need for Scientific Observations of the Earth System
- New Techniques
- New Platforms
- Summary

NASA and JPL have been in the news lately….



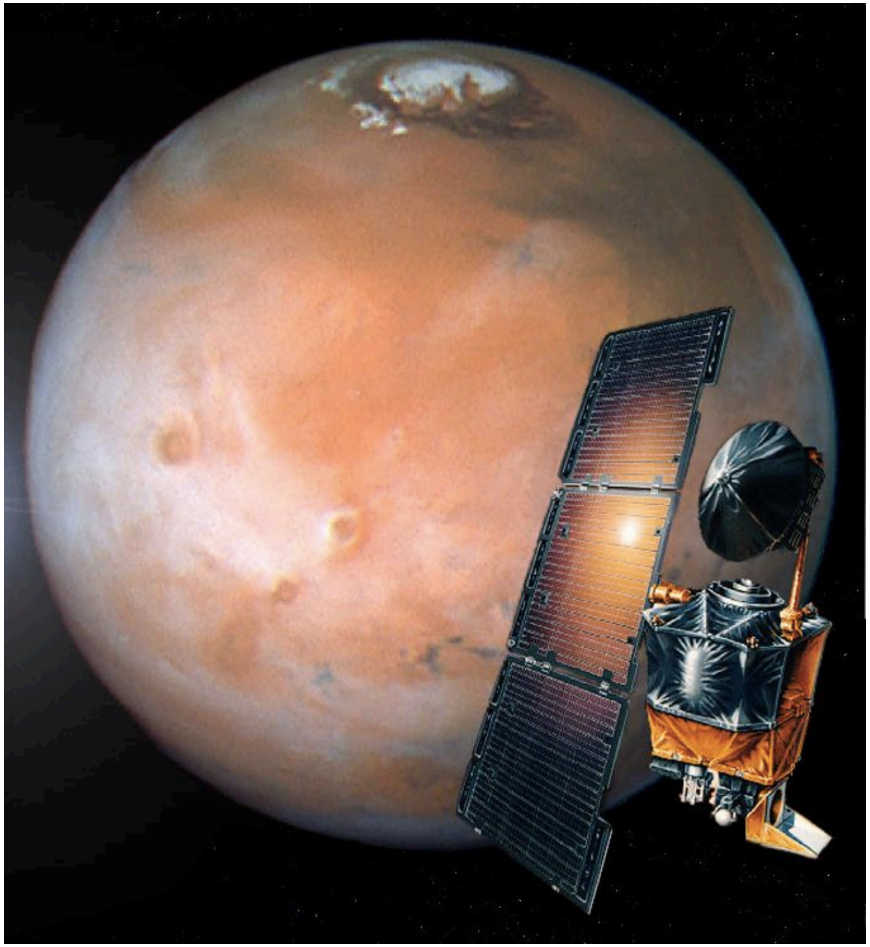
Curiosity was captured by MRO during landing



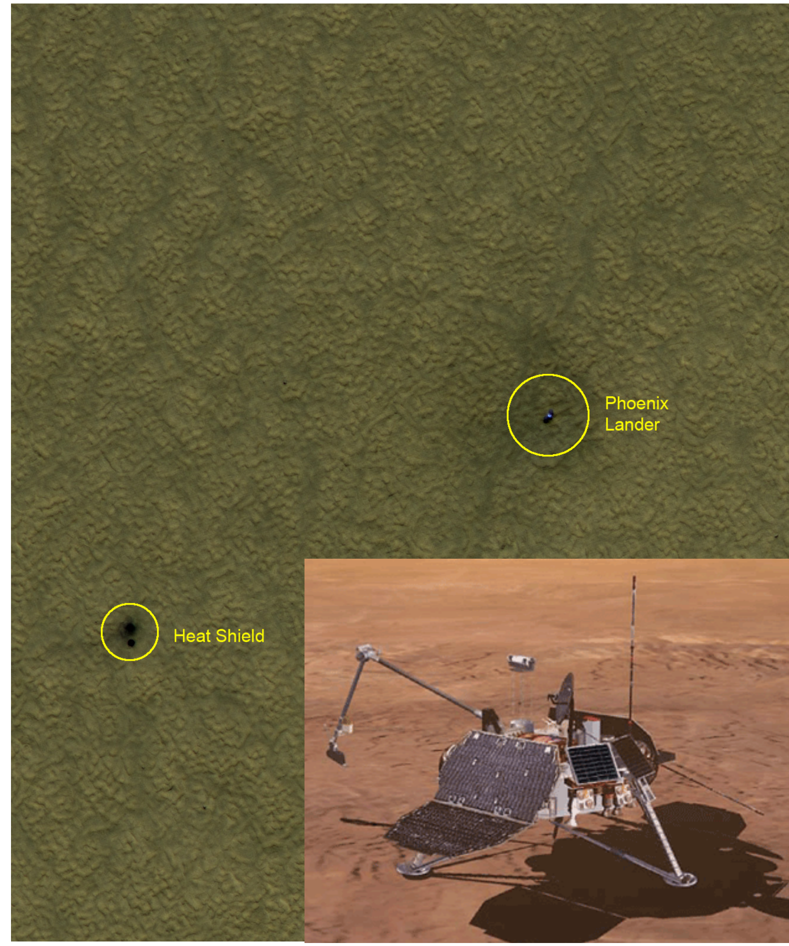

And met the RSPSoc Chair….
Touching
mars

13 years earlier….
MCO/MPL Failures (1999)

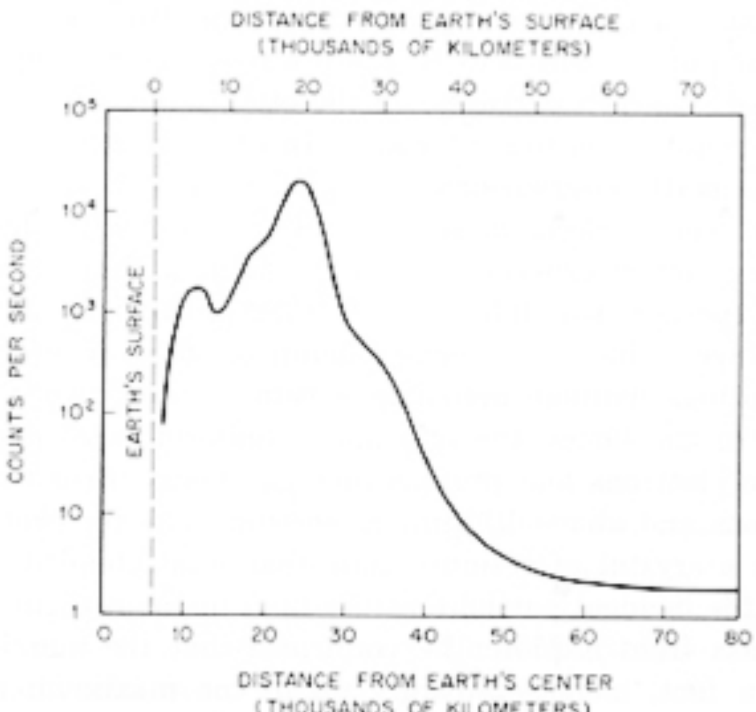
Mars Climate Orbiter

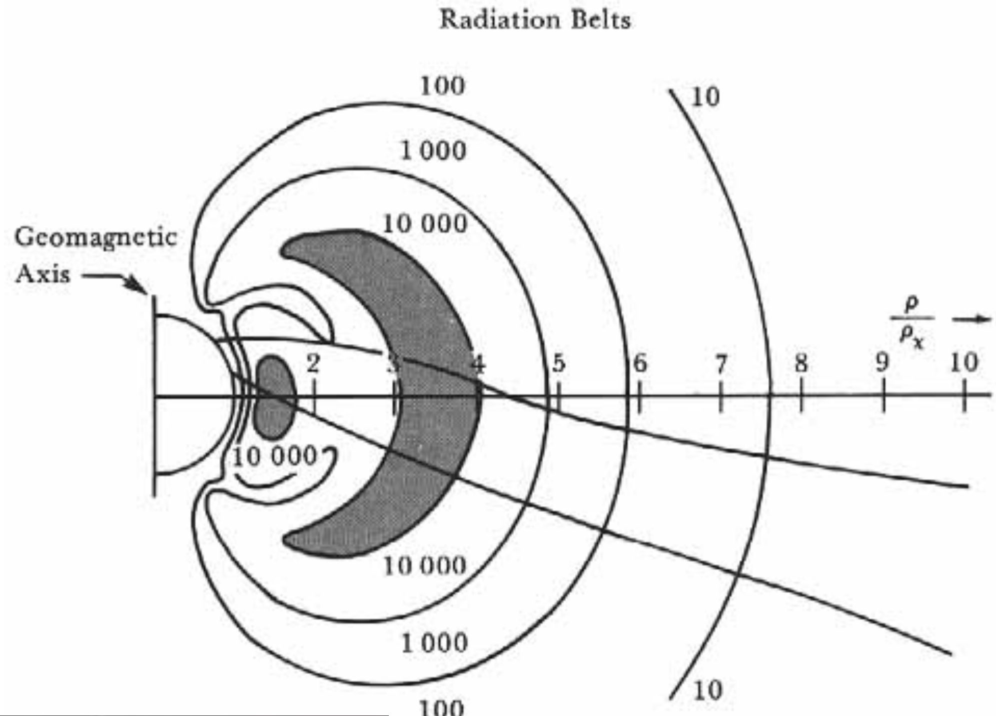


Mars Polar Lander



Let's go back to the dawn of the age of Space Exploration

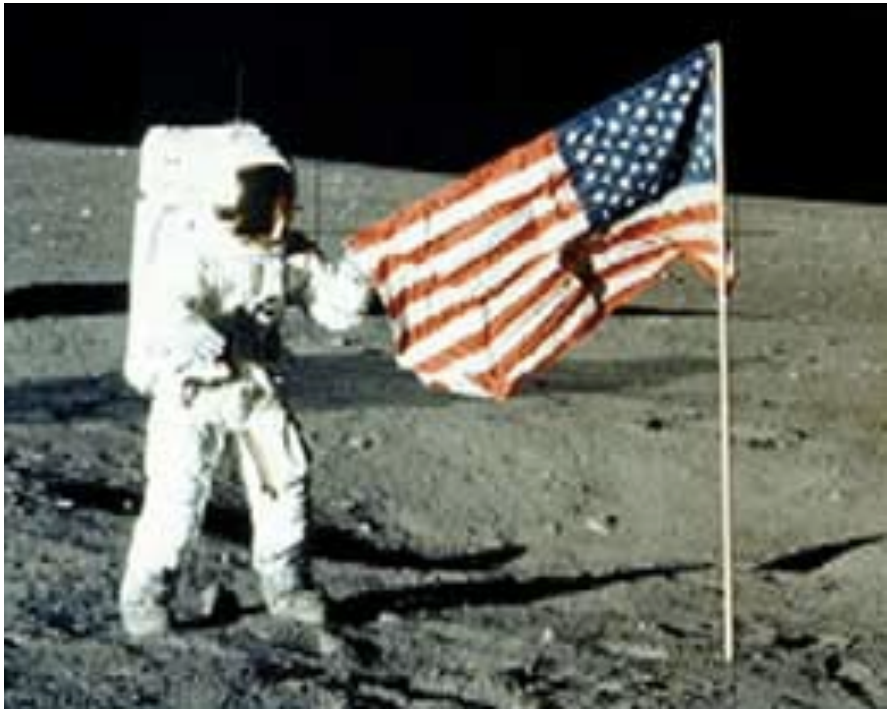




In 1958 JPL's Explorer-I discovered the Van Allen Radiation Belts

13 years later, NASA had…

Walked on the Moon



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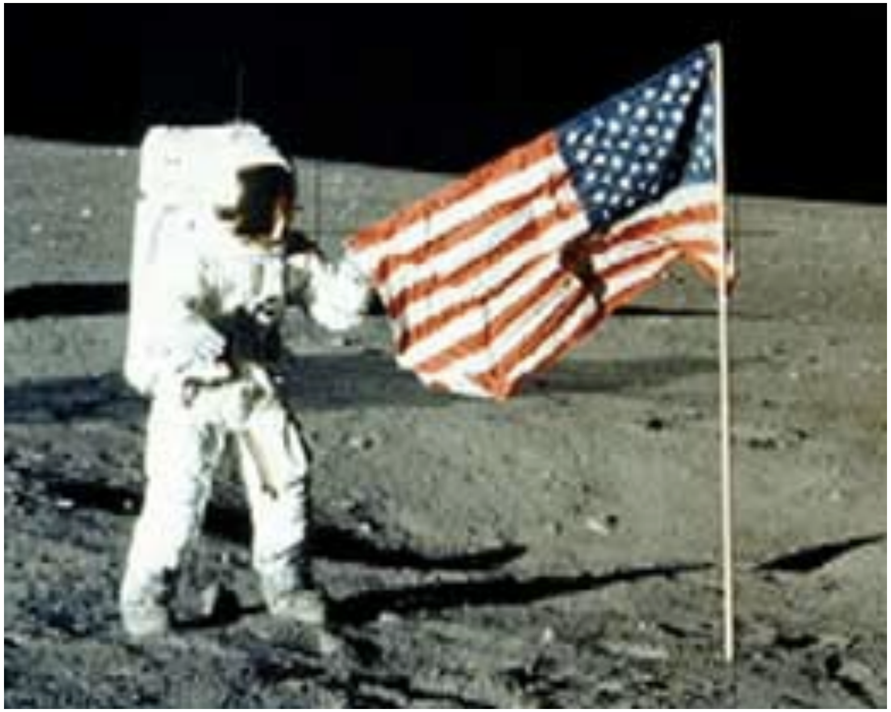

Put up a constellation of weather satellites

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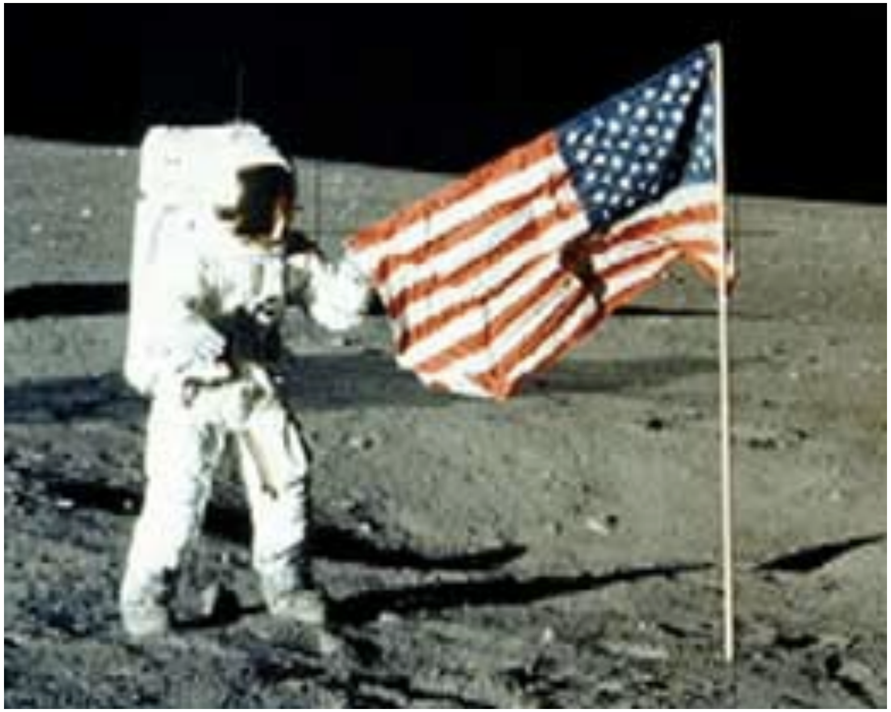
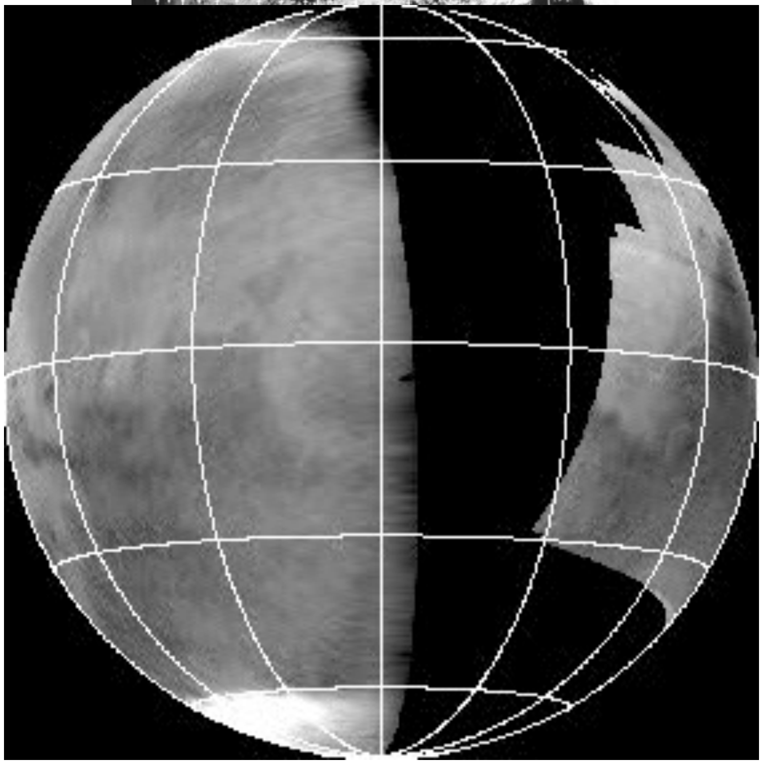


