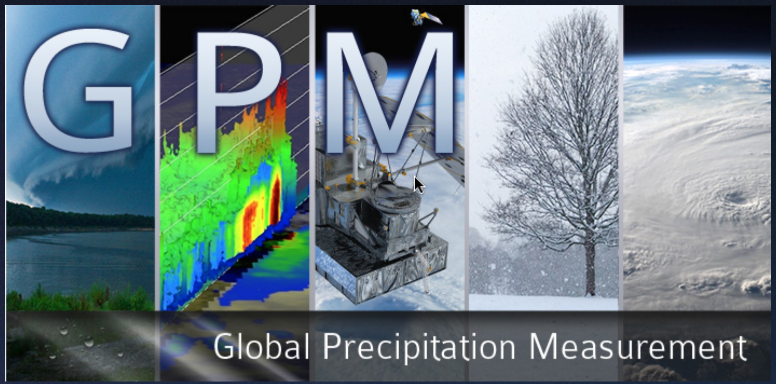
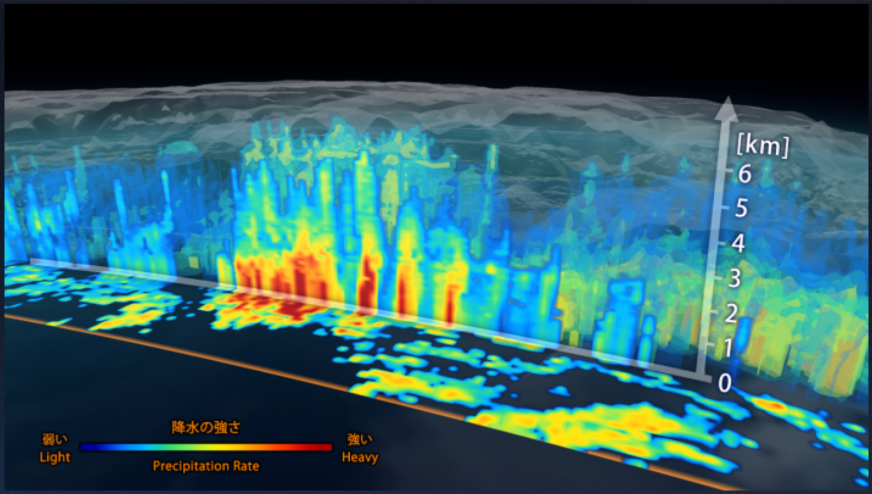




The Global Precipitation Measurement (GPM) Mission After Three Years in Orbit

Dr. Joe Turk
Jet Propulsion Laboratory, California Institute of Technology
Radar Science and Engineering jturk@jpl.nasa.gov

November 3, 2017, Univ. of Minnesota

Outline

Introduction to NASA’s current precipitation and cloud radar systems

Orbital characteristics and precipitation constellation concept

Examples from different types of weather systems

Applications

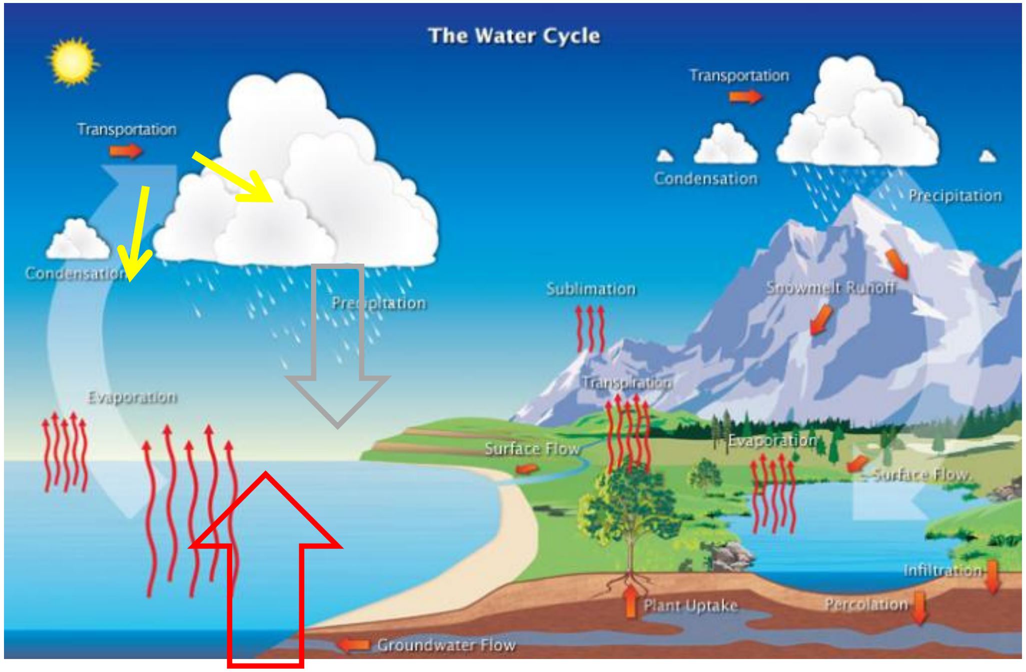
Where the technology is leading for next-generation precipitation and cloud observing systems

Precipitation as an Energy Balancer

*Only about **one fourth** of the energy needed to drive the global atmospheric circulation comes from direct solar energy. The other **three-fourths** of the energy is transferred to the atmosphere by evaporating water.*

- As the water vapor rises, it carries energy needed to turn liquid into water vapor (*Latent Heat of Evaporation*). This energy is released into the atmosphere in huge cloud clusters near the equator.
  - Latent heat energy contained in clouds ***cannot*** be seen or measured directly but rainfall, a product of this energy release, ***can*** be measured

We need to better define the **amount** of rainfall and the energy released when rain occurs in order to improve climate models, understand the global water and energy budget, and monitor our vital water resources.



Courtesy G. Skofronick-Jackson, GSFC

Evolution of Precipitation-Sensitive Satellite Observations

RESEARCH-ORIENTED

1970s

NIMBUS/SeaSat (late 1970s)
10-ch (SMMR) MW imager

1987

DMSP through F-15 (1987-)
7-ch SSMI MW Radiometer

TRMM (1997- 2015)
9-ch MW Radiometer (TMI)
Ku Radar (PR)

1998

NOAA-15 through NOAA-19 (1995-)
5-ch (AMSU-B/MHS) MW Sounder

EOS-Aqua (2002-)
12-ch MW imager (AMSR)

2002

DMSP beginning with F-16 (2004-)
SSMIS 7-ch MW Imager/14-ch MW Sounder

Cloudsat/CALIPSO (2006-)
CloudSat Profiling Radar (light rain climatology)

Coriolis/Windsat (2004-)
22-ch MW Radiometer/Polarimeter

2008

MetOp (2007-)
5-ch (MHS) MW Sounder

Megha-Tropiques (2011-)
9-ch MW Imager/6-ch MW Sounder

2012

Suomi NPP (2012-)
ATMS MW Sounder

GCOM-W1 (2012-)
12-ch MW imager (AMSR-2)

GPM-core (2014-)
13-ch MW imager (GMI)
Ku/Ka radar (DPR)