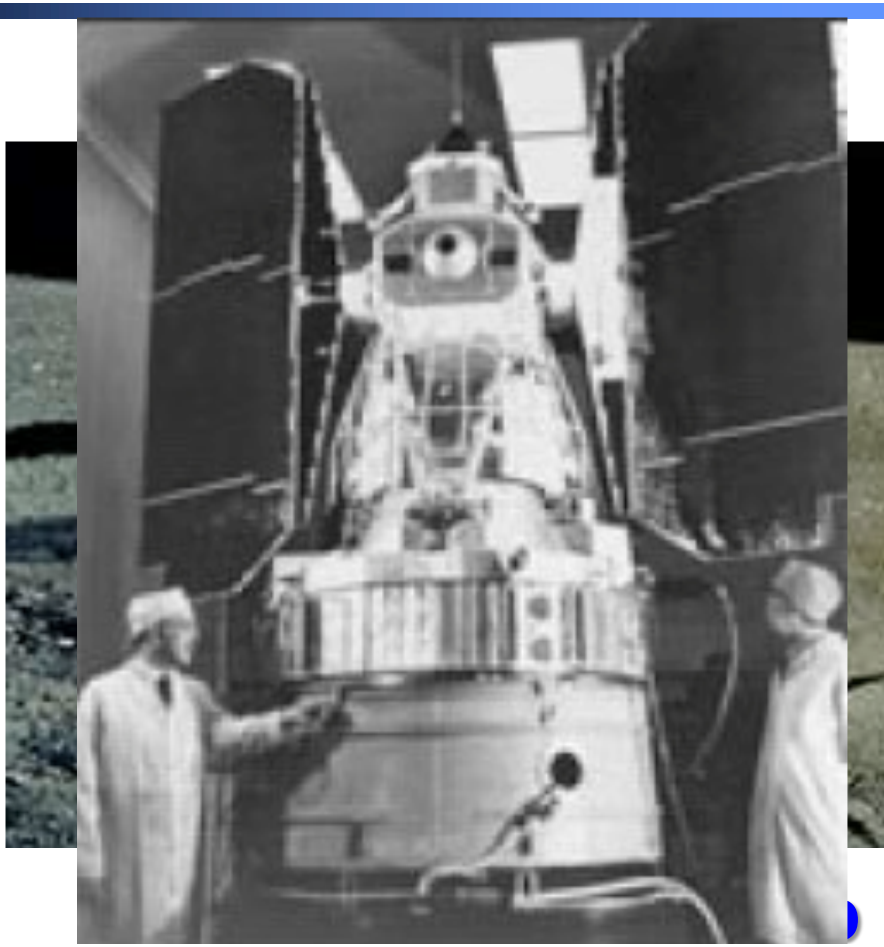
Put up a constellation of weather satellites



Got our first close-up view of Mars (Mariner-6/7)

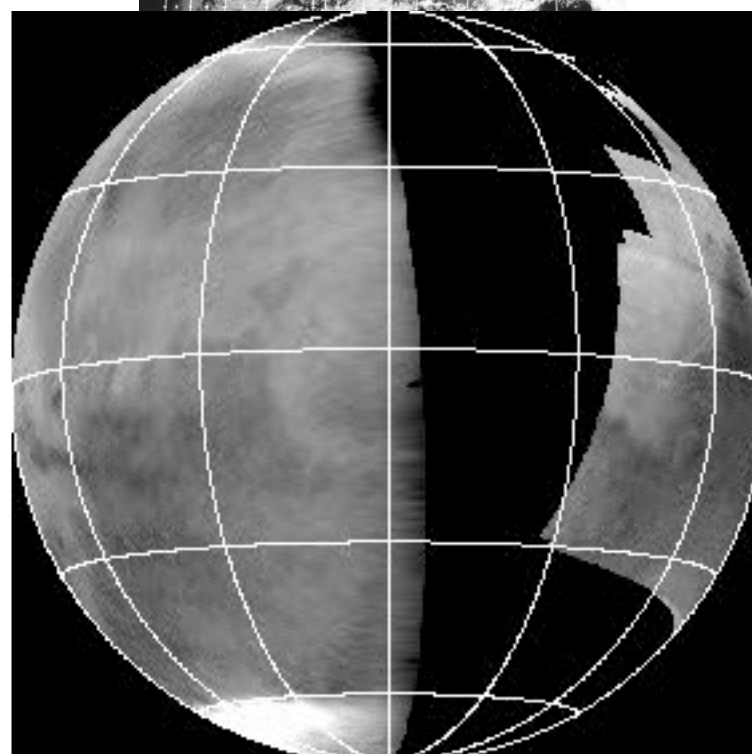
13 years later, NASA had…

Jet Propulsion Laboratory
California Institute of Technology



Built the first in the Landsat series

Put up a constellation of weather satellites



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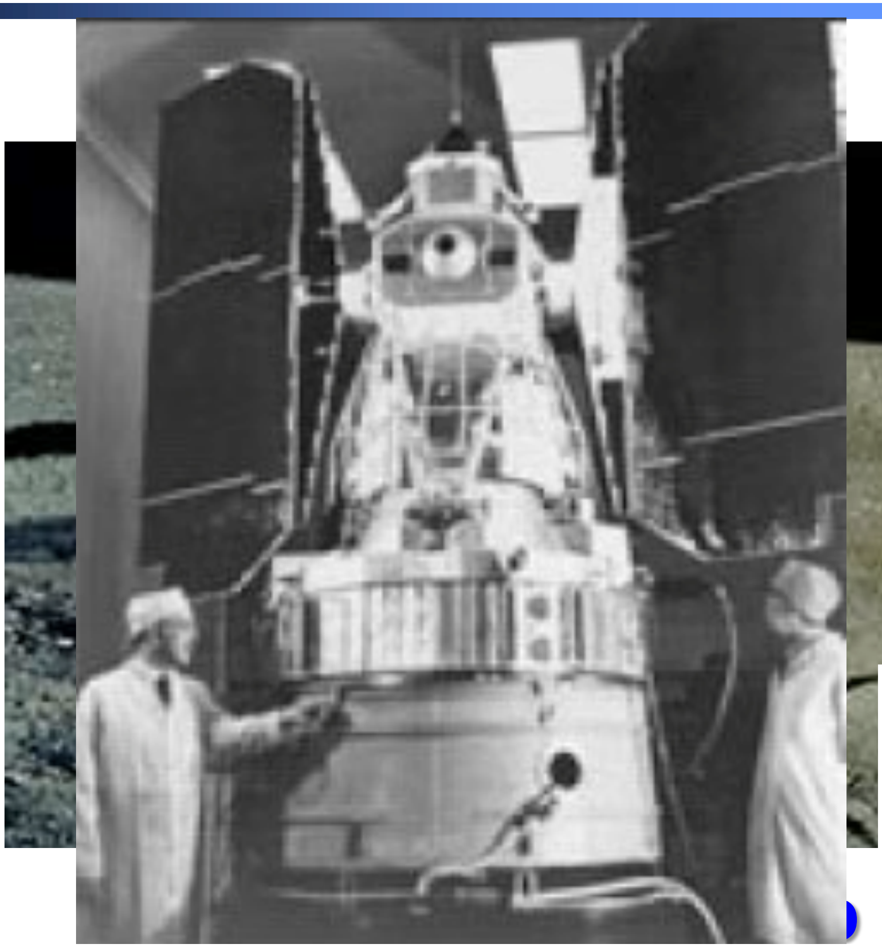
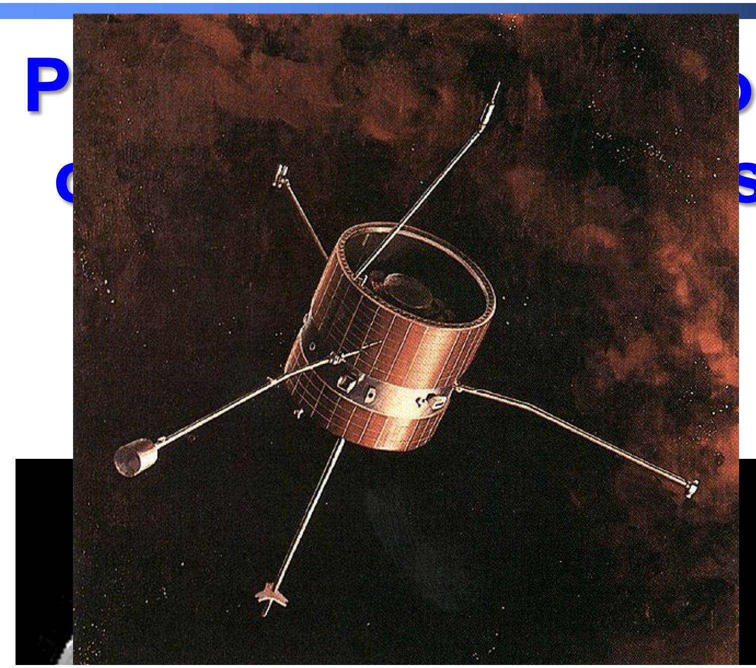
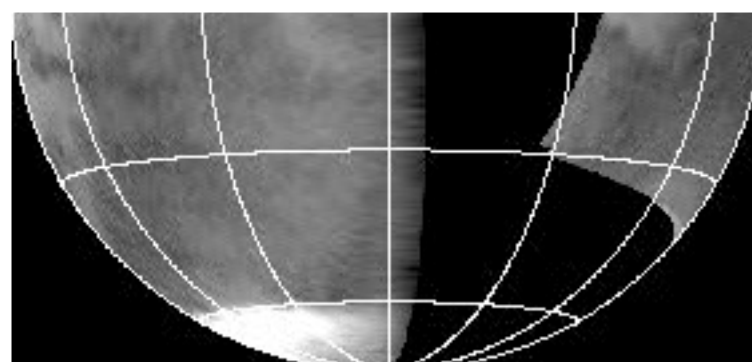


Built the first in the Landsat series



Pioneered measurements of the Solar Wind



So… Earth Observation from Space

- Began with the dawn of Space Exploration in 1958
- We are currently in the 3rd wave of satellite remote sensing:

1. First of a kind views and basic physics
2. Calibrated measurements we can relate to underlying physics
3. Measurements → Information for Decision-makers

First of a kind views and basic physics

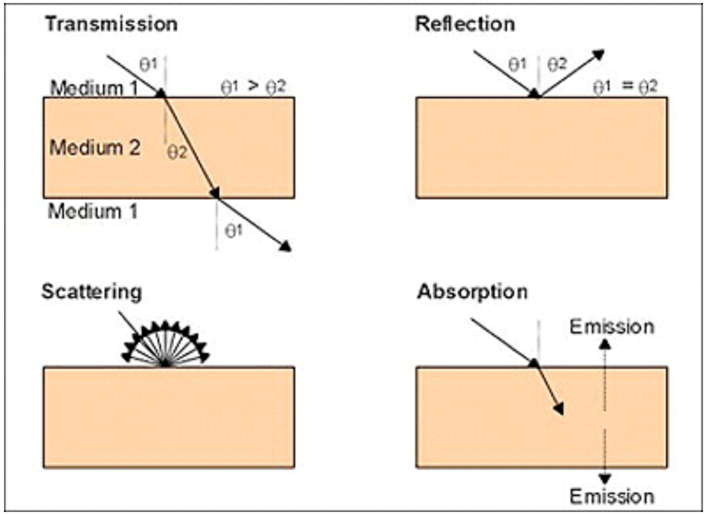
Planet Earth from TIROS 1: First TV Image

Resolve cloud and surface features

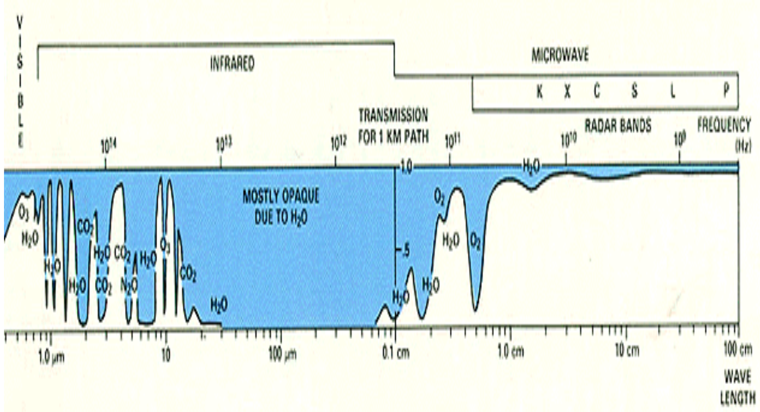
Served as a "storm patrol"

Possibility of measuring the heat budget of the planet

Physics of Remote Sensing

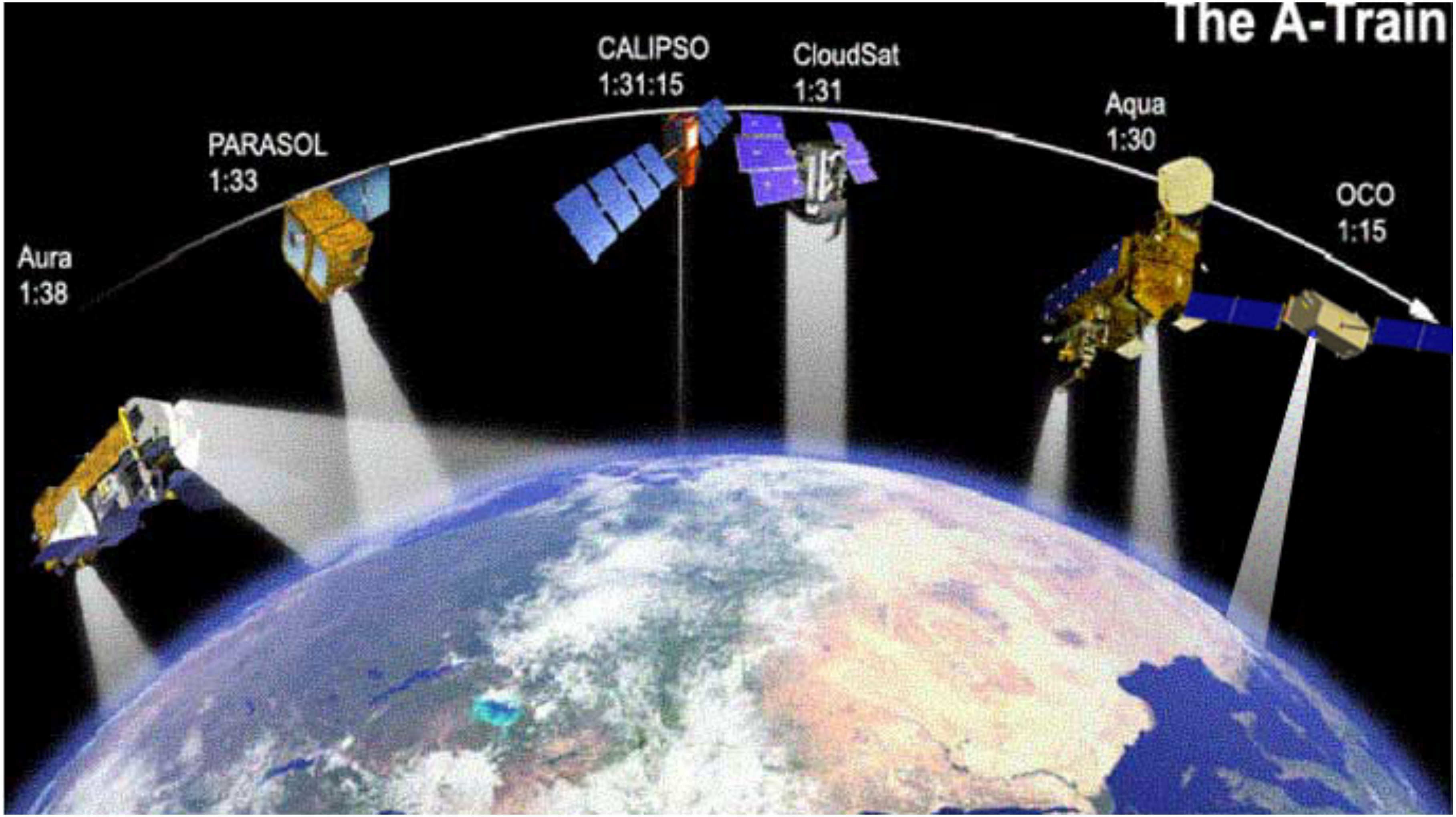


Radiative Transfer Theory



The A-Train

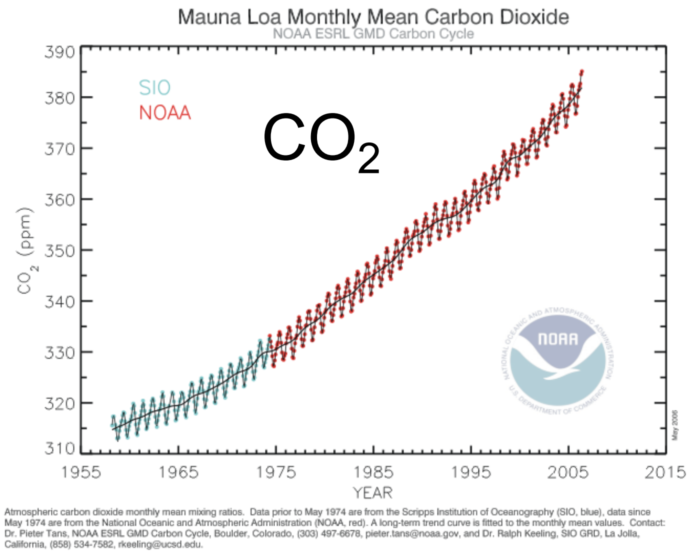
Calibrated Measurements of the Earth System

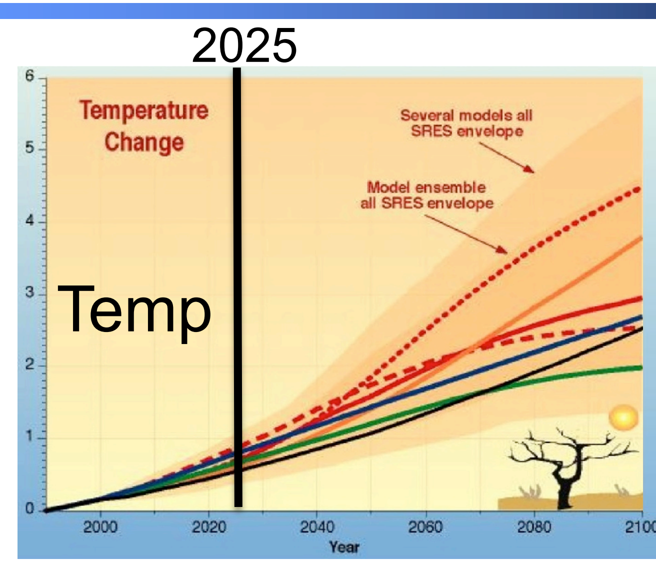


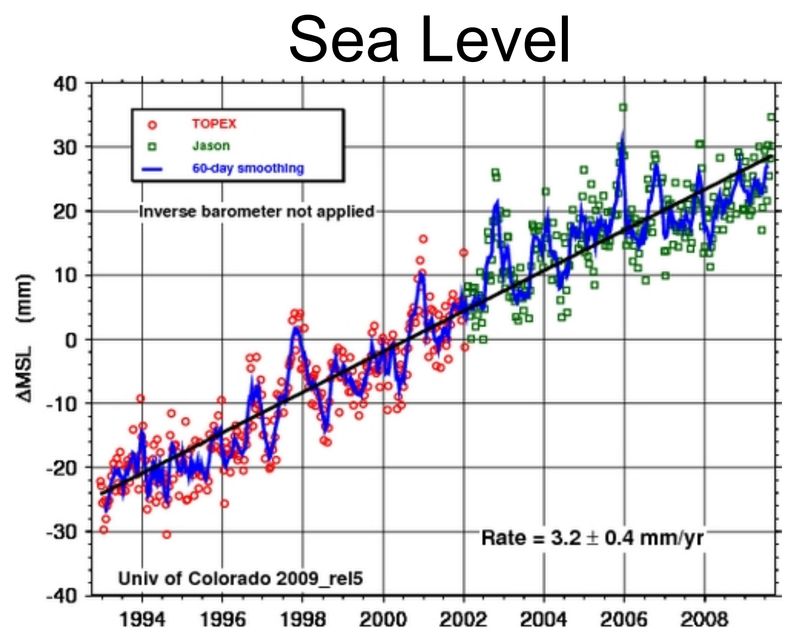
Information for Decision-Makers
The Earth's Vital Signs

http://climate.nasa.gov/

Decision-Makers note that the Trends are all in the 'Wrong' Direction





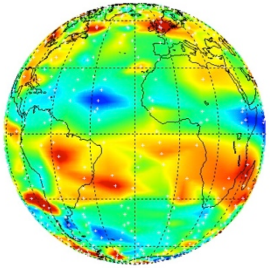


Today is September 12th, 2012

How will we view the Earth from Space 13 years from now?