2014

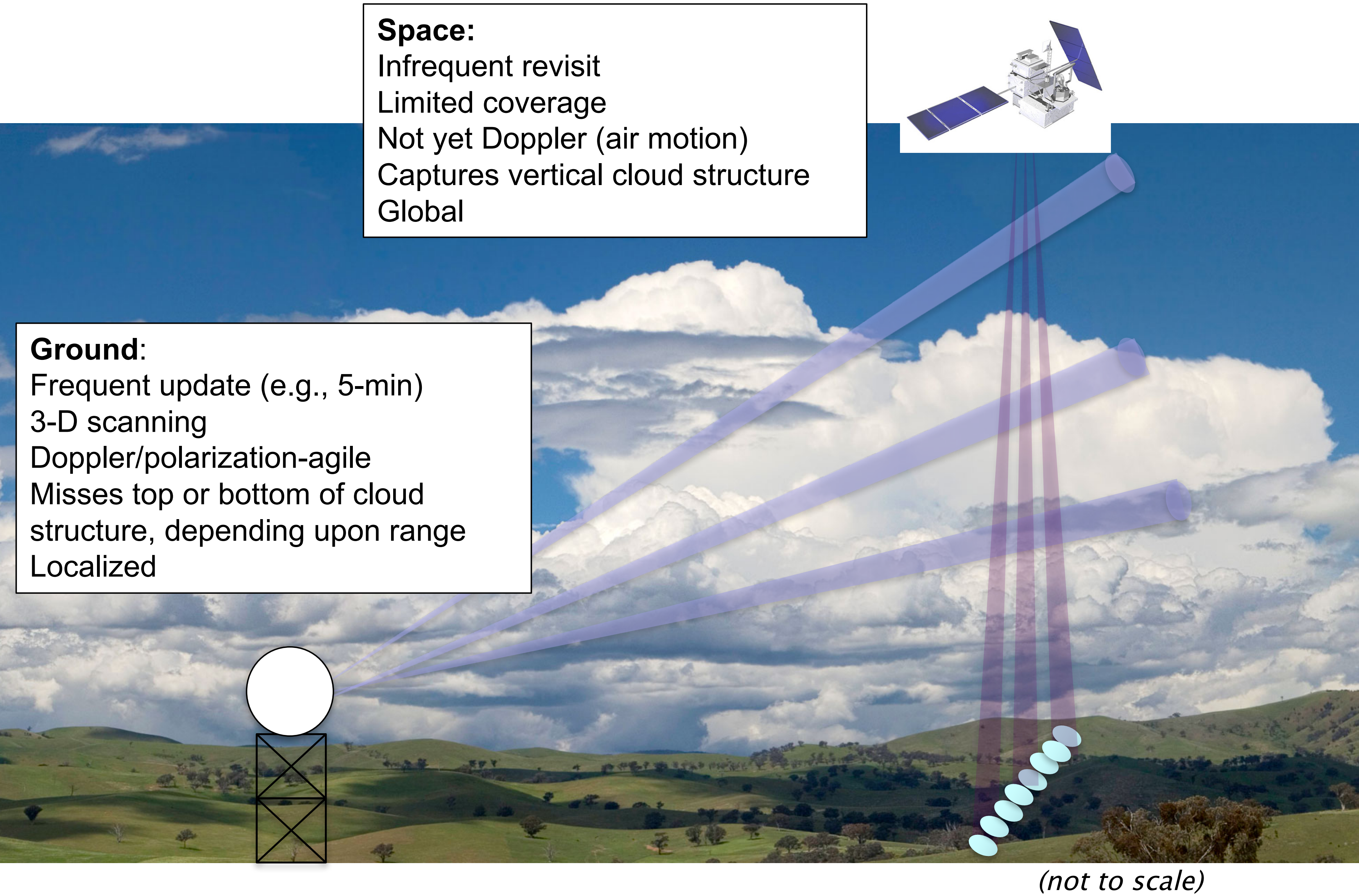
JPSS (2017-)
ATMS MW sounder

2017

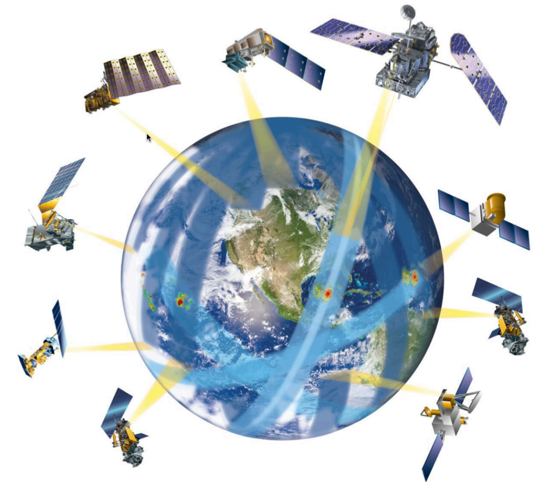
EarthCARE (2018) W-band radar

TOWARDS MORE USE IN OPERATIONS

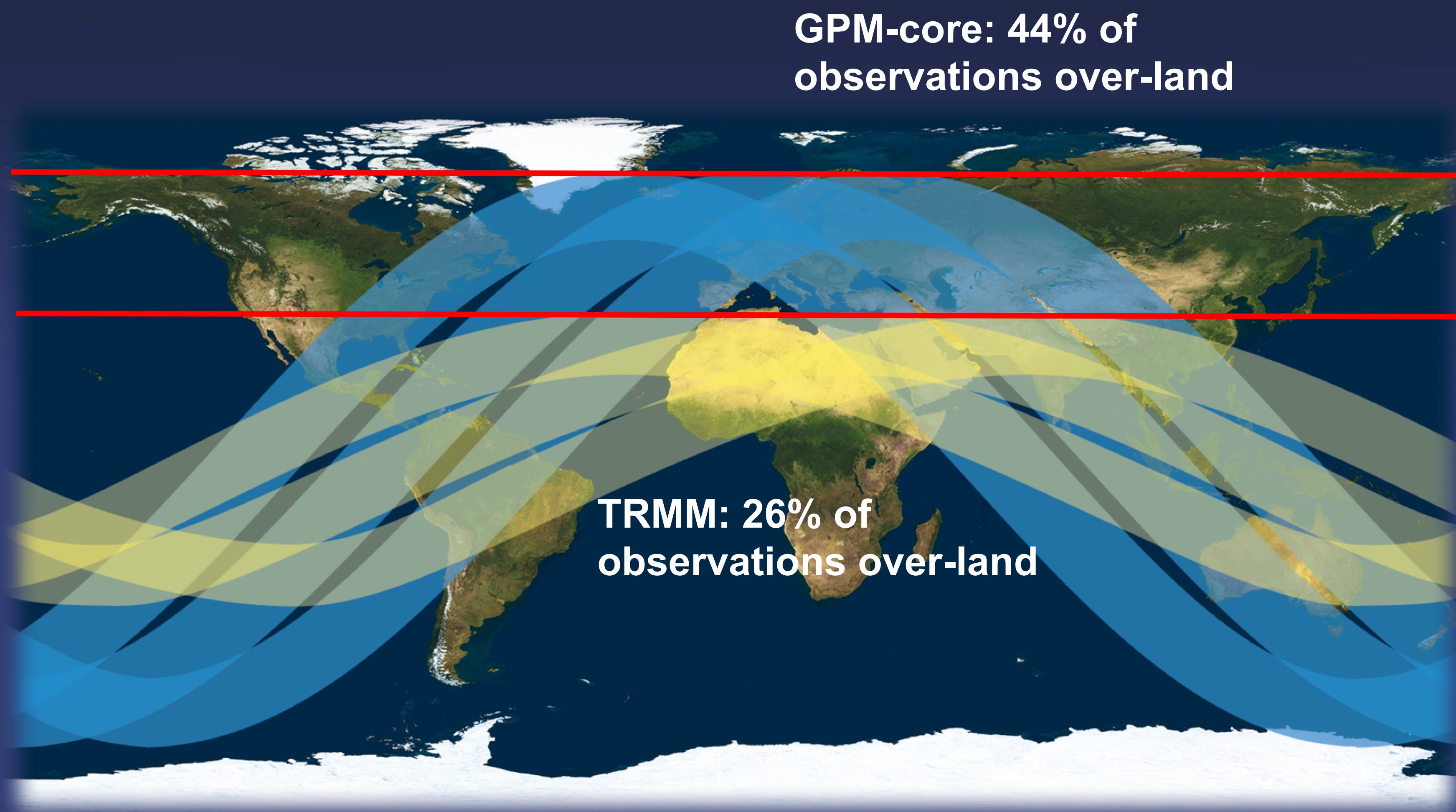
Complementary Nature of Space- and Ground-Based Radar



NASA's Space-Based Atmospheric Radar Systems



- **TRMM: Tropical Rainfall Measuring Mission (11/97-06/2015)**
  - single satellite mission (26% of observations are over land)
  - First precipitation radar in space
  - science oriented, for climate scale (monthly, 5-degree)
- **GPM: Global Precipitation Measurement (3/2014-current)**
  - "core" satellite anchors a constellation (44% observations over land)
  - Like TRMM but with dual-frequency radar
  - science and operations/applications in scope
- **CloudSat (6/2006-current):**
  - 94-GHz cloud radar: 30x higher frequency than the NWS 3-GHz NEXRAD ground radars
  - Part of NASA's "A-Train" sequence of satellite systems



Blue: GPM's orbit path

Yellow: TRMM's orbit path

The **GPM Core Observatory** carries **two advanced instruments** to observe rain & snow and serve as a **calibrator** for measurements taken on partner satellites.

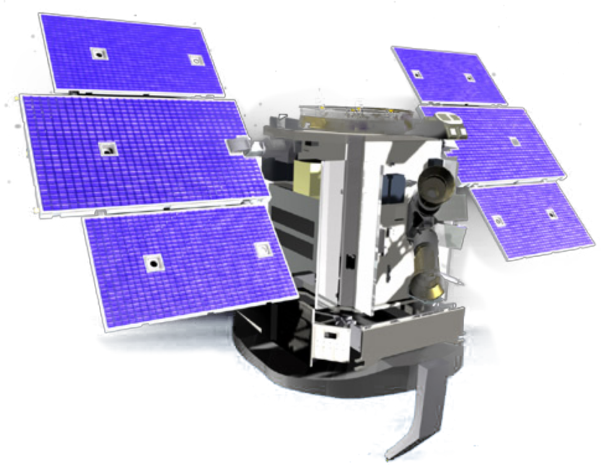
GPM Microwave Imager (GMI): 10-183 GHz (NASA)
13 channels provide an integrated picture of the energy emitted by precipitation, including light rain to heavy rain to falling snow.

Dual-frequency Precipitation Radar (DPR): Ku-Ka bands (JAXA)
Two different radar frequencies that measure precipitation in 3-D throughout the atmospheric column.

Launched February 28, 2014 by JAXA

Dual-frequency Precipitation Radar (DPR)

- The DPR sends out two different pulses of energy at 35 GHz (0.8 cm wavelength) and 13.6 GHz (2.2 cm) to determine the size and distribution of rain and snow particles in the cloud
- Resolution: 5-7 km horizontally, 250-500 m vertically



CloudSat Profiling Radar

- CloudSat operates at 94 GHz (3-mm wavelength), much more sensitive to cloud drop sizes, but greatly attenuated by precipitation
- Resolution: 1-km horizontally, 250-m vertically (does not scan)
- Part of NASA's A-Train formation

Role of the Surface: Precipitation Radar

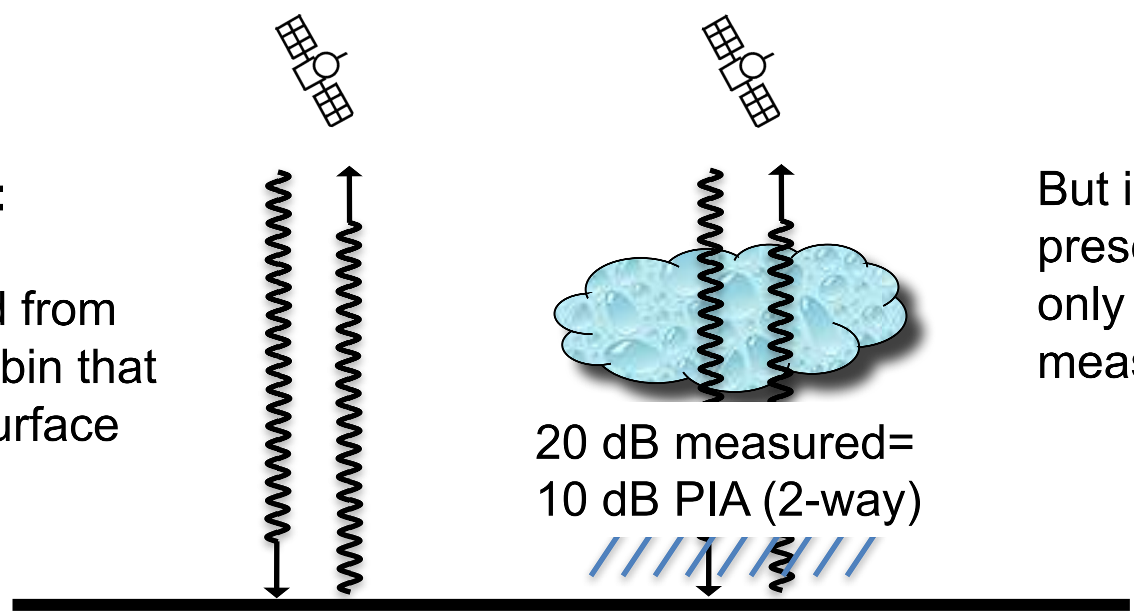
Unlike the US NEXRAD nationwide radars, the GPM radar operates at frequencies where the radar propagation is attenuated by rain, and to a lesser extent, clouds.

Knowledge of the Path Integrated Attenuation (PIA) is used as a constraint to partition the radar attenuation, and derive rainrate

Clear Scene

Rainy Scene

Example:
30 dB is measured from the radar bin that hits the surface

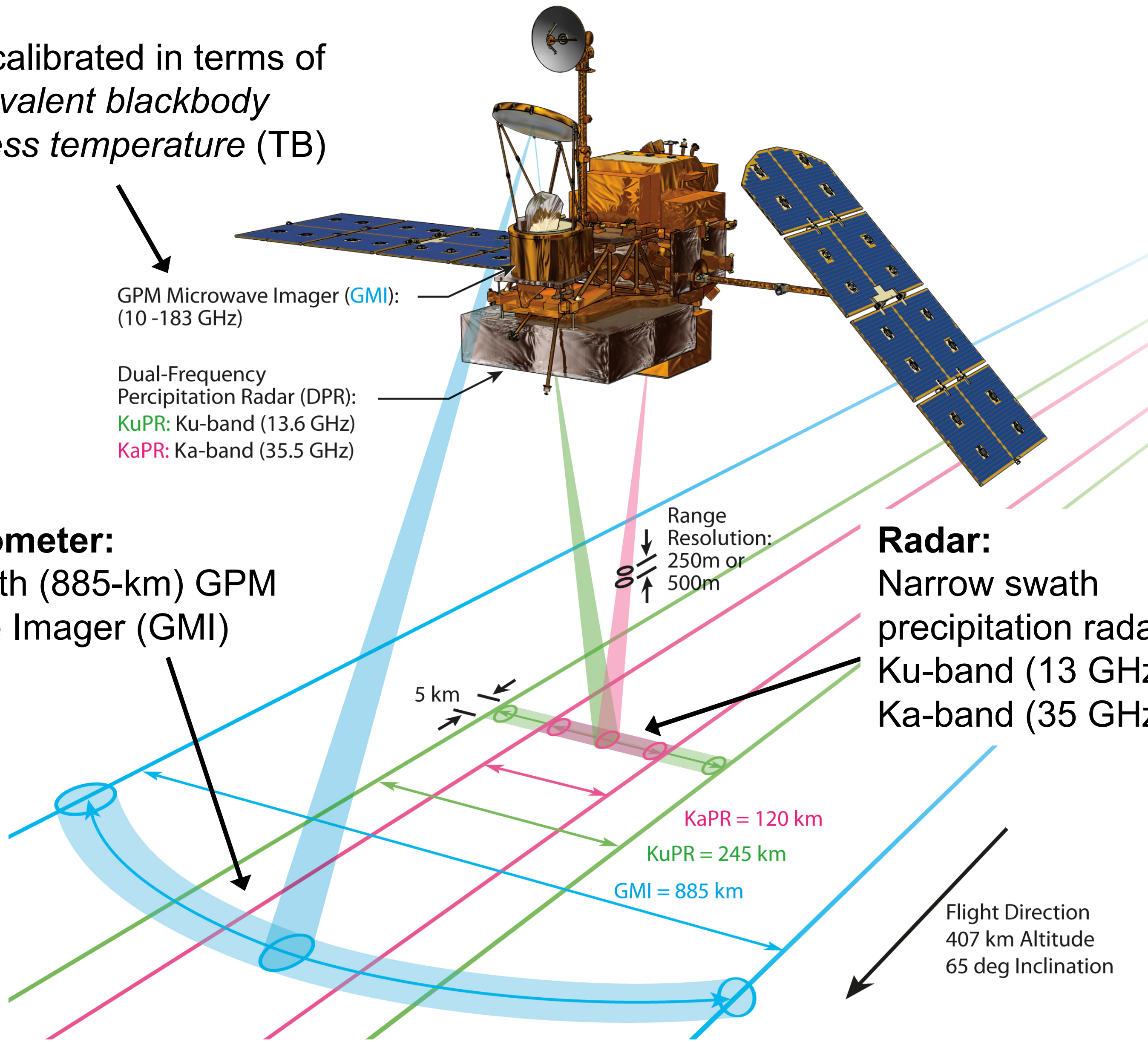


But in the presence of rain, only 20 dB is measured

Strongly reflecting ocean surface (easier)
Highly variable land surface (difficult)

Global Precipitation Measurement (GPM) core satellite

GMI is calibrated in terms of *equivalent blackbody brightness temperature* (TB)