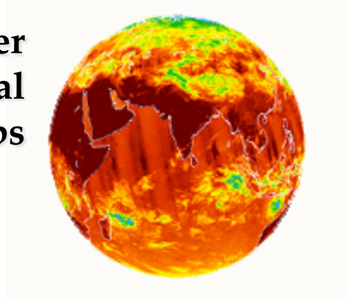
Observations from Space Reduce Uncertainties In Radiation Budget

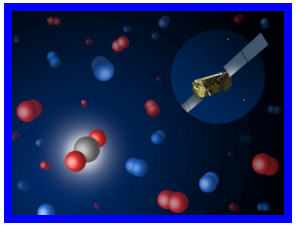
Jet Propulsion Laboratory
California Institute of Technology



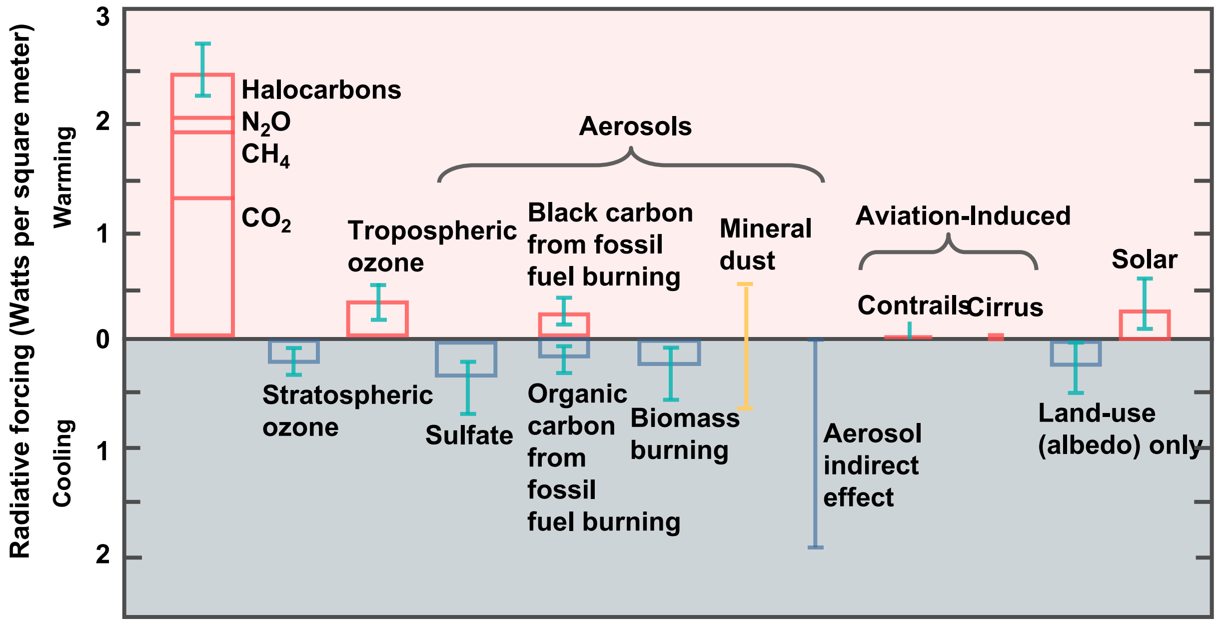
The Tropospheric Emission Spectrometer (TES) is making the first-ever measurements of tropospheric ozone from space

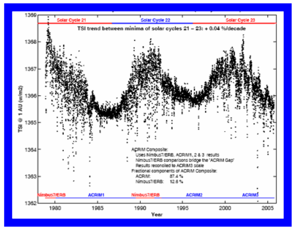
Atmospheric Infrared Sounder (AIRS) provides monthly global temperature maps



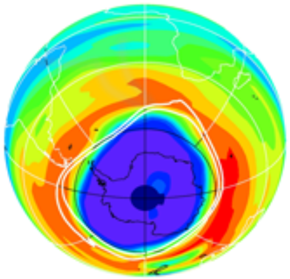


Orbiting Carbon Observatory (OCO) will measure 1 molecule of CO_2 in 1,000,000 molecules of air

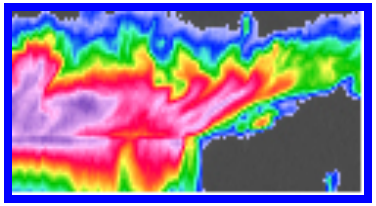




ACRIMSAT measures the total amount of solar energy reaching the Earth

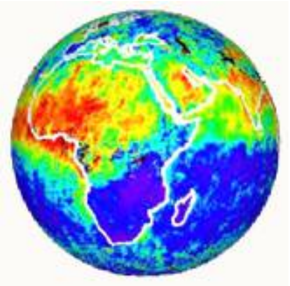


The Microwave Limb Sounder (MLS) is making measurements of stratospheric ozone



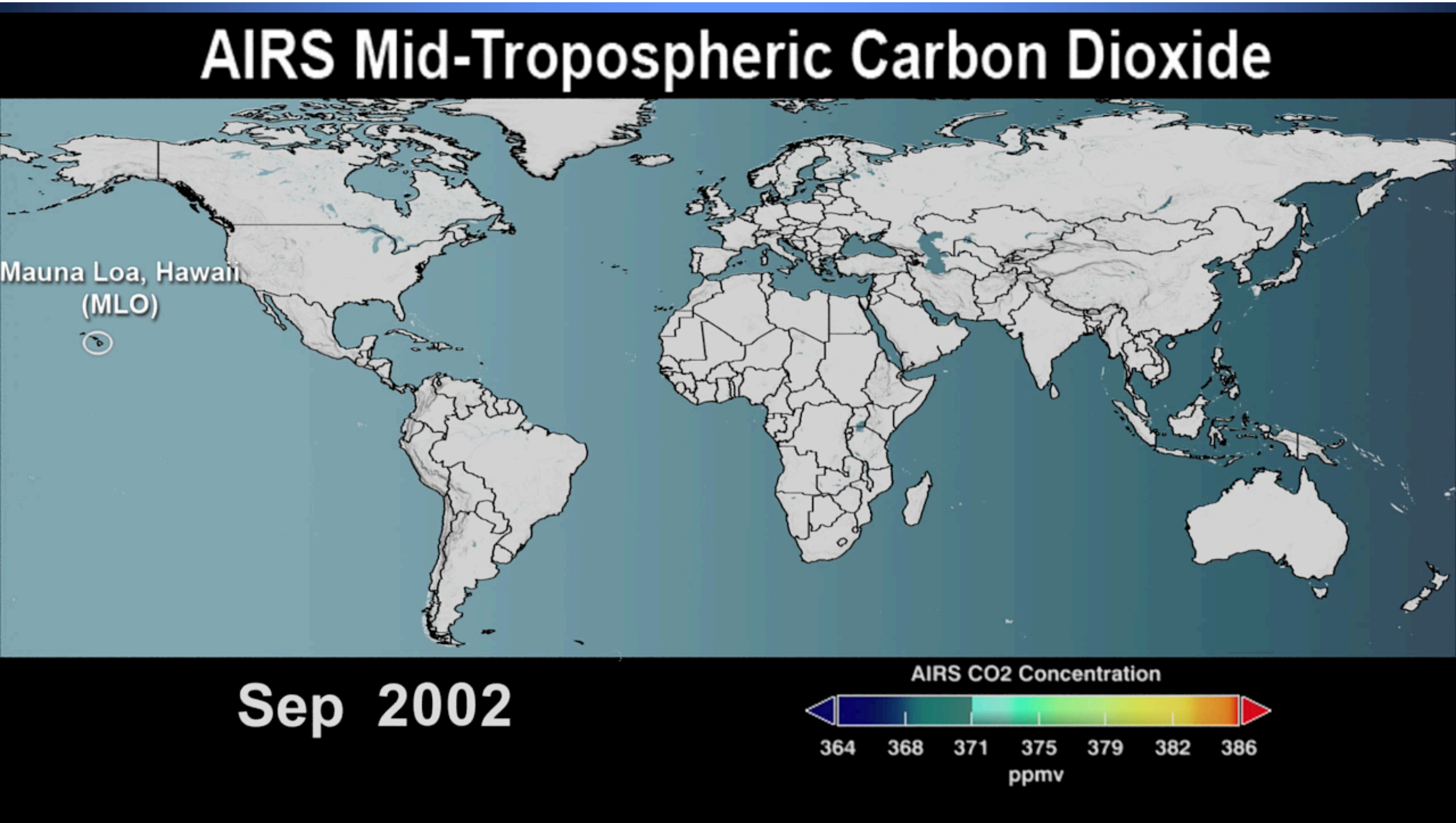
CloudSat is providing profiles of clouds

Multi-angle Imaging Spectro Radiometer (MISR) provides monthly global aerosol maps



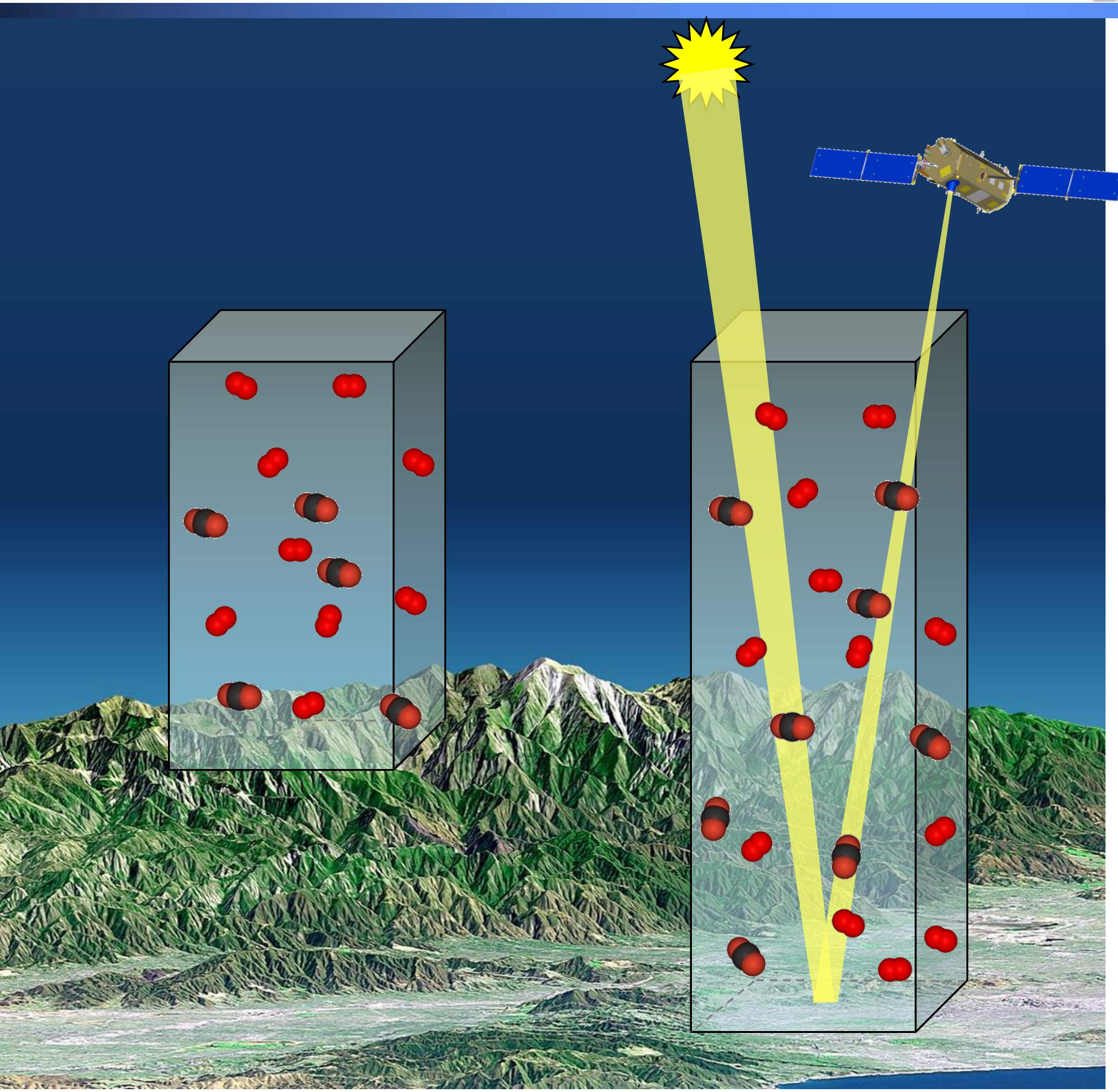
AIRS mid-troposphere CO_2 results are linked to seasonal growth of vegetation

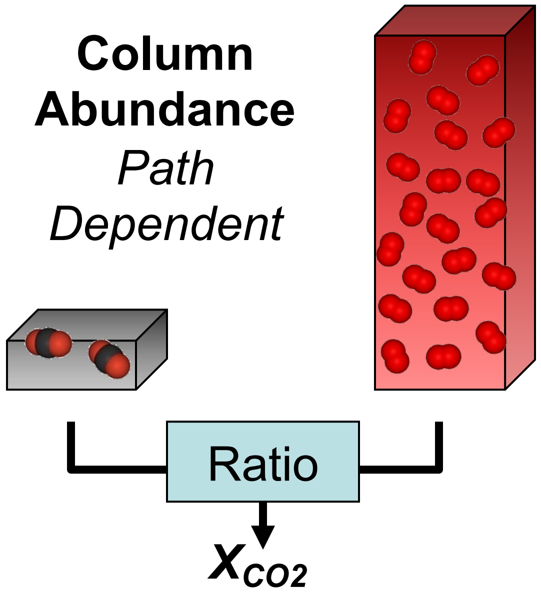
Jet Propulsion Laboratory
California Institute of Technology



… but the overall levels show a steady increase each year

Orbiting Carbon Observatory (OCO) will measure column CO_2 from space





X_{CO2} is the normalized CO_2 mixing ratio in a column of air.

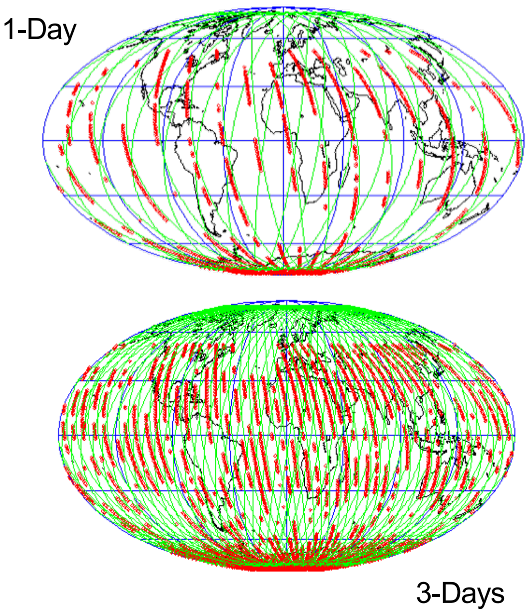
Accuracy: 1 part per million ppm (or 0.3%)

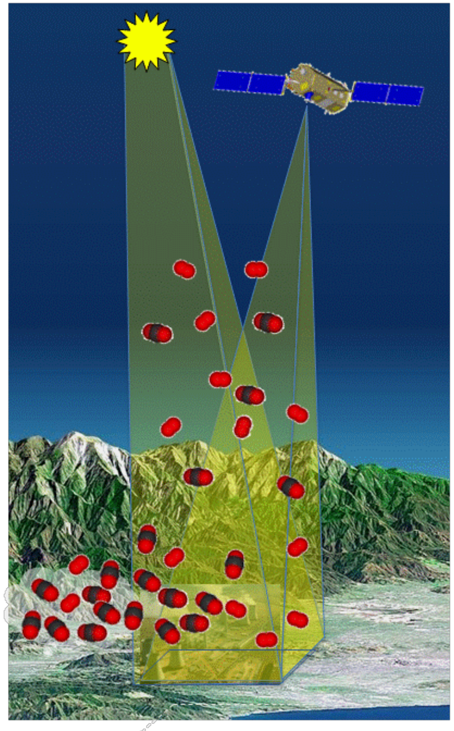
Column Density CO_2 Concentrations from Space

Orbiting Carbon Observatory (OCO)

- Spectral resolution: 0.25 – 0.6 cm^{-1}
- Spatial resolution: 1.29 x 2.3 km
- Daytime, cloud-free measurements only
- Measurement precision <1 ppm
- Tracks sun glint to achieve high SNR over the ocean
- Launch scheduled for 2014
- OCO-3 on ISS planned for 2017

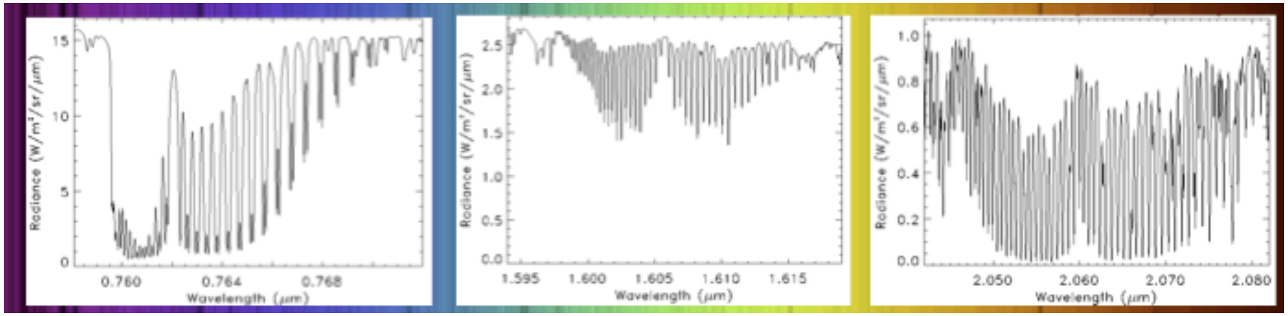
100,000 cloud-clear soundings per day



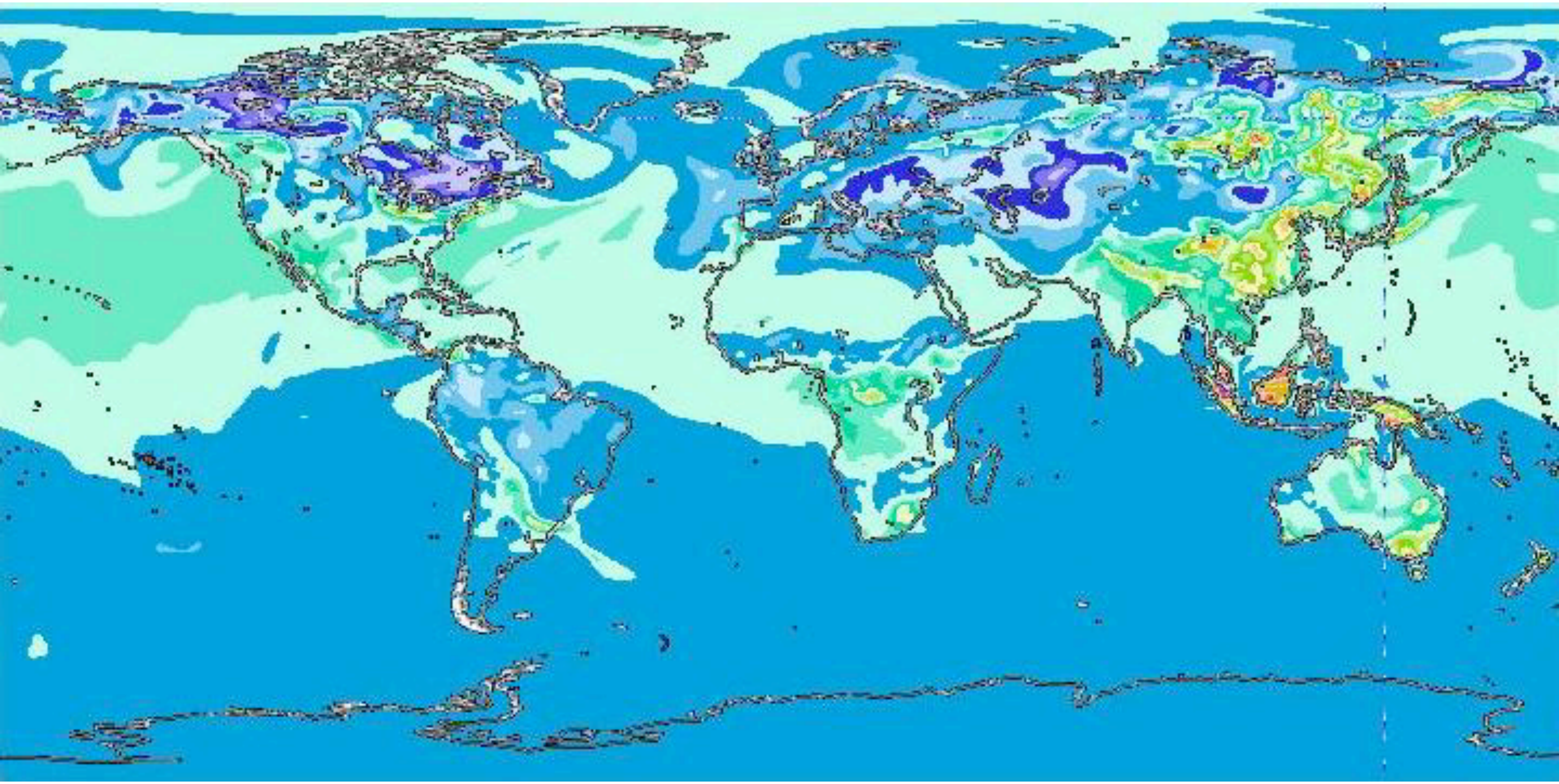


Measurement of sunlight reflected off the Earth's surface

0.76, 1.6, and 2 μm band spectroscopy



Surface CO_2 fields (from Model)



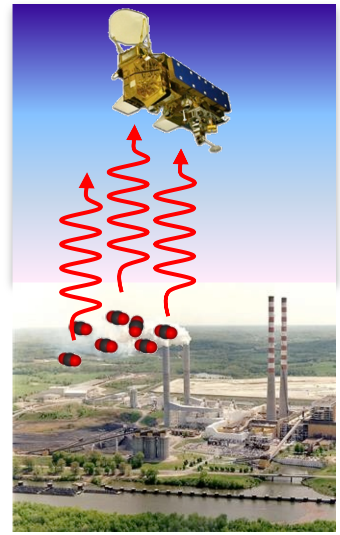
Source: R. Kawa, GSFC

Estimating Near-surface CO_2 Concentrations from Space

Jet Propulsion Laboratory
California Institute of Technology

Combining OCO-2 and AIRS measurements

- TIR bands: 4 – 15 µm
- Spatial resolution: 13.5 km (IR) 2 km (NIR)
- Initial simulations are promising
- Both data types will be available when OCO-2 flies with AIRS in 2015
- TIR only retrievals being investigated using AIRS only (all-weather capability)



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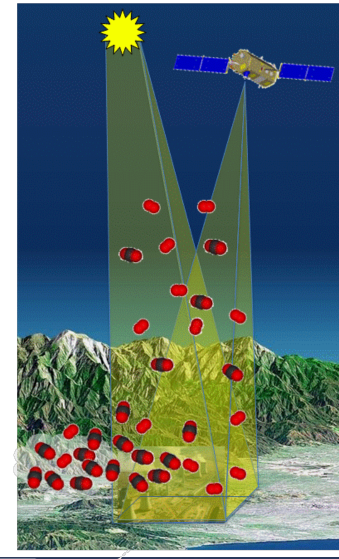
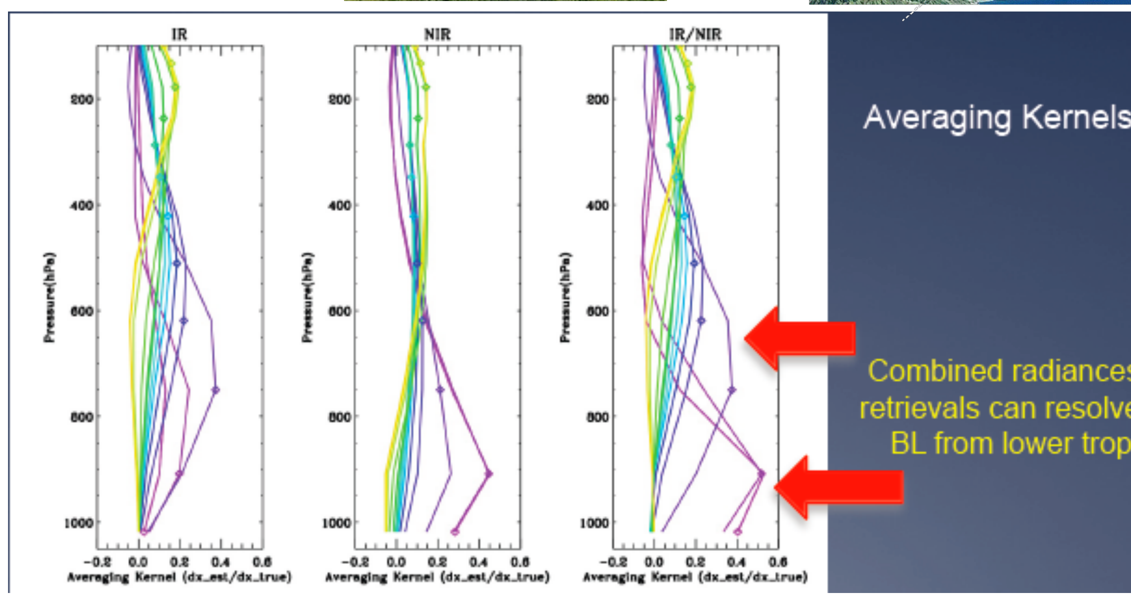
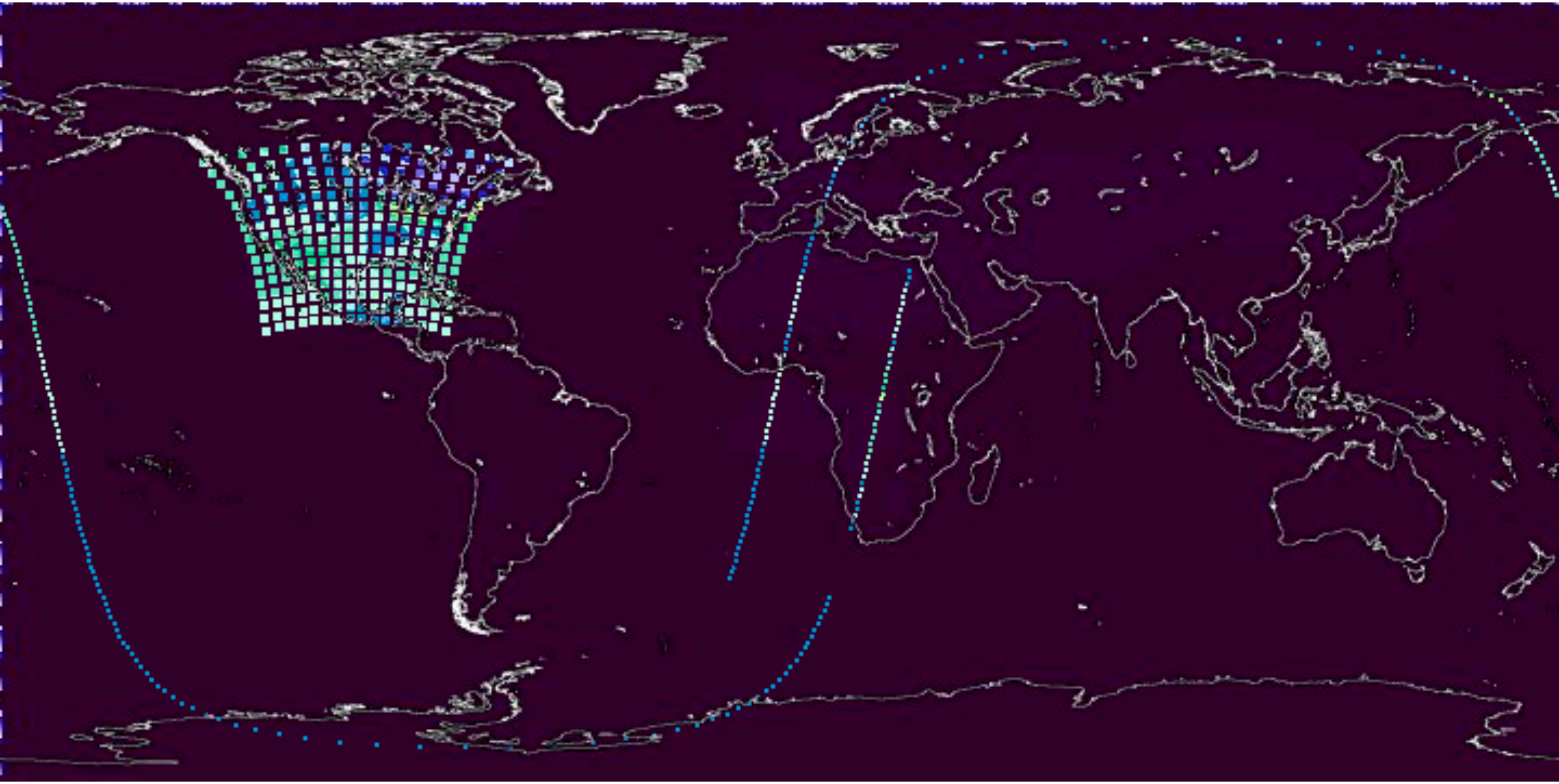




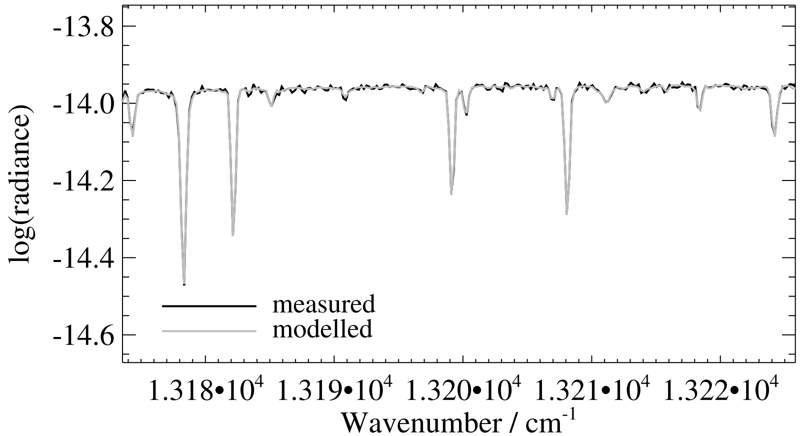
LEO+GEO Sampling of Surface CO_2

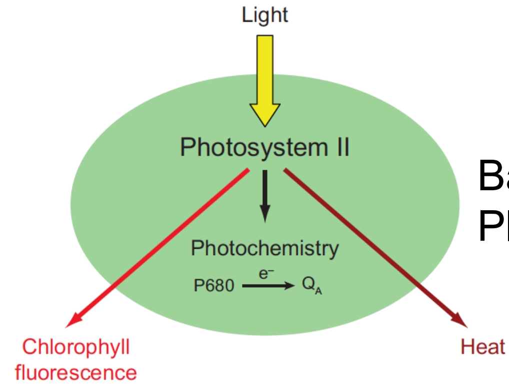


A-train LEO orbit and GEO sampling

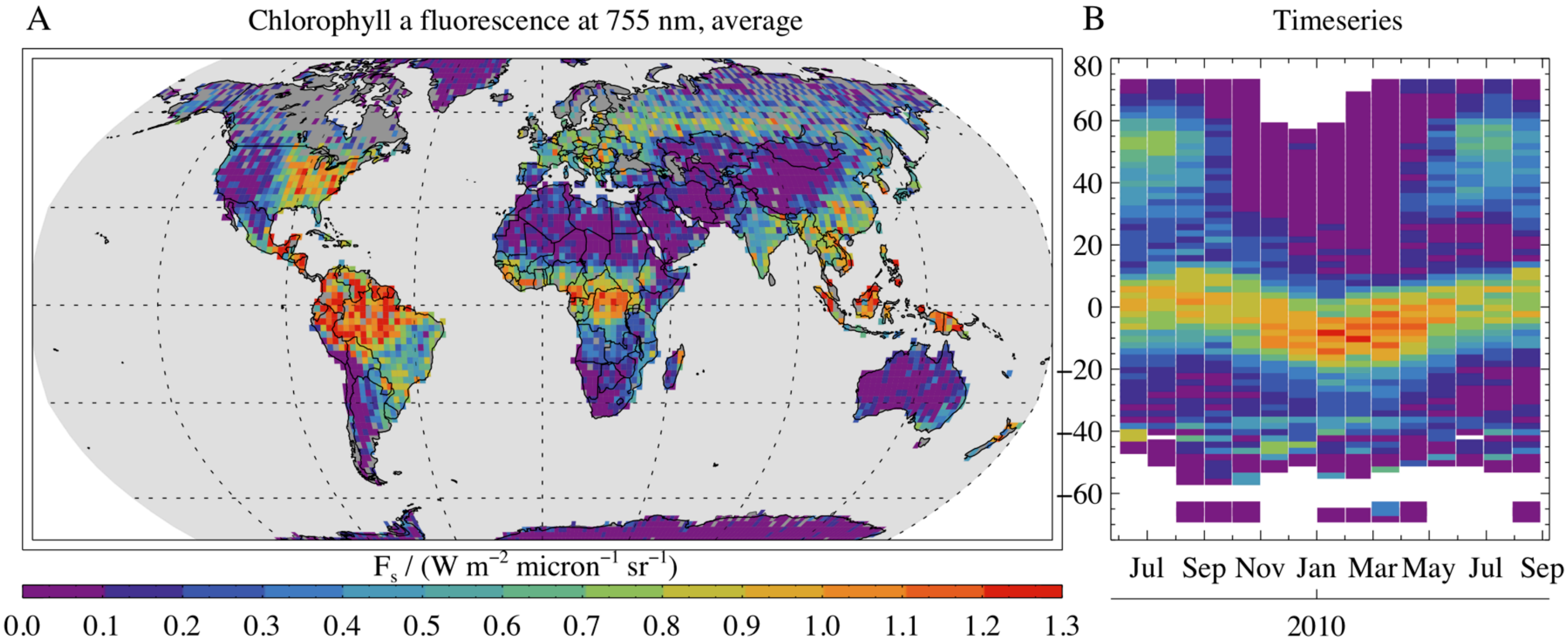
Fluorescence using Spectroscopy

- Fraunhofer lines due to fluorescence (C. Frankenberg et al, 2011)





Baker, Annu. Rev. Plant Biol 2008

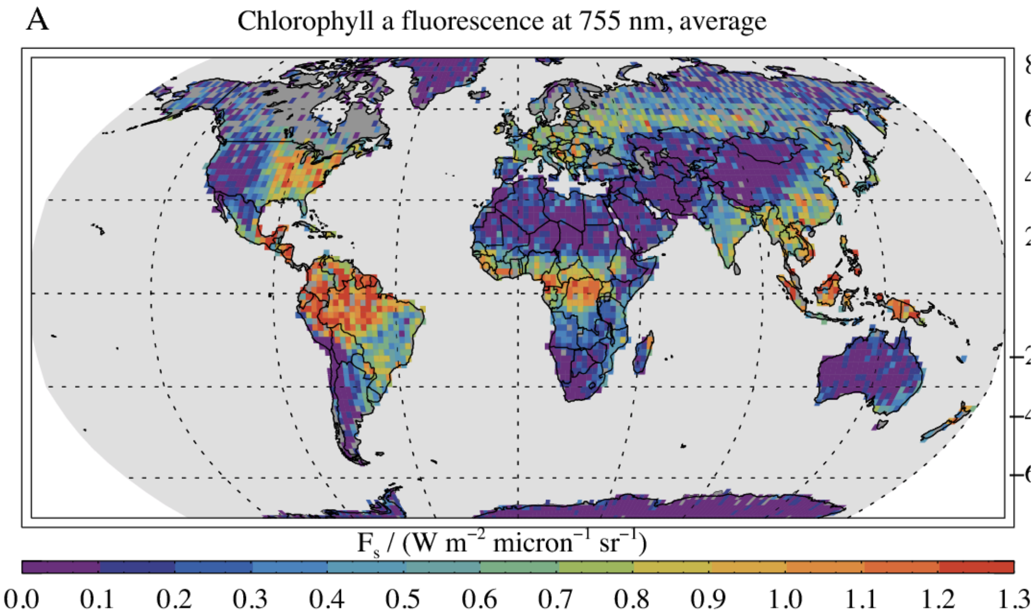


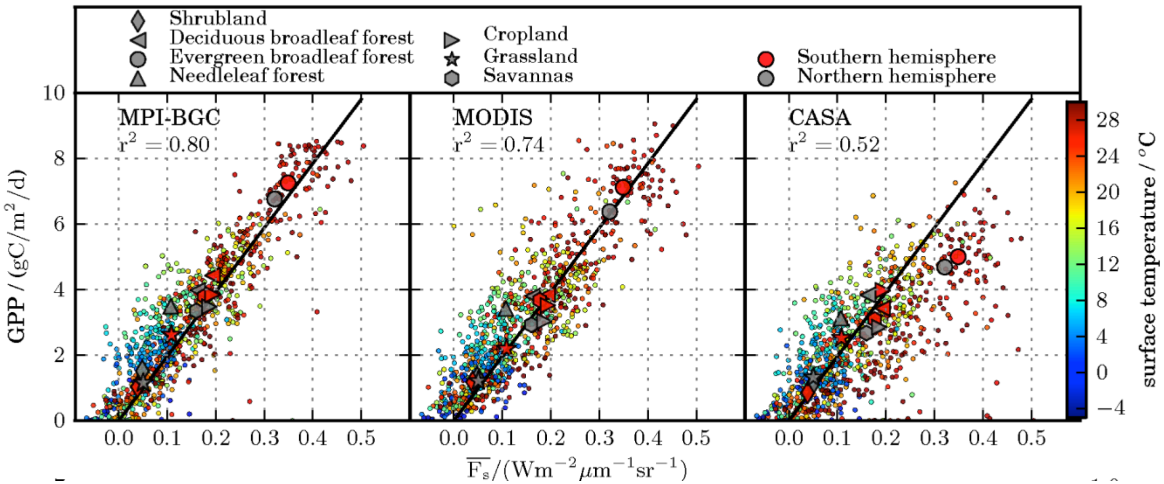
Satellite Measurements Of Chlorophyll Fluorescence Provide New Constraint Of Carbon Uptake

Jet Propulsion Laboratory
California Institute of Technology

Chlorophyll fluoresces when performing photosynthesis

Disentangling chlorophyll fluorescence from atmospheric scattering effects in O_2 A-band spectra of reflected sun-light
Frankenberg, Butz, Toon (2011) Geophys. Res. Lett.