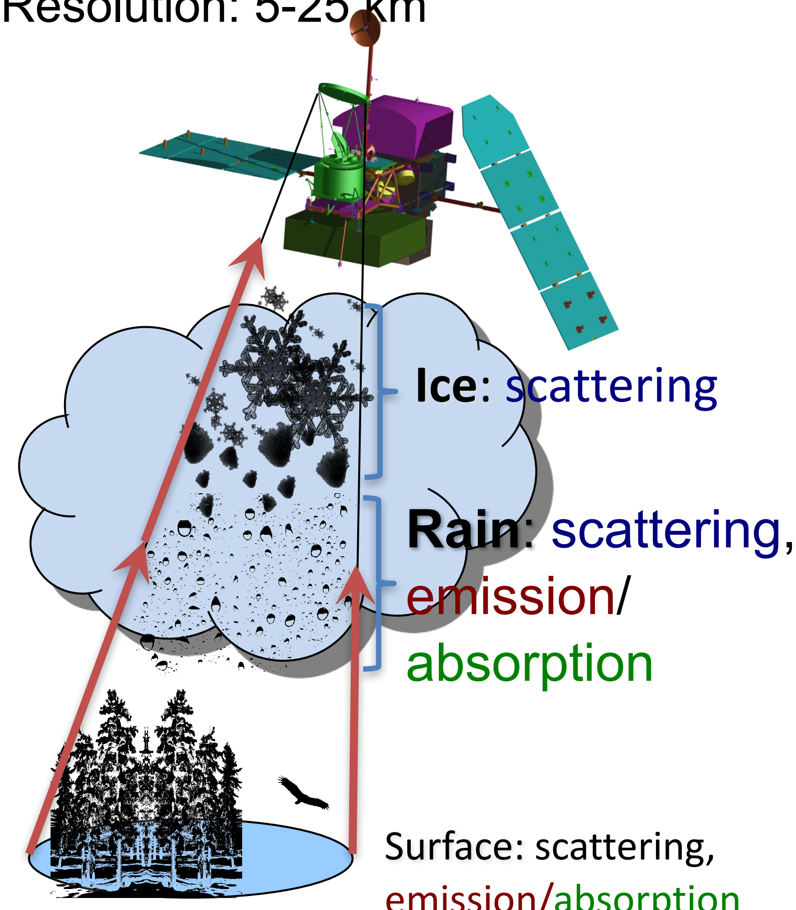
MW Radiometer:
Wider swath (885-km) GPM Microwave Imager (GMI)

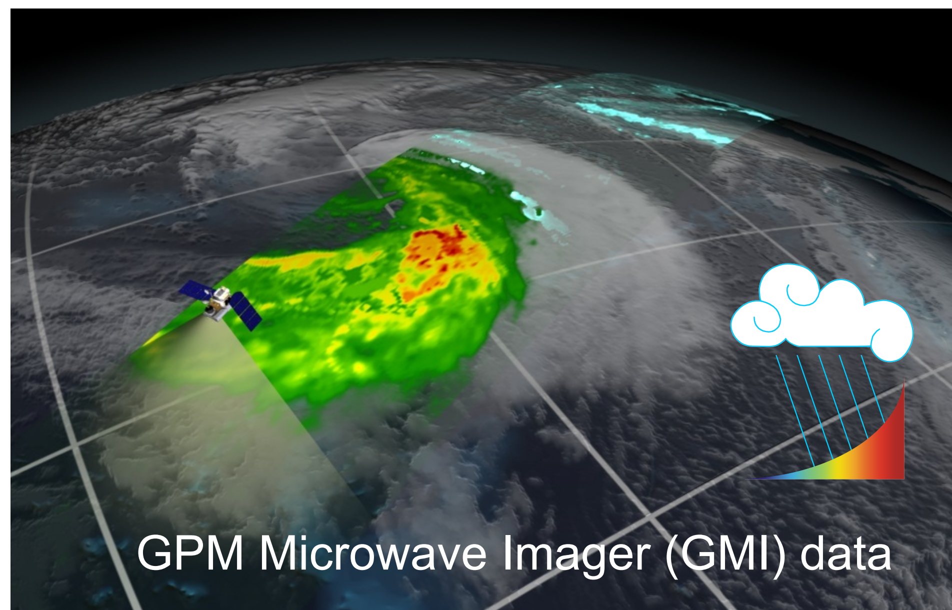
Radar:
Narrow swath precipitation radar
Ku-band (13 GHz, 245-km)
Ka-band (35 GHz, 120-km)

Courtesy G. Skofronick-Jackson, GSFC

GPM Microwave Imager (GMI)

- Precipitation & surface features emit energy at different frequencies (GHz). The GMI passively observes this energy to estimate surface precipitation
- Proven best calibrated instrument of its kind (to within 0.5 K or 1.0 F)
- Resolution: 5-25 km





Passive Microwave Radiometry: A Study in Contrast

Analogy with IR thermal sensor

warm forehead (305K)

medium

cold nose (290K)

JPL Visitor Museum exhibit

Passive Microwave Radiometry: A Study in Contrast

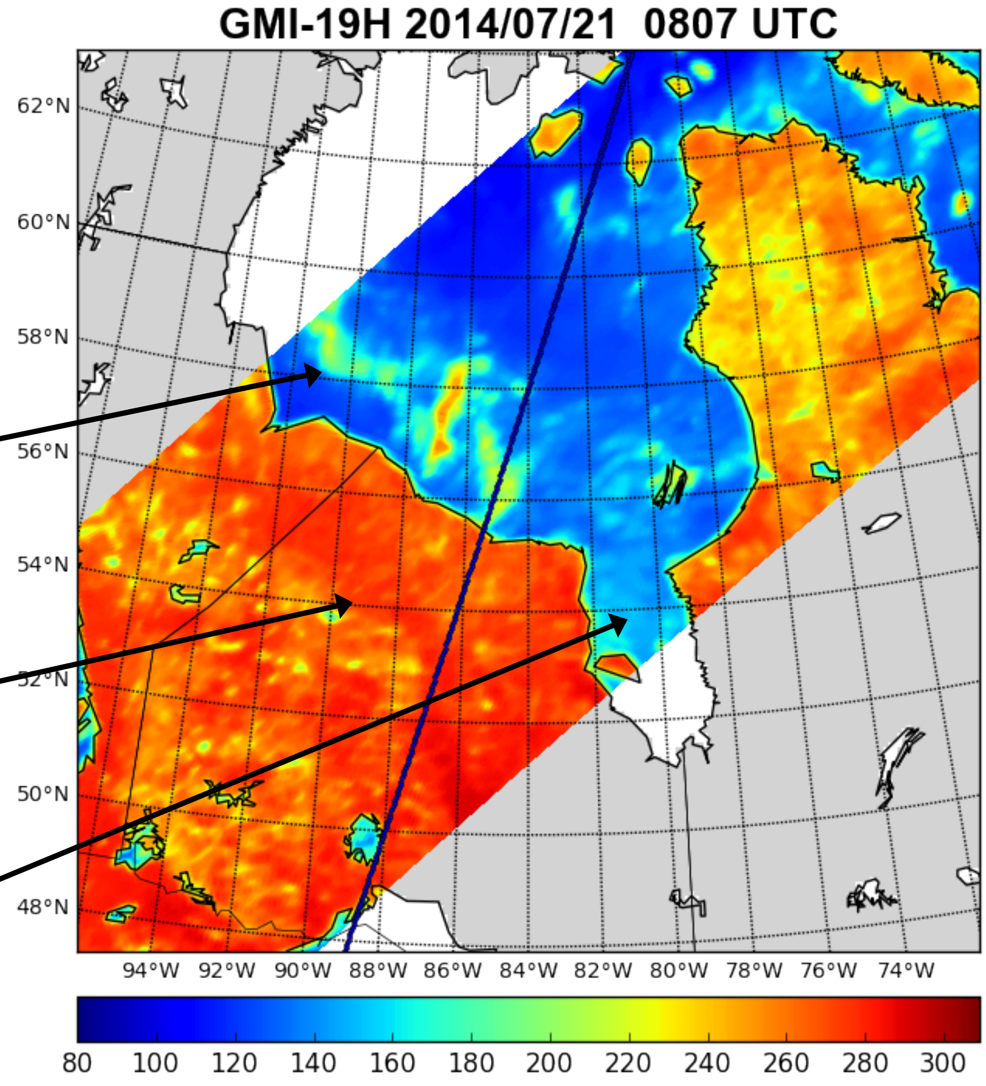
In the microwave, Earth constituents both emit and reflect