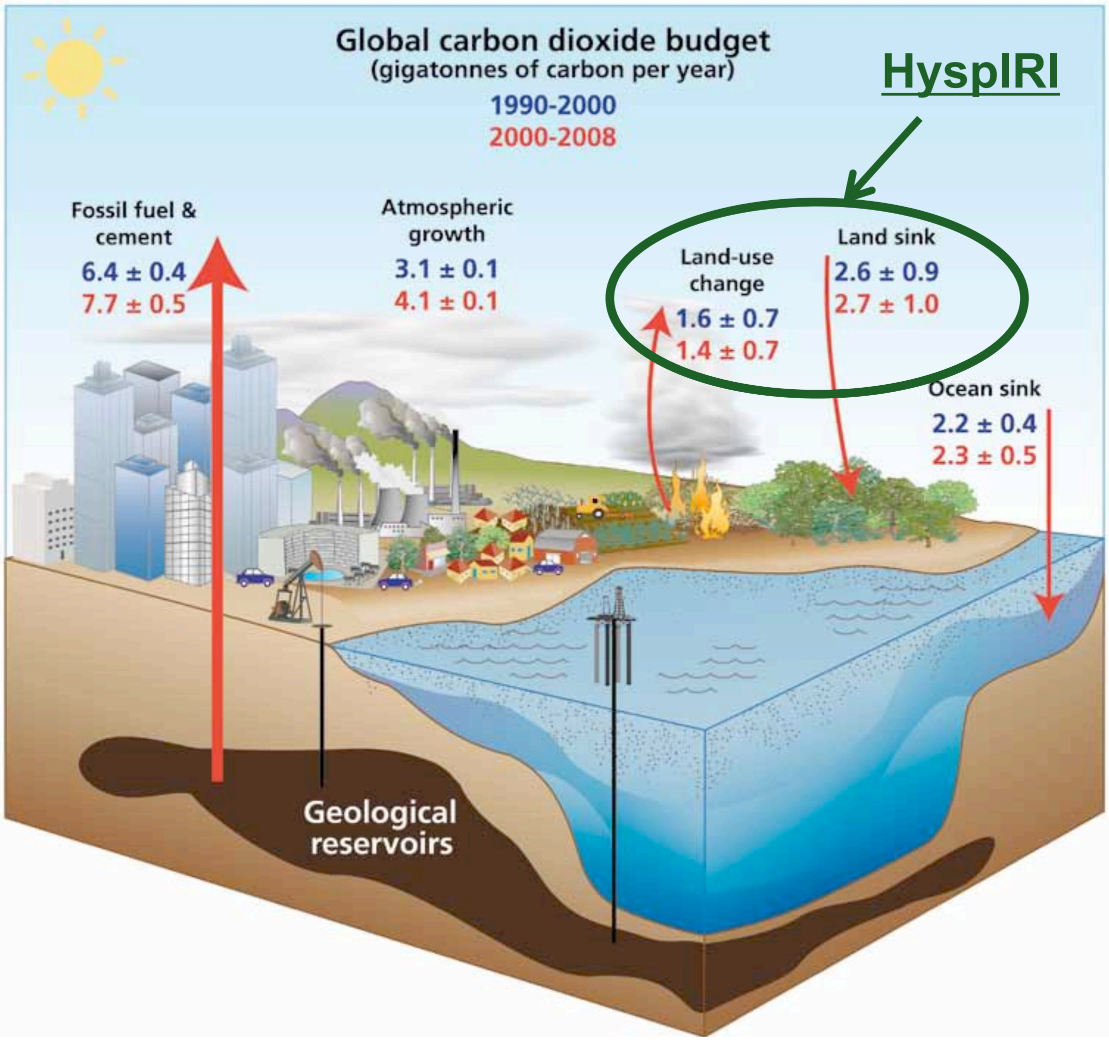
A linear relationship is seen between fluorescence with gross primary production

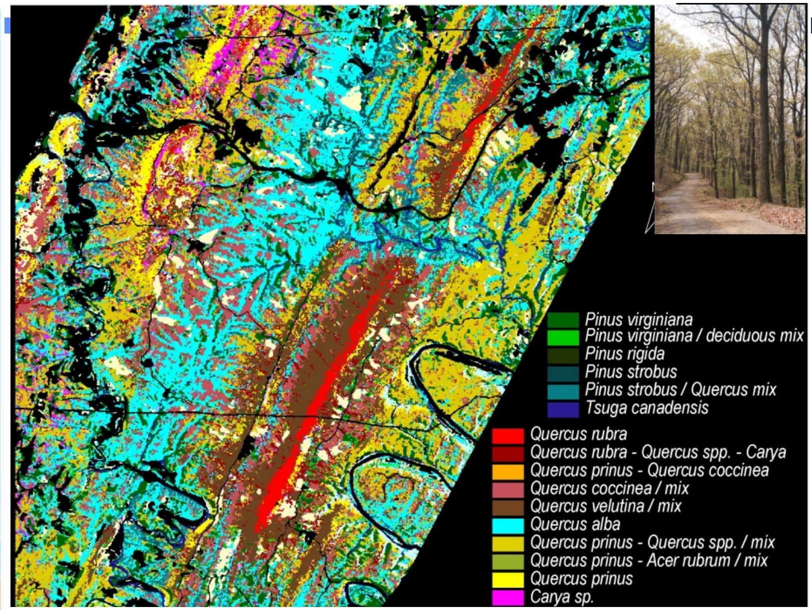
New satellite based fluorescence measurements (GOSAT, OCO-2) provide global constraint on carbon uptake

New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity
Frankenberg, Fisher, Lee, Saatchi, Worden, et al, Geophys. Res. Lett., under review

Imaging Spectroscopy: Global Measurement of Terrestrial Ecosystem Composition and Function

Jet Propulsion Laboratory
California Institute of Technology





Accurate constraint of Carbon fluxes associated with land-use and terrestrial vegetation are key missing elements for closing the carbon budget.

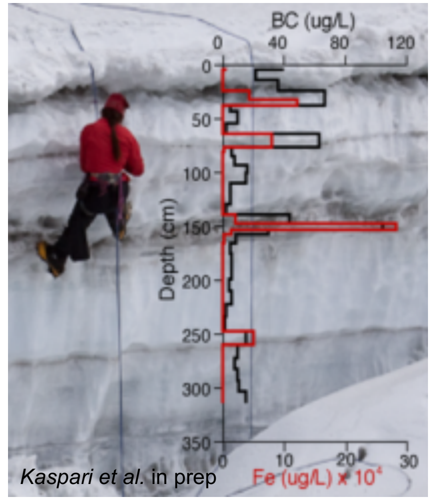
The Physical Science Basis. Chapter 7: Couplings Between Changes in the Climate System and Biogeochemistry. Executive Summary: "Nonlinear interactions between the climate and biogeochemical systems could amplify (positive feedbacks) or attenuate (negative feedbacks) the disturbances produced by human activities."

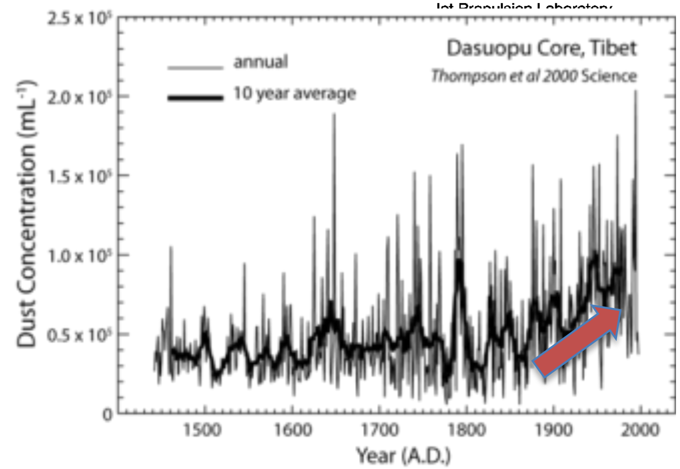
Global CO_2 budget for 1990-2000 (blue) and 2000-2008 (red) (GtC per year). Emissions from fossil-fuel and land-use change are based on economic and deforestation statistics. Atmospheric CO_2 growth is measured directly. The land and ocean CO_2 sinks are estimated using observations for 1990-2000 (Denman *et al.* IPCC 2007). For 2000-2008, the ocean CO_2 sink is estimated using an average of several models, while the land CO_2 sink is estimated from the balance of the other terms.

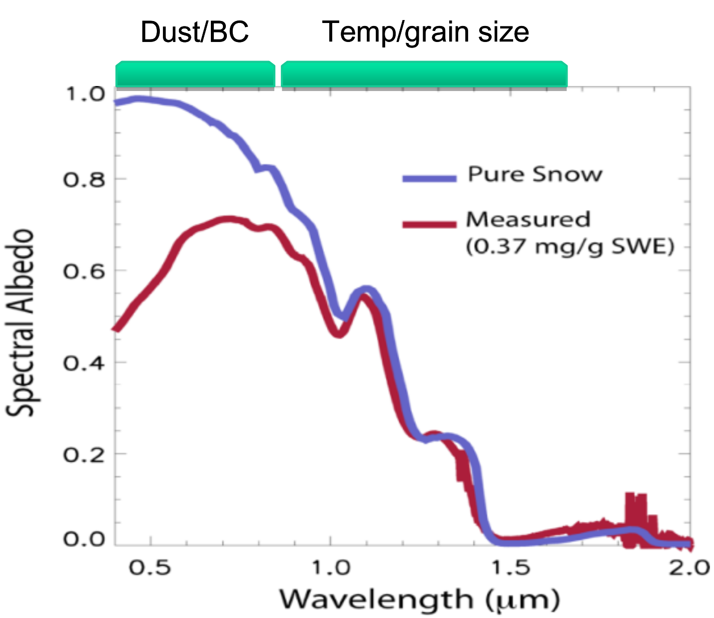
Albedo and Black Carbon/Dust Effects in Snow/Ice - using Spectroscopy

Himalayan glaciers

For snow and ice in the Himalaya, increasing temperatures and increasing dust and soot can combine in unknown proportions to accelerate melt through their changes in albedo. Imaging Spectoscopy is the only sensing technique that allows us to attribute changes in albedo into effects from temperature and dust/black carbon and at a fine enough spatial resolution that heterogeneous terrain can be resolved. Multi-band sensors such as NPOESS VIIRS have neither capacity.





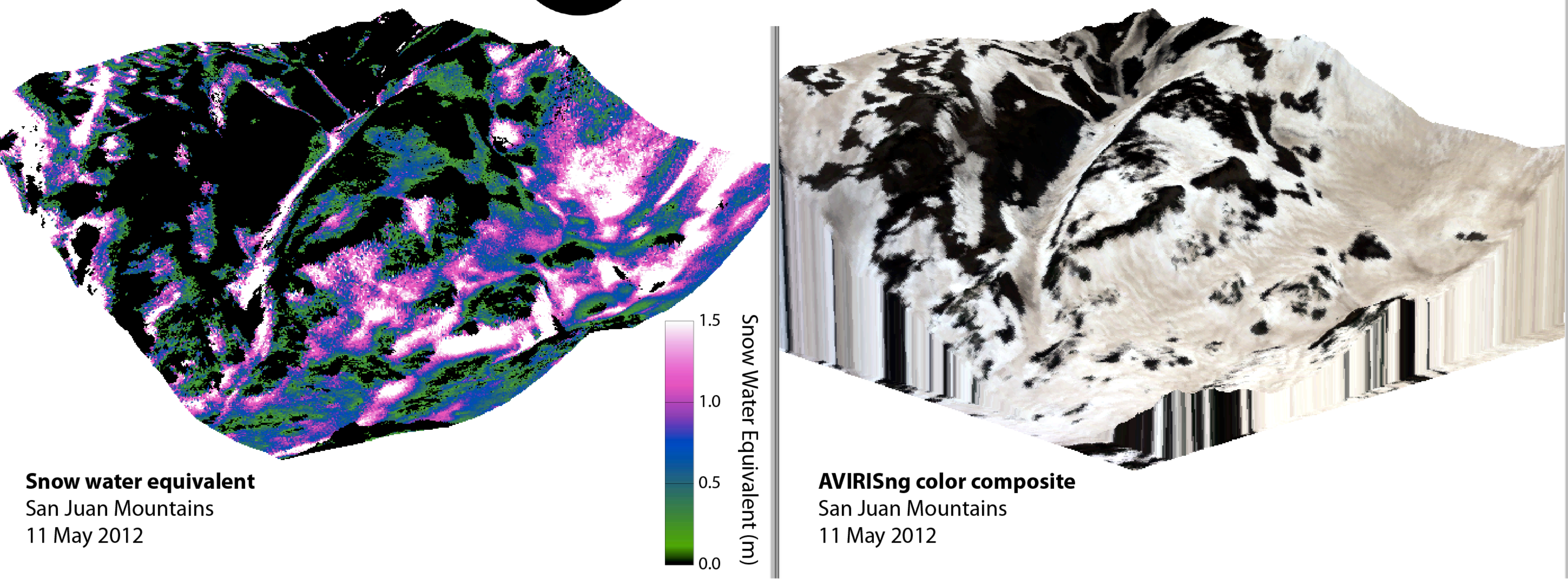


Required Measurement: Global glacial covered area, full solar spectrum, < 100 m spatial, <20 days revisit (HyspIRI)

courtesy Tom Painter and Rob Green, JPL

Airborne Snow Observatory
First Results

Airborne Snow Observatory

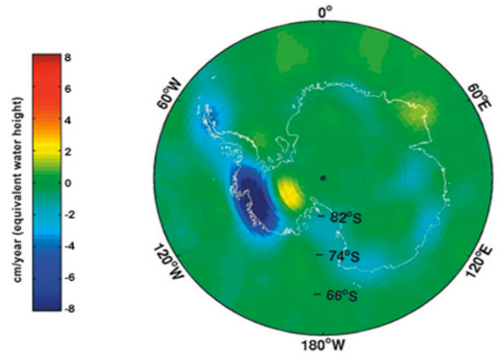


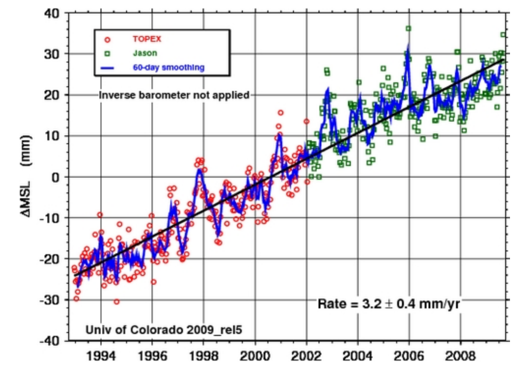
- Lidar/Imaging Spectrometer combination

Courtesy Tom Painter, JPL

Gravity Recovery and Climate Experiment (GRACE) – Follow-on Mission

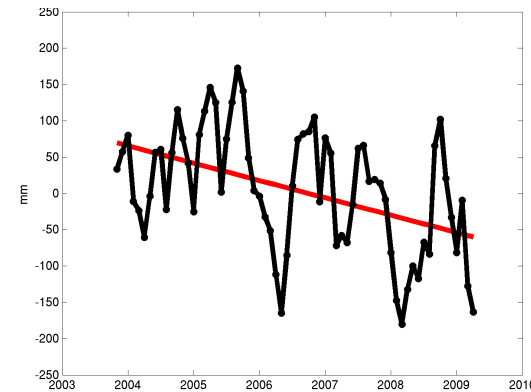
Jet Propulsion Laboratory
California Institute of Technology





Improved prediction of changes in sea level

GRACE F/O
will use microwave and experimental laser-based satellite-to-satellite ranging, along with precision accelerometers to measure climate related changes in Earth's mass distribution.



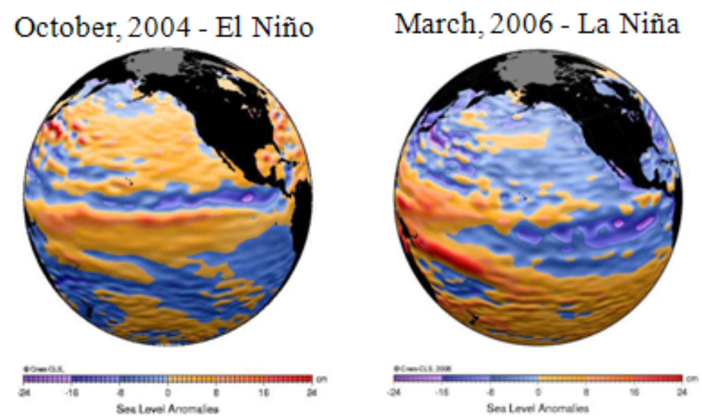
Significant loss of stored water in the combined Sacramento-San Joaquin River Basin. (University of California Center for Hydrologic Modeling)

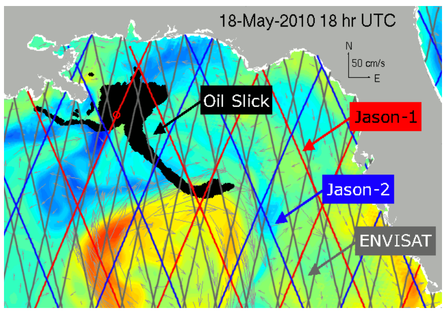
DLR

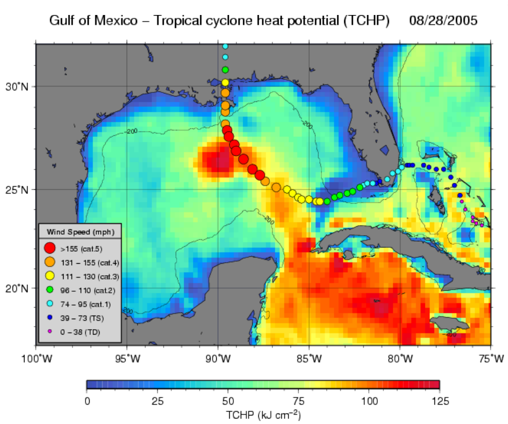
Launched: 2018

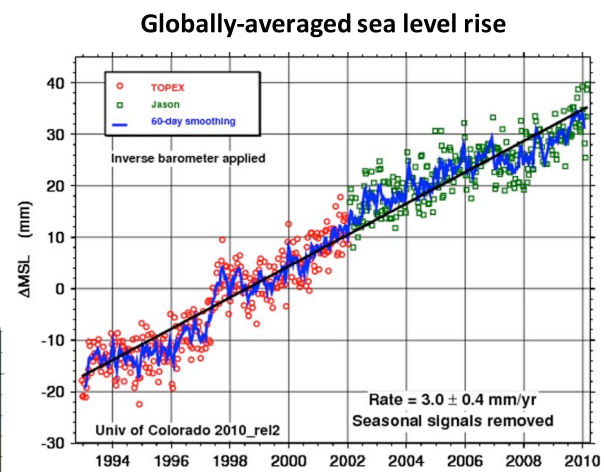
Jason-3 Mission: Altimetry – Going Operational

- **2016 launch**
- **Four partners: NOAA, EUMETSAT, NASA, and CNES.**
- Continue the time series of global sea level rise.
- Seasonal, inter-annual and decadal ocean variability.
- Hurricane intensity forecasting.









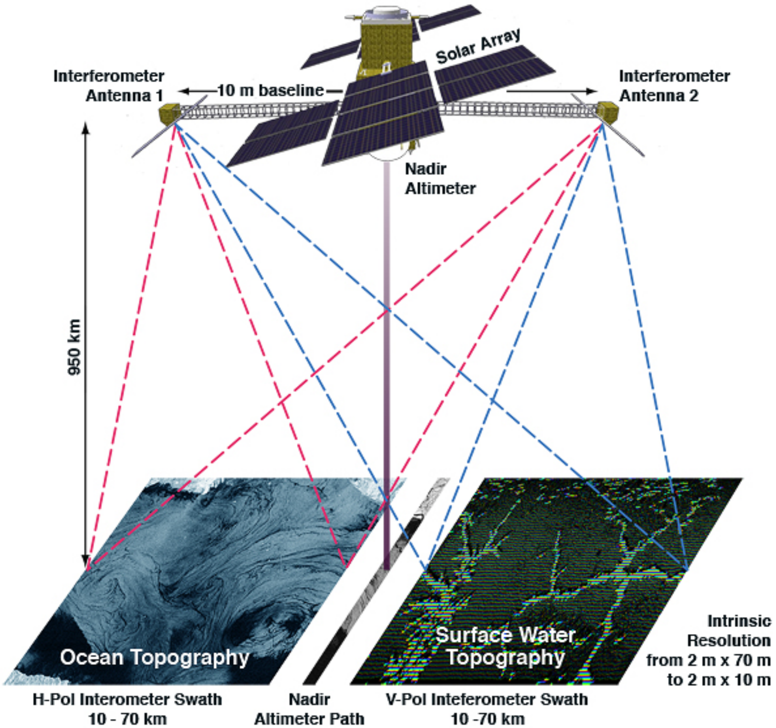
Surface Water and Ocean Topography (SWOT)
Extending the Research Capability

Mission Science

Hydrology: To provide a global inventory of all terrestrial water bodies whose surface area exceeds $(250m)^2$ (lakes, reservoirs, wetlands) and rivers whose width exceeds 100 m (requirement) (50 m goal) (rivers).

- To measure the global storage change in fresh water bodies at sub-monthly, seasonal, and annual time scales.
- To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.

Oceanography: Characterize the ocean mesoscale and submesoscale circulation at spatial resolutions of 10 km and greater.



Mission Overview

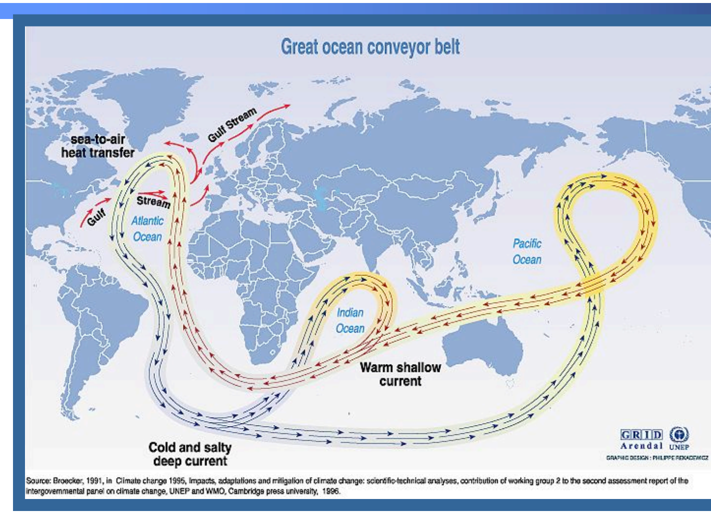
- **Planned as a partnered mission with CNES**
- **Mission life of 3 years**
- **970 km Orbit, 78º Inclination, 22 day repeat**
- **S/C: ~1300Kg, ~2.1kW**
- **Launch Vehicle: US Medium class**
- **Readiness for launch by 2021**

Instruments

- **KaRIn: Ka band Radar INterferometer**
- **Nadir Altimeter: Ku/C Band**
- **Advanced Microwave Radiometer (AMR)**
- **GPS Payload (GPSP)**
- **DORIS**
- **Laser Retroreflector Array (LRA)**

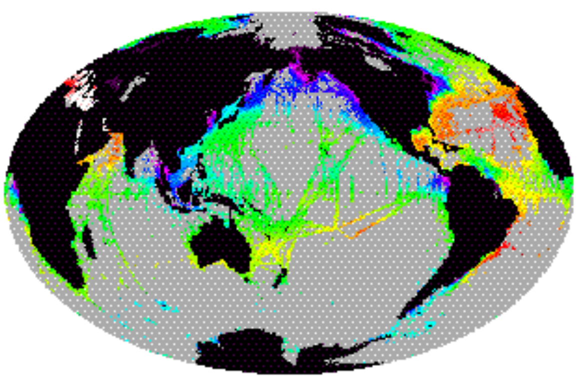
New Measurements of Ocean Surface Salinity

Jet Propulsion Laboratory
California Institute of Technology

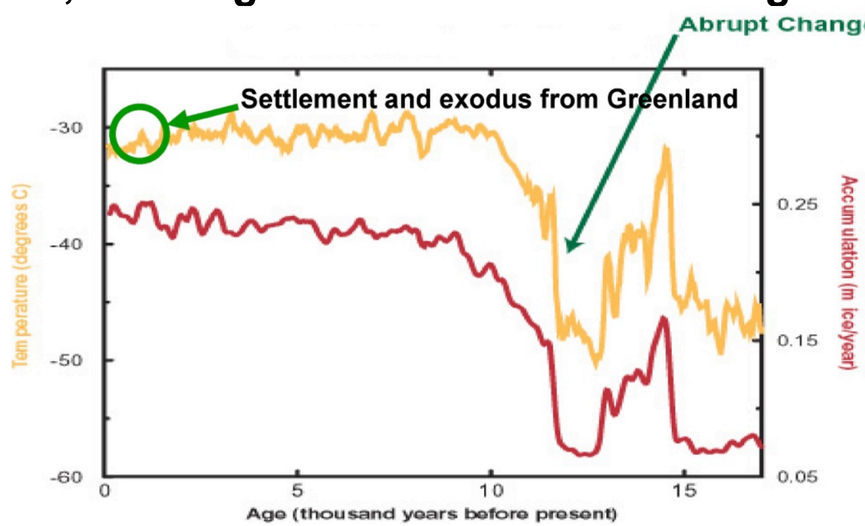


Aquarius (2011) measures changes less than 0.2 grams per kilogram of water.

Cold, dense salty water in the North Atlantic sinks, allowing warmer water into the region.

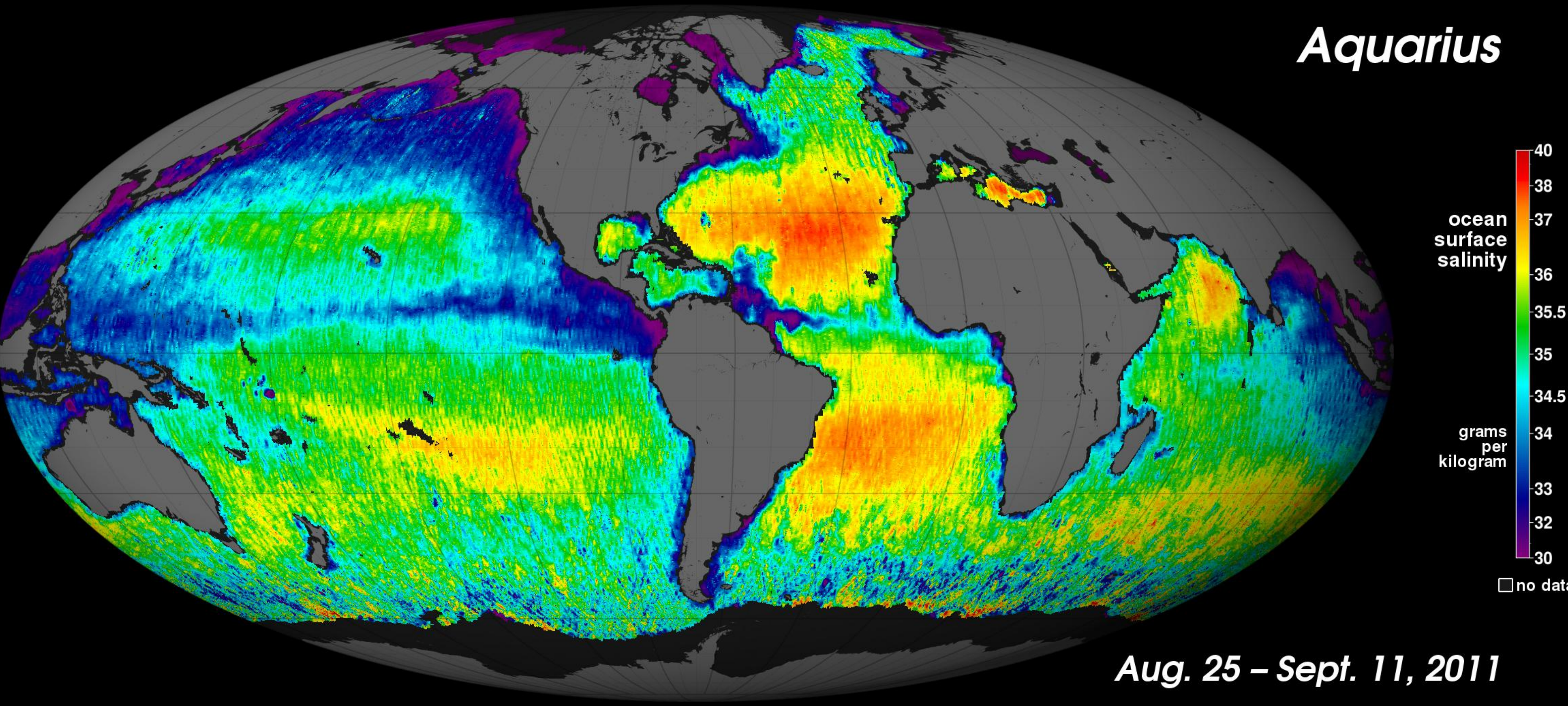


Ship observations (very sparse)



Slowing of the "conveyor belt" causes severe winters in New England and Europe

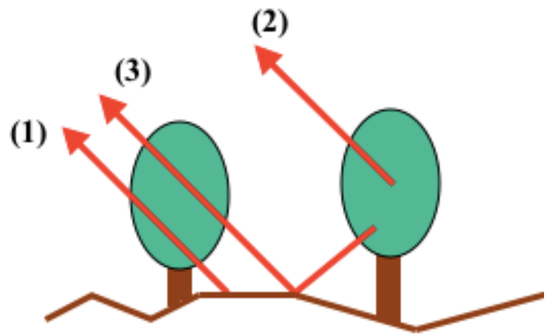
Aquarius First Results

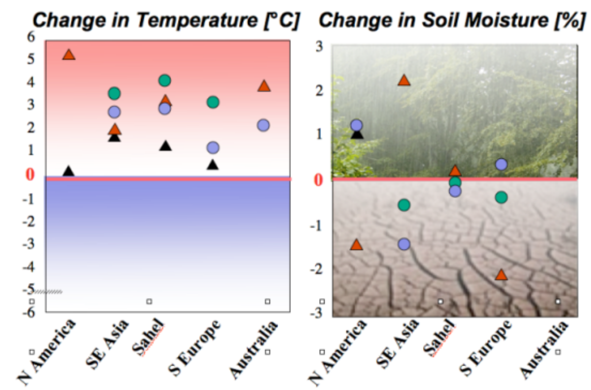


Microwave Radiometers Measuring Soil Moisture

Jet Propulsion Laboratory
California Institute of Technology

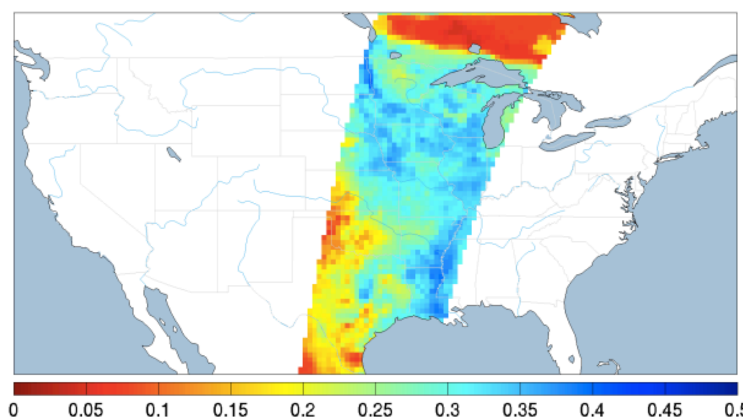
Thermal Emission



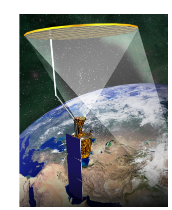


Improved climate models

% vol. soil moisture



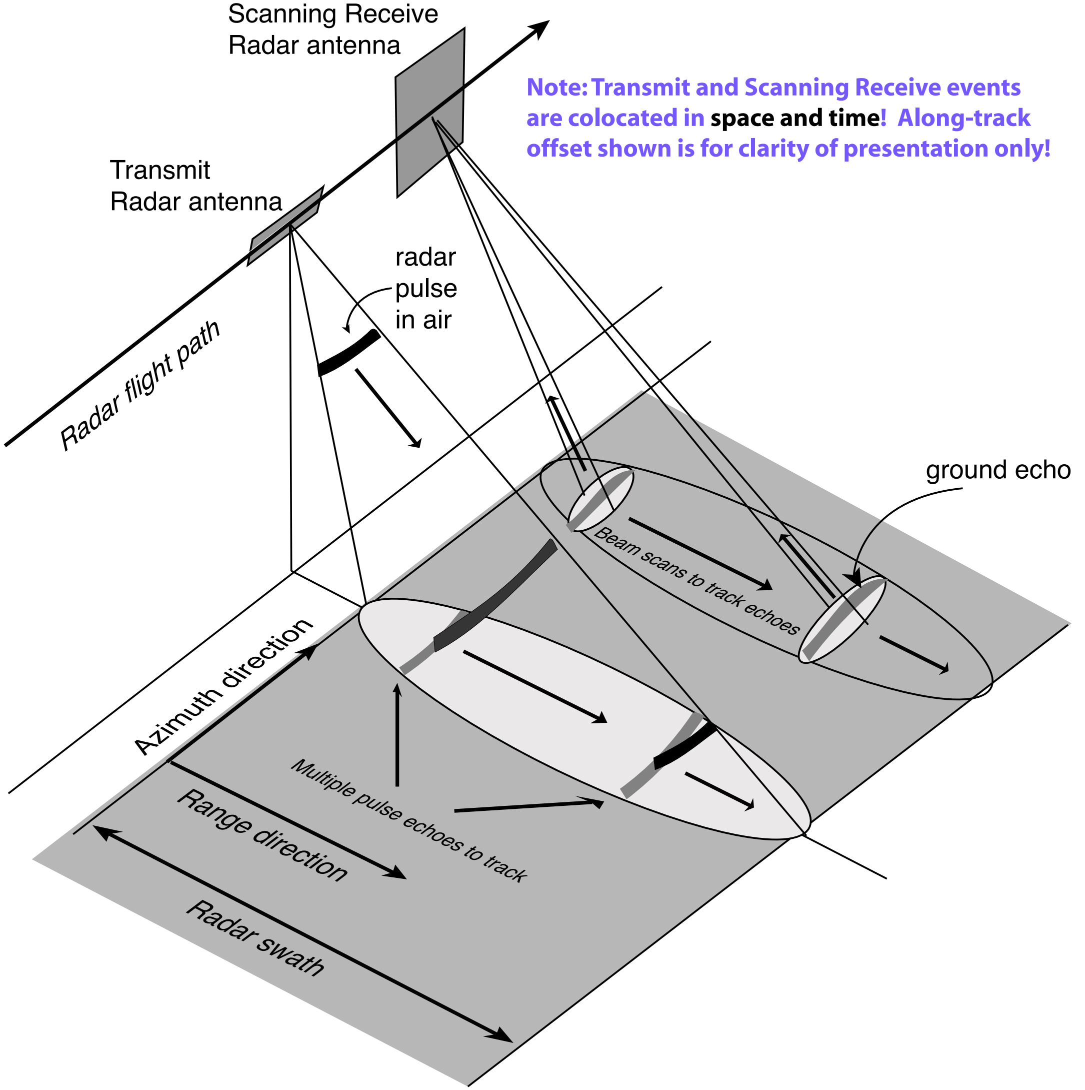
Starting in 2014, SMAP will use a rotating 6-m deployable mesh antenna shared by an L-band radar & radiometer to map soil moisture and freeze/thaw state and resolution of 10 km every 3 days