19 GHz (1.5 cm)

clouds
(good emitter)

land
(good emitter)

water surface
(emits and scatters)



0 < emissivity < 1

Passive Microwave Radiometry: A Study in Contrast

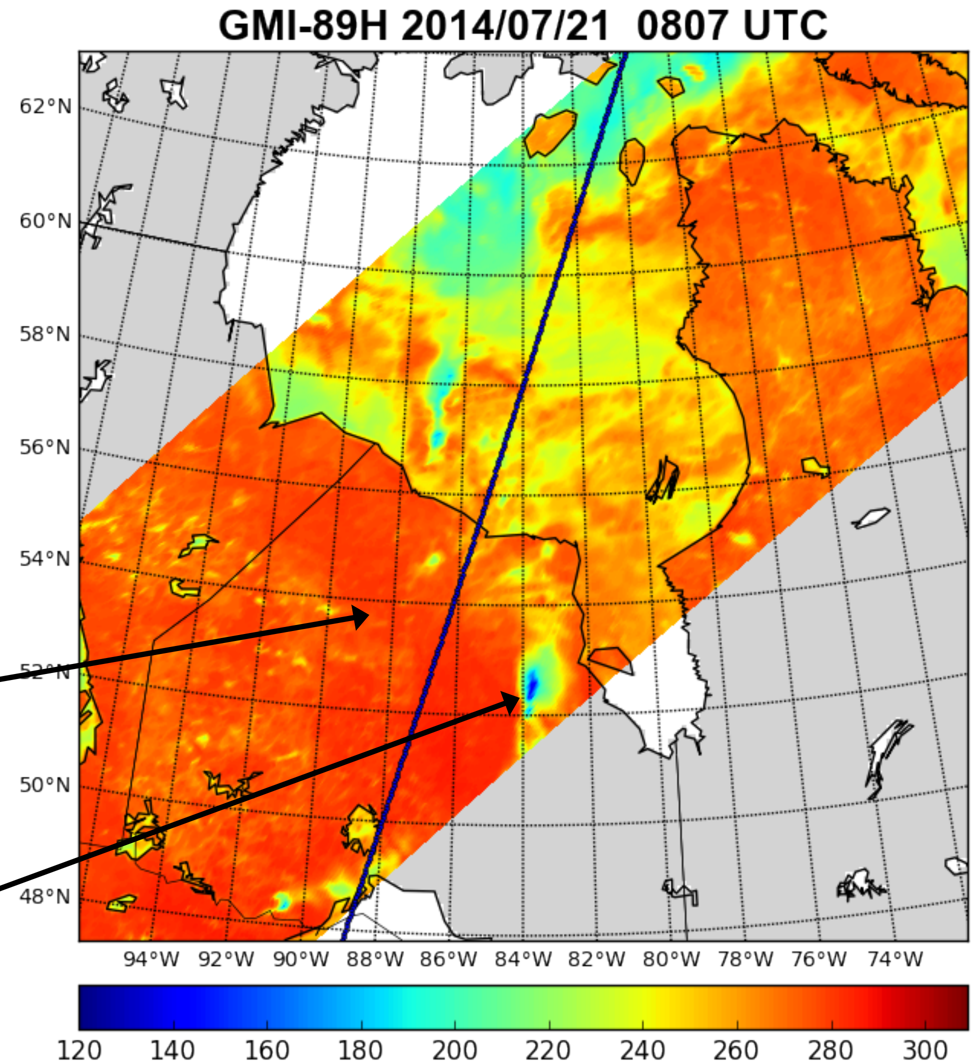
In the microwave, Earth constituents both emit and reflect

89 GHz (3 mm)

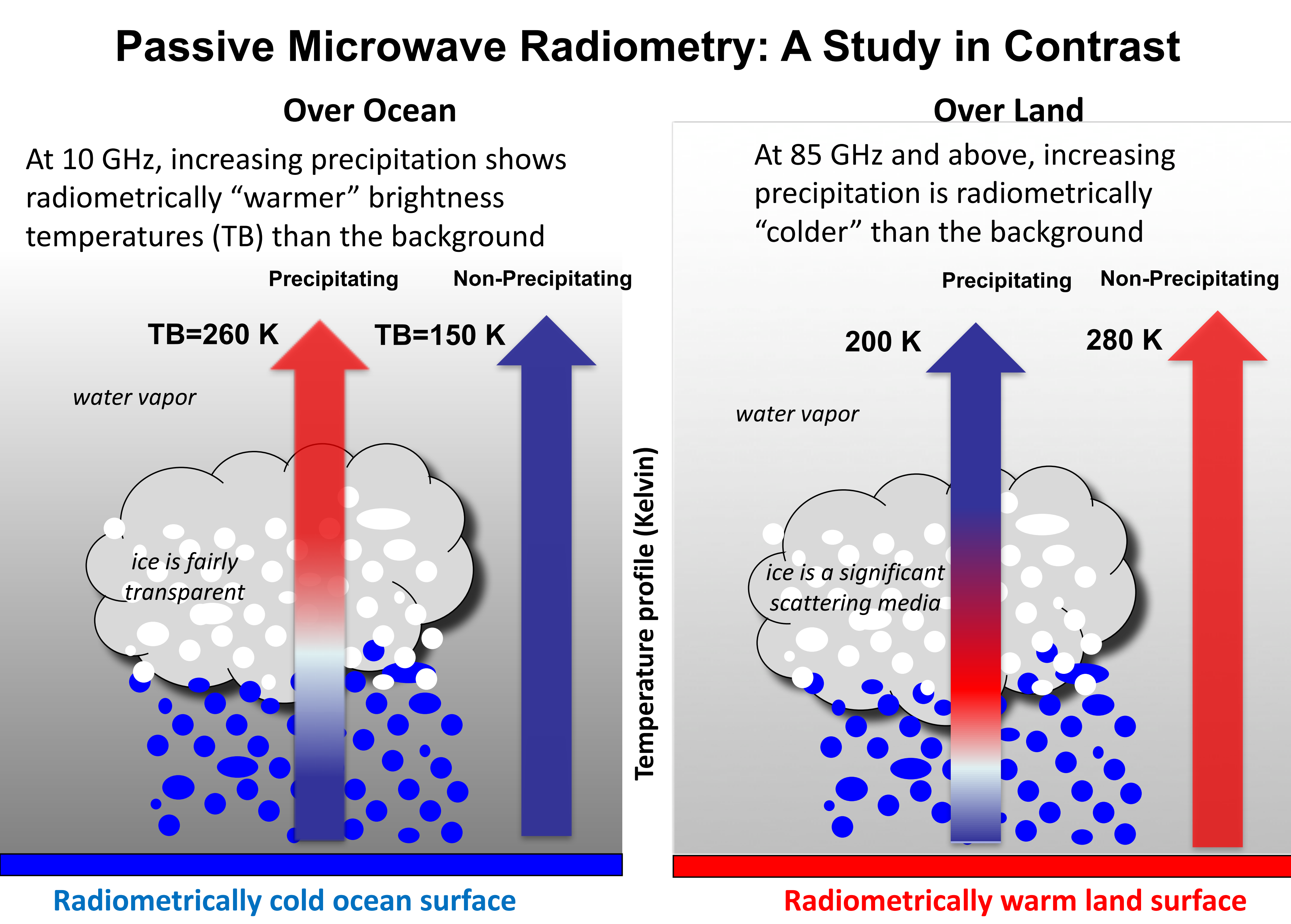
water vapor (more emission)