SMAP

NISAR's SweepSAR Technique

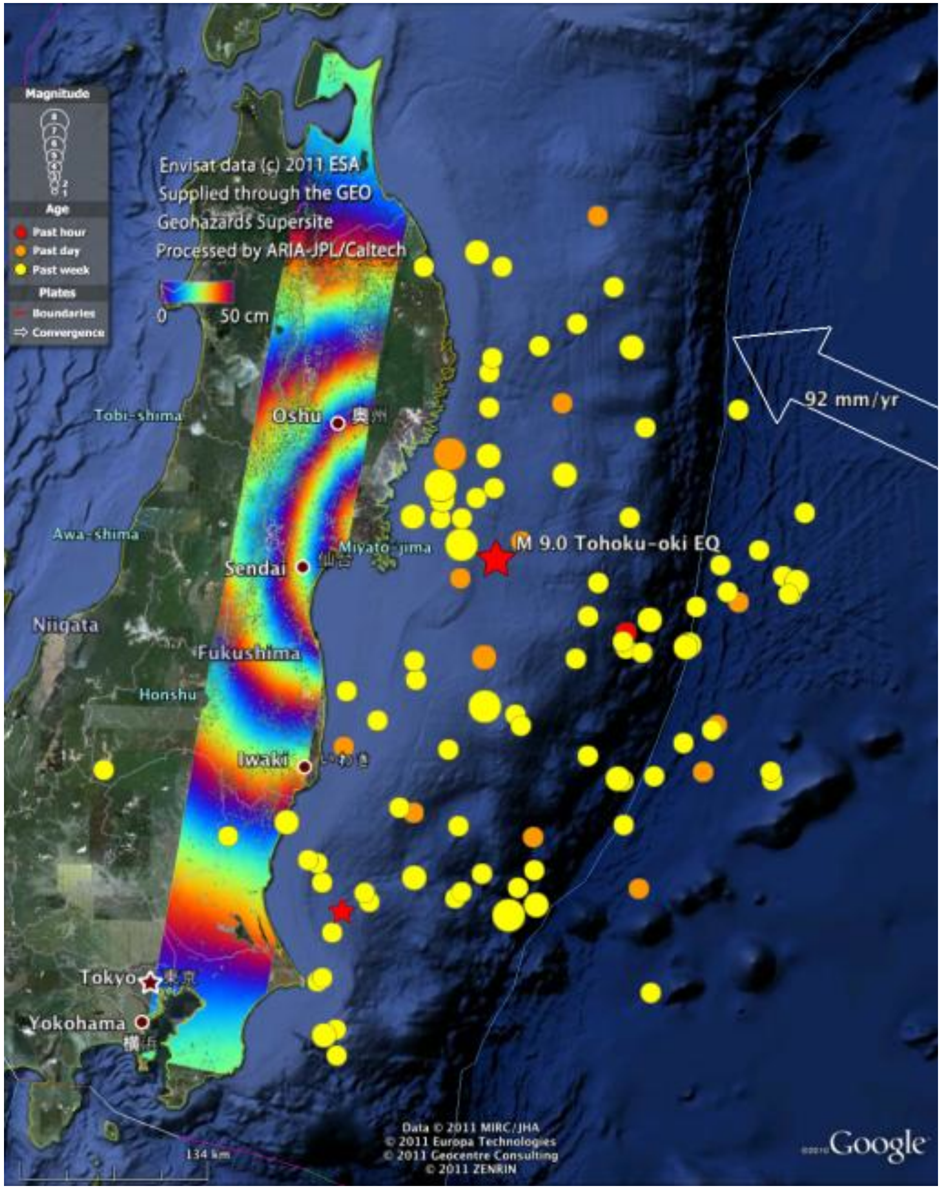
- What is SweepSAR?
  - Transmit pulse over wide beam in elevation
  - Receive echo over narrow beam tracking echo with scanning receive beam (Scan on Receive)
  - Can require multiple simultaneous receive beams to track multiple echoes
- A completely new capability
  - Solves the traditional large, complex antenna problem with a large passive reflector and compact digital feed electronics
  - Breaks out of the standard SAR performance limits by separating transmit and receive apertures with digital beamforming techniques
- SweepSAR revolutionizes radar imaging by achieving very high area coverage rates at fine, selectable resolutions, full polarization



NISAR will observe Surface Deformation due to Seismic Activity

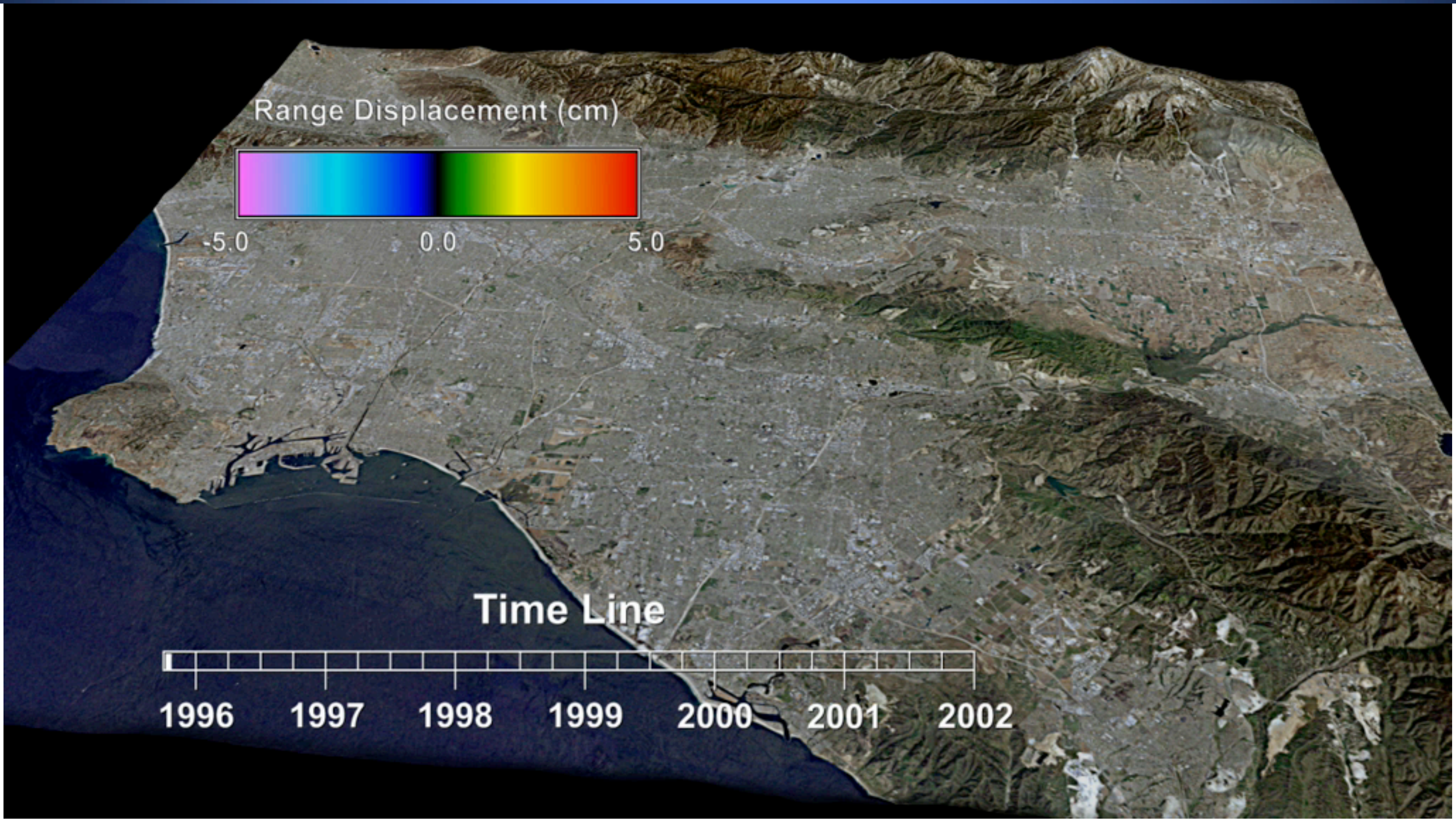
Jet Propulsion Laboratory
California Institute of Technology

Ground displacements from the March 11, 2011, magnitude 9.0 Tohoku earthquake in Japan, overlaid on a map of recent earthquake activity from the U.S. Geological Survey. The total surface displacement in the line of sight measured by this Envisat ASAR interferogram is about 2.5 meters.



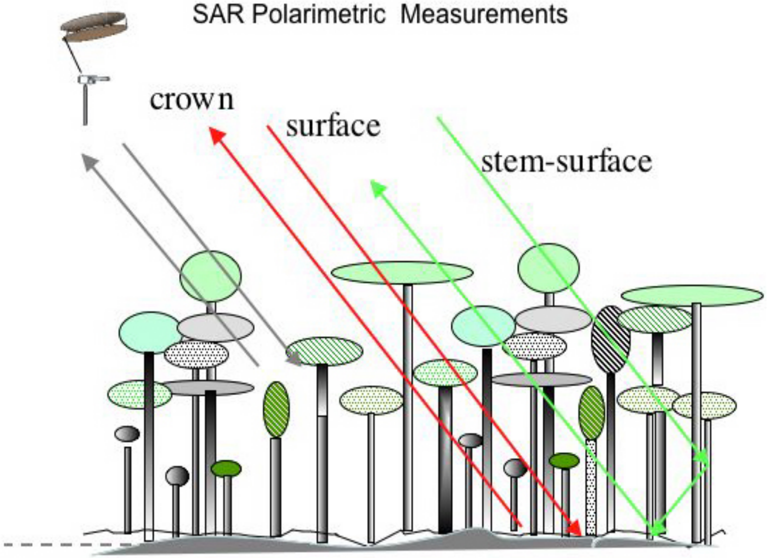
Ground Displacements from the March 2011 Tohoku Earthquake in Japan

And the effects of aquifer charge/discharge



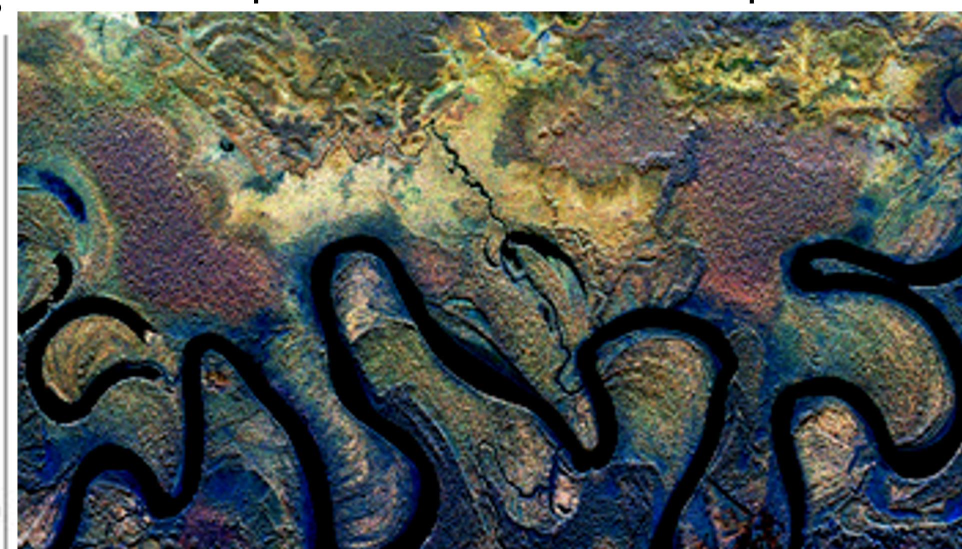
Southern California InSAR Time Series

NISAR’s Polarimetric Measurements
Forest Canopy Structure

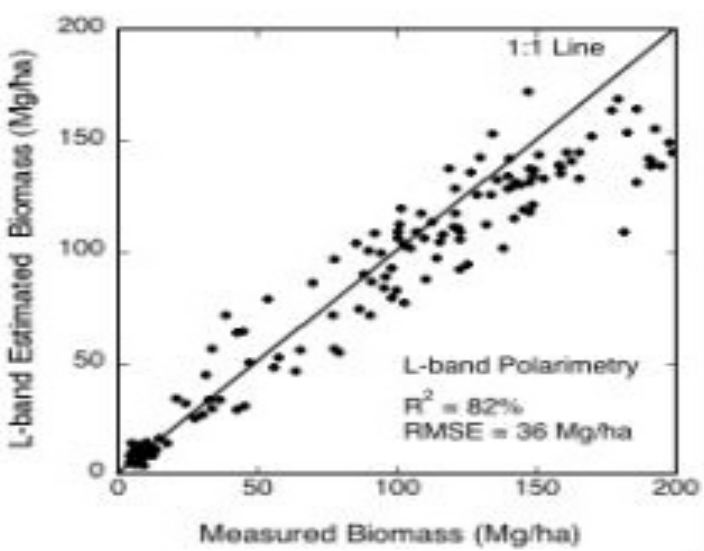


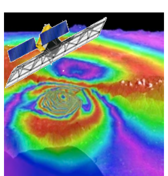
- Radar reflectivity measurements are from different layers in the canopy
- Depends on the polarization(s) used

Tropical Rain Forest Example



Radar reflectivity correlates with biomass

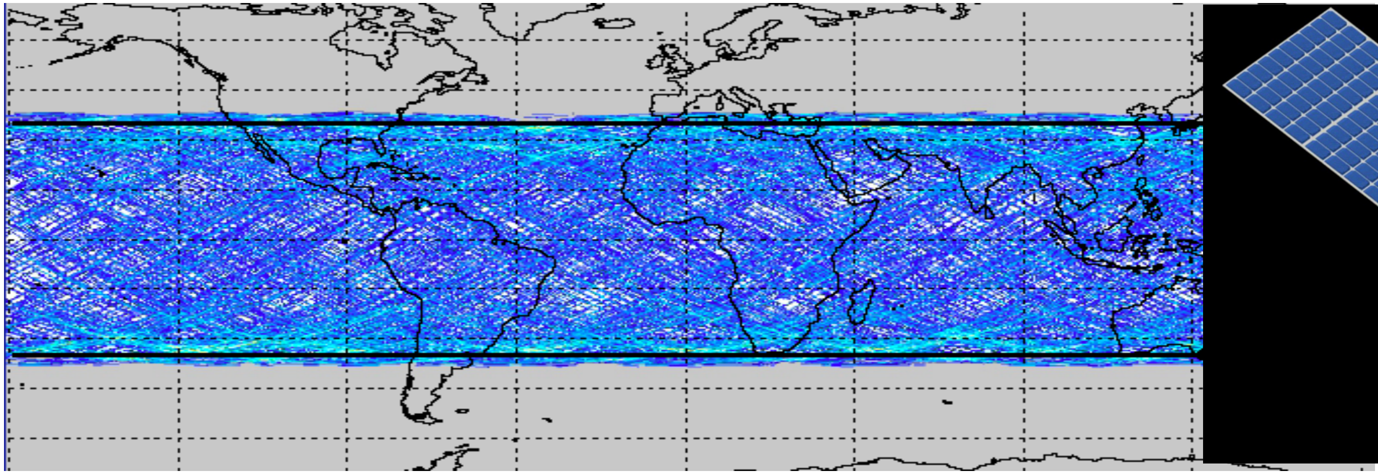




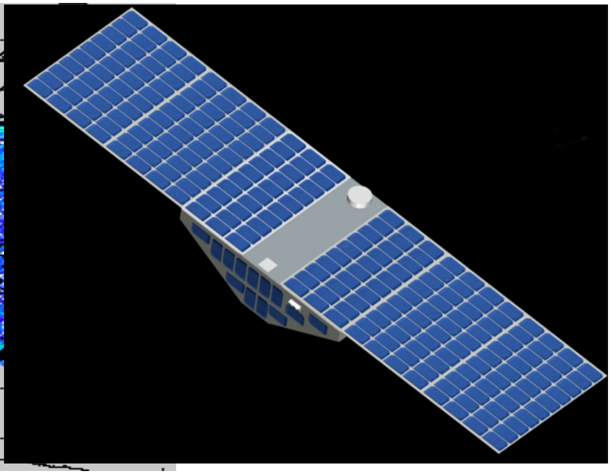
DESDynI

NASA's 2012 EV-2 Selection: GPS Reflections - CyGNSS

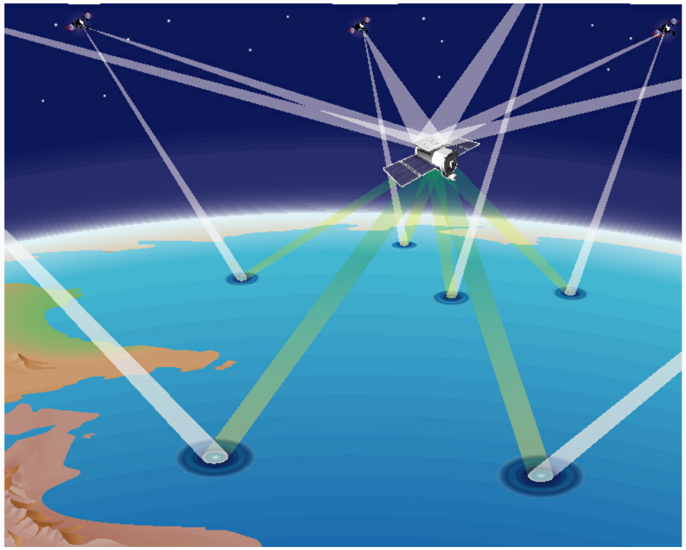
1-Day Coverage



Nanosat (1 of 8)



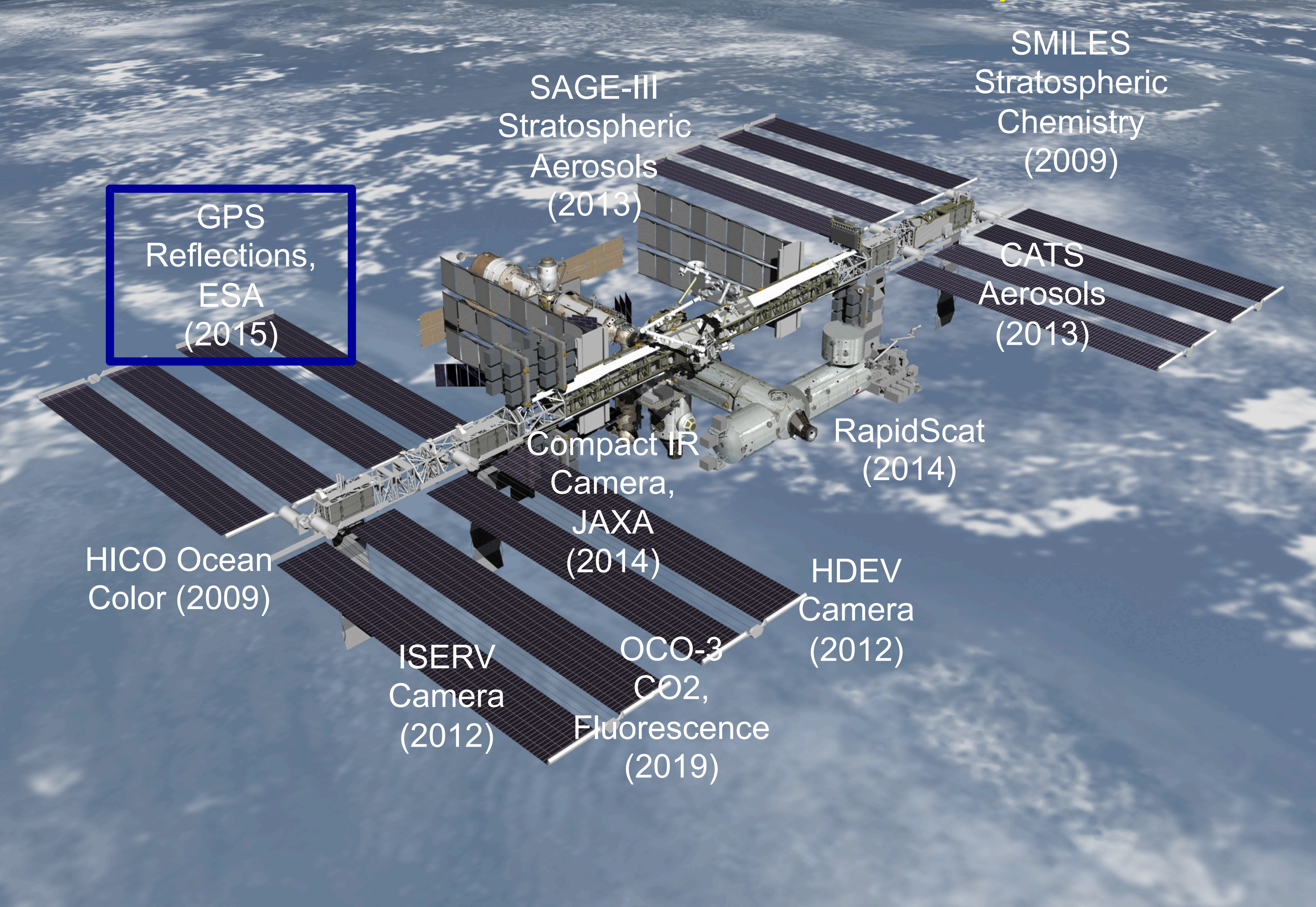
Measurement Concept



- Recent EV-2 selection (CyGNSS) for wind speed
- Focus on Hurricane winds
- 35^{o} inclination orbit
- 8 nanosats, built by SWRI
- PI is Chris Ruf, Umich
- 8 GPS instruments from SSTL
- Nanosat Dispenser from NASA-Ames
- Pegasus L/V
- Launch 2016

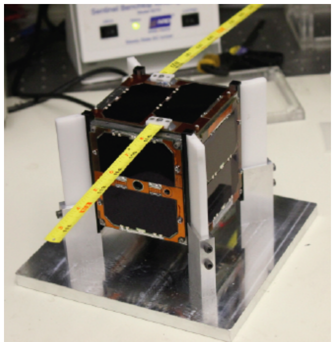
Material courtesy Chris Ruf, U. of Michigan

Earth Observation from the International Space Station



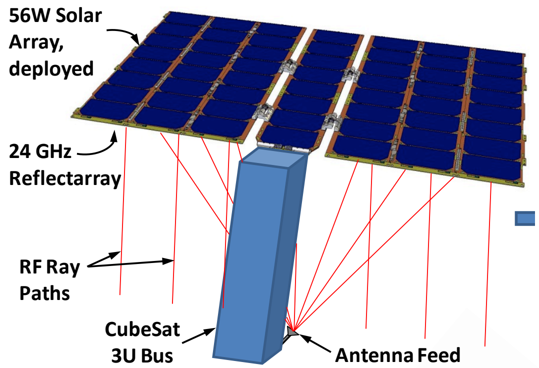
Earth Observation from Cubesats

OnBoard Processing/FPGA Tech Demo



M-cubed/COVE

Reflectarray Antenna for enhanced Downlink



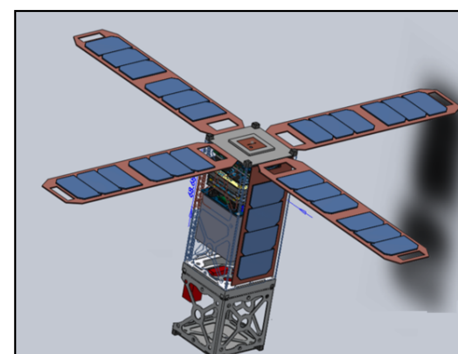
ISARA

Focal Plane Array

Tech Demo

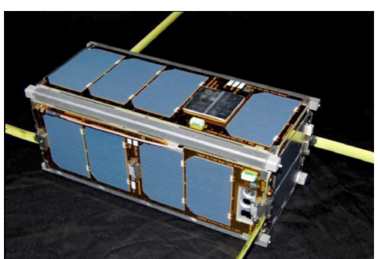
GRIFEX

183 GHz radiometer pathfinder for Precipitation Science



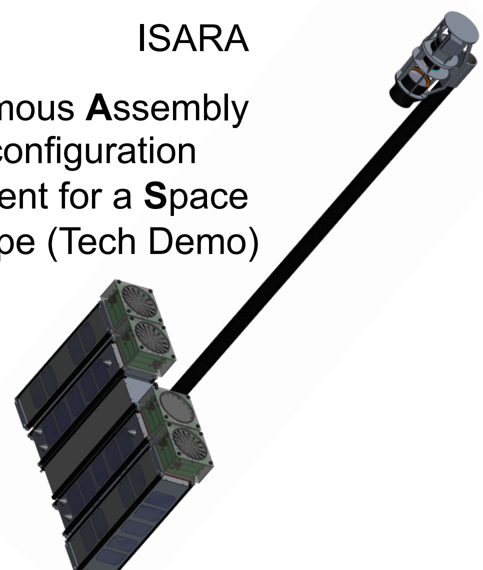
CHARM

Deep Space Transponder Tech Demo



LMRST-Sat

Autonomous **A**ssembly and **R**econfiguration **e**xperiment for a **S**pace **T**elescope (Tech Demo)



AAReST

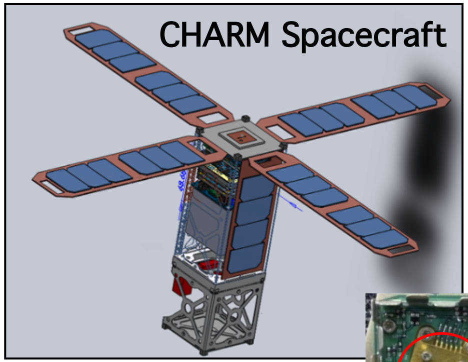
CHARM: CubeSat Hydrometric Atmospheric Radiometer Module

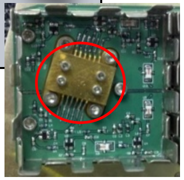
Spaceborne validation of Indium Phosphide (InP) MMIC radiometer

Implementation verifies subsystem for future missions (PATH and SWOT) in addition to constellation concepts

Project Objectives

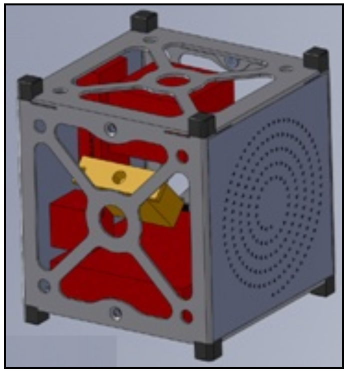
- Develop a 3U CubeSat cross track scanning radiometer for water vapor and precipitation profiling
- 183 GHz radiometer payload development at JPL (1U)
- Demonstrate, flight qualify and calibrate:
  - Low noise InP MMIC RF front ends developed at JPL
- Low-cost project





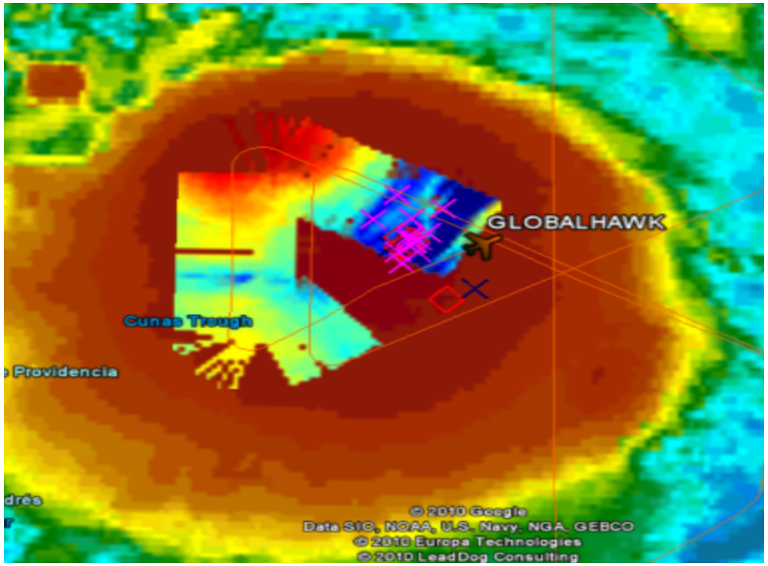
JPL 183 GHz MMIC receiver developed for PATH Approximately the size of a US quarter

Side-facing RLSA antennas with integrated MMIC receivers in 1U payload cube



Justification

- Provide scientific data for atmospheric observations
- Launched as RACE in 2014 – launch failed
- Raise the TRL (4 -> 6) of InP MMIC receiver front ends
  - –PATH (DS tier 3) and SWOT (DS tier 2)
  - – Other Earth science missions (AMSU-B, SSMIS)
- Leverage existing CubeSat developments to reduce budget and schedule risk
- Allow for end to end development of flight-like project for personnel training



Boon Lim, JPL

New Platforms for Extended Duration Airborne Remote Sensing

NASA's Earth Observing System in 2012
-14 satellites in Earth orbit

Jet Propulsion Laboratory
California Institute of Technology

What's made NASA's Earth Observing System unique up 'til now, is the more than 20-year old 'free and open' data policy

http://climate.nasa.gov/Eyes/eyes.html

NASA's Earth Observing System in 2012
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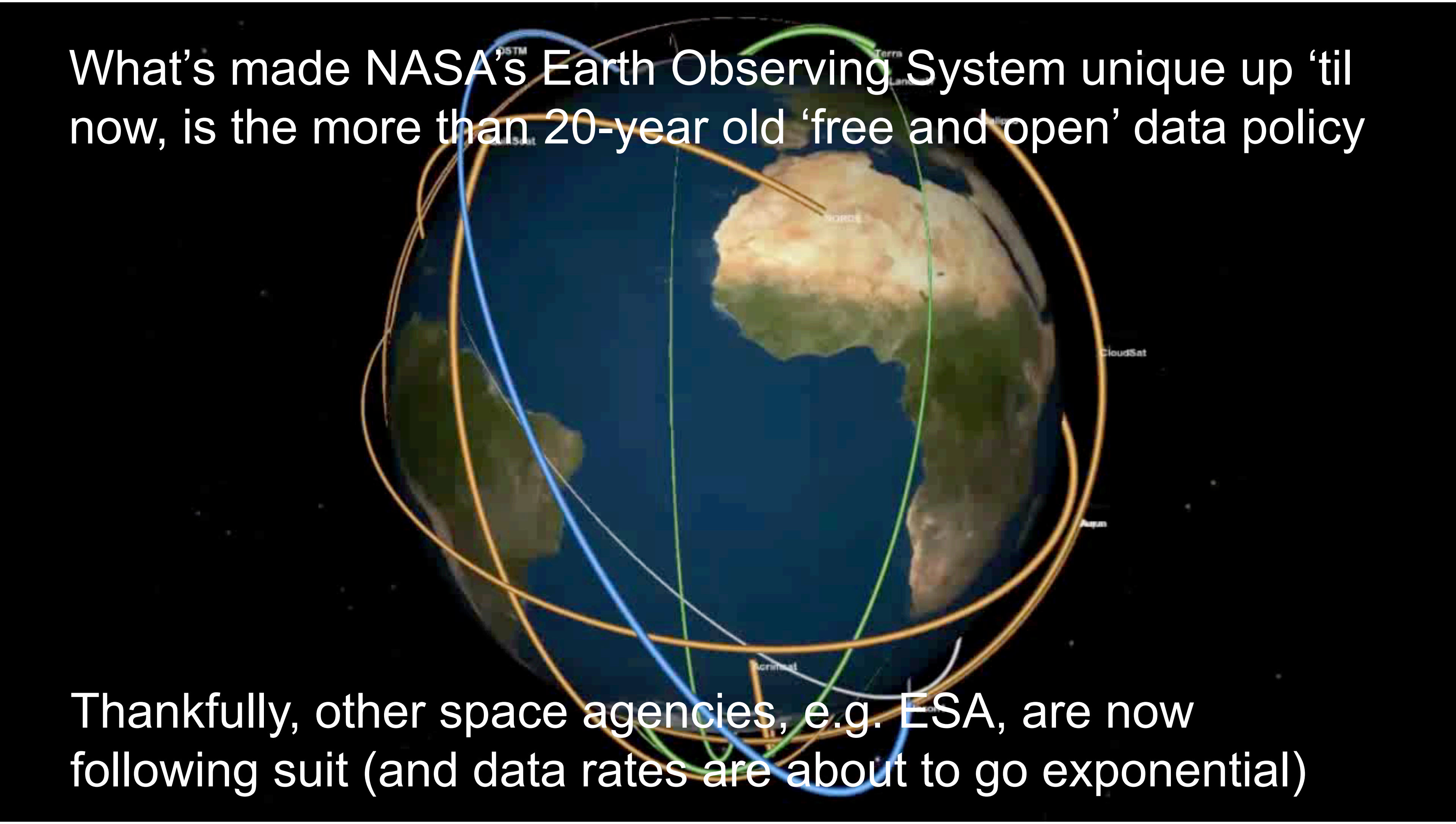

What's made NASA's Earth Observing System unique up 'til now, is the more than 20-year old 'free and open' data policy

Thankfully, other space agencies, e.g. ESA, are now following suit (and data rates are about to go exponential)

http://climate.nasa.gov/Eyes/eyes.html

EARTHNOW iPhone App

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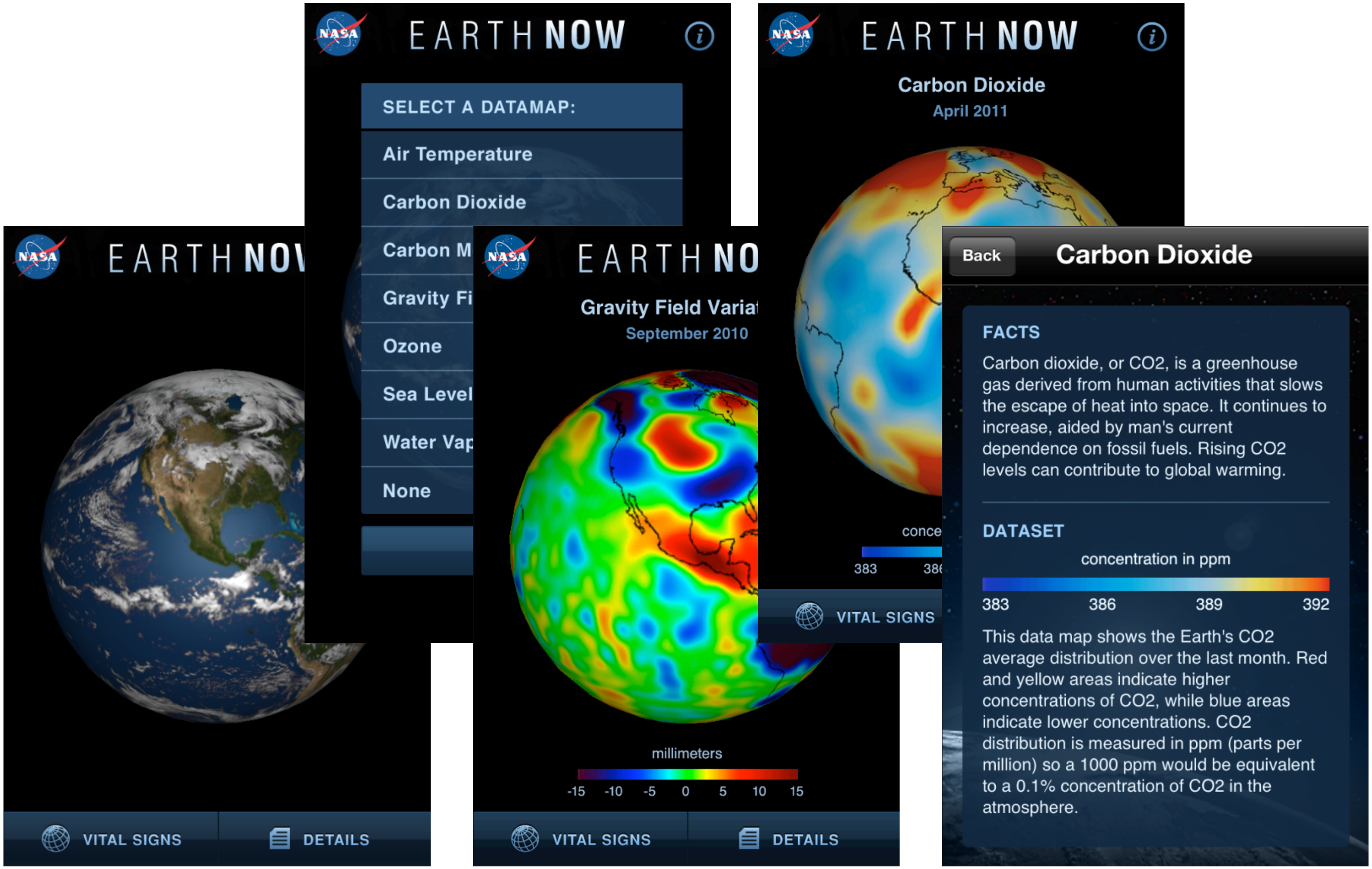
California Institute of Technology



http://jplmobile.jpl.nasa.gov/

So how will we view the Earth in 2025?

Jet Propulsion Laboratory
California Institute of Technology

- This is the Third Wave of Remote Sensing (and the surf is up!)
- Remote Sensing is rapidly evolving into powerful information for decision-makers
- By 2025, we should have a vastly improved understanding of CO_2 and other greenhouse gases, and their evolving role in the carbon cycle
- Spectroscopy is the asymptote in Visible/IR Earth Observation
- By 2025, we should have a greatly improved understanding of the water cycle, and trends in freshwater availability
- SweepSAR technique can revolutionize SAR data utility
- GPS Reflections has come of age
- ISS is evolving into a capable, major platform for Earth observation
- Cubesats/nanosats are at their Explorer-I moment
- UAVs such as Globalhawk are changing the airborne vs. space calculation
- Data access (and volumes) are on the increase!

What a great time to be involved in Remote Sensing

Thank you