warm land (good emitter)

precipitation (emits and scatters even more)



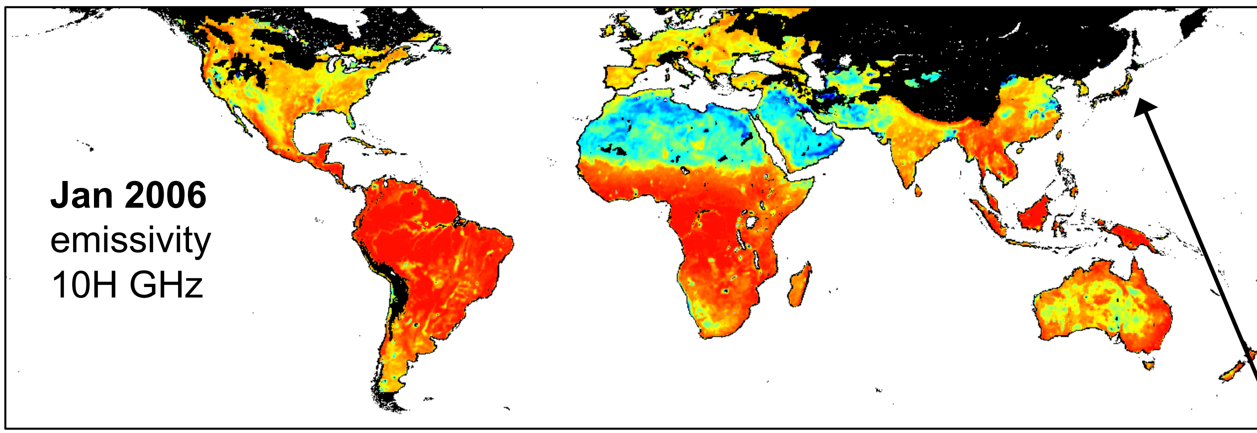
Many factors influence emissivity- roughness, soil moisture, vegetation, etc.

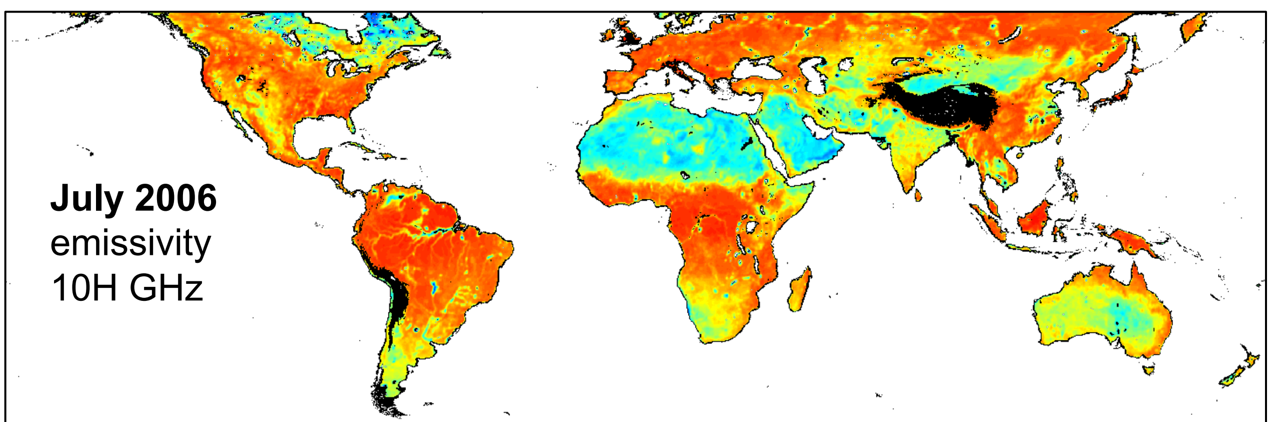

Passive Microwave Radiometry: A Study in Contrast
Over Ocean
At 10 GHz, increasing precipitation shows radiometrically "warmer" brightness temperatures (TB) than the background
Precipitating
Non-Precipitating
TB=260 K
TB=150 K
water vapor
ice is fairly transparent
Radiometrically cold ocean surface
Temperature profile (Kelvin)
Over Land
At 85 GHz and above, increasing precipitation is radiometrically "colder" than the background
Precipitating
Non-Precipitating
200 K
280 K
water vapor
ice is a significant scattering media
Radiometrically warm land surface

Space-Based Over-Land Precipitation Estimation

The satellites have to contrast precipitation against a wide variety of land surfaces and terrain, that are dynamically changing (soil conditions, snowcover, temperature, vegetation)

In some conditions, a non-raining scene can "look like" a precipitation scene (false alarm)





snow/ice cover and cold surface not shown

In general, dry surfaces exhibit higher 10 GHz emissivity

Range of Emissivity

0.65 --> 0.99

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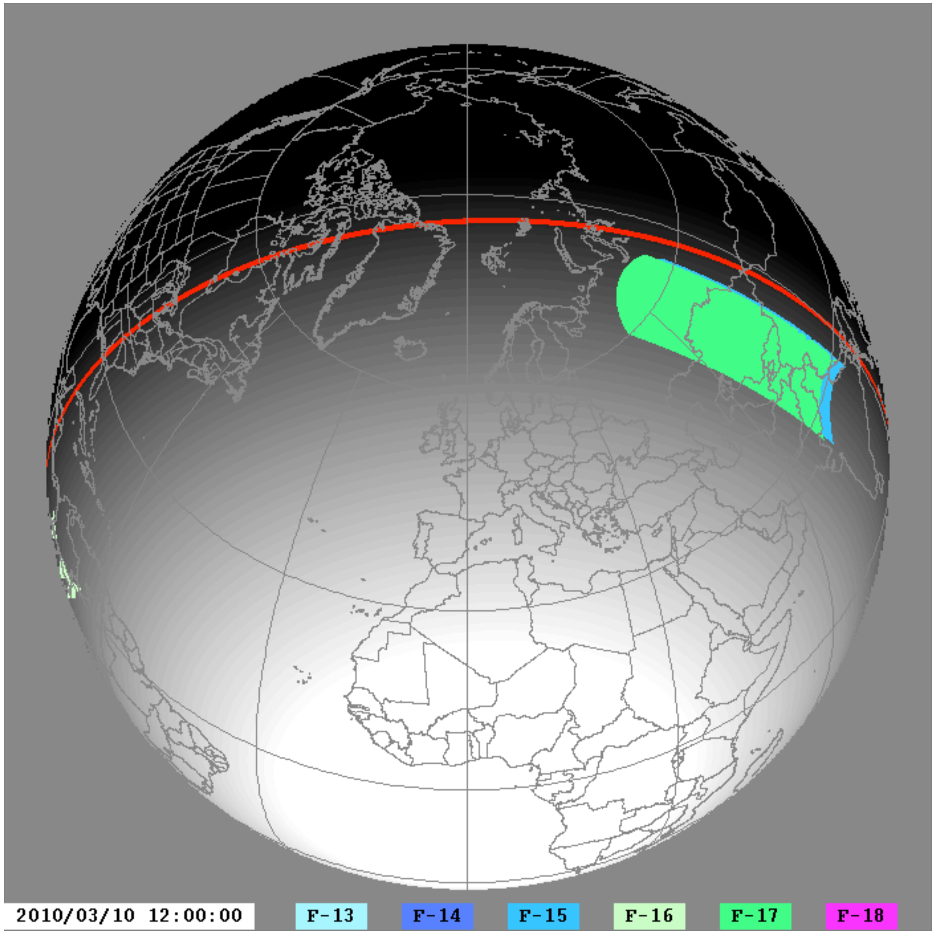


Example from DMSP satellites on March 10, 2010

Solar zenith is indicated by the white shades and the red stripe indicates the day-night terminator. Note how each satellite follows the sun (nearly the same local time) each orbit

Factors Limiting the Ability to Quantify Precipitation from Space

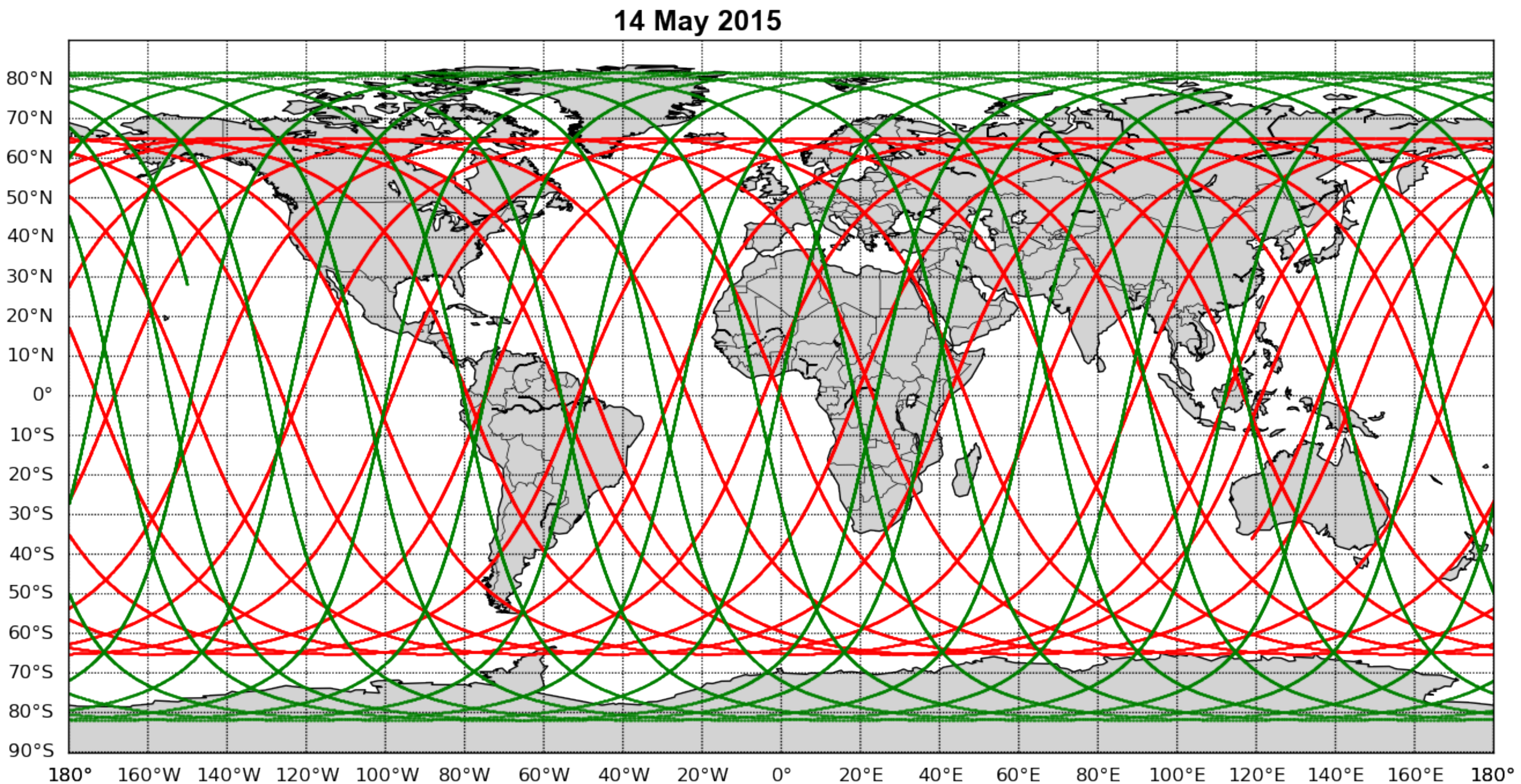
Revisit Time

A typical satellite orbits the Earth every 90 minutes and commonly observes at (nearly) the same local time

Non-Uniform Beamfilling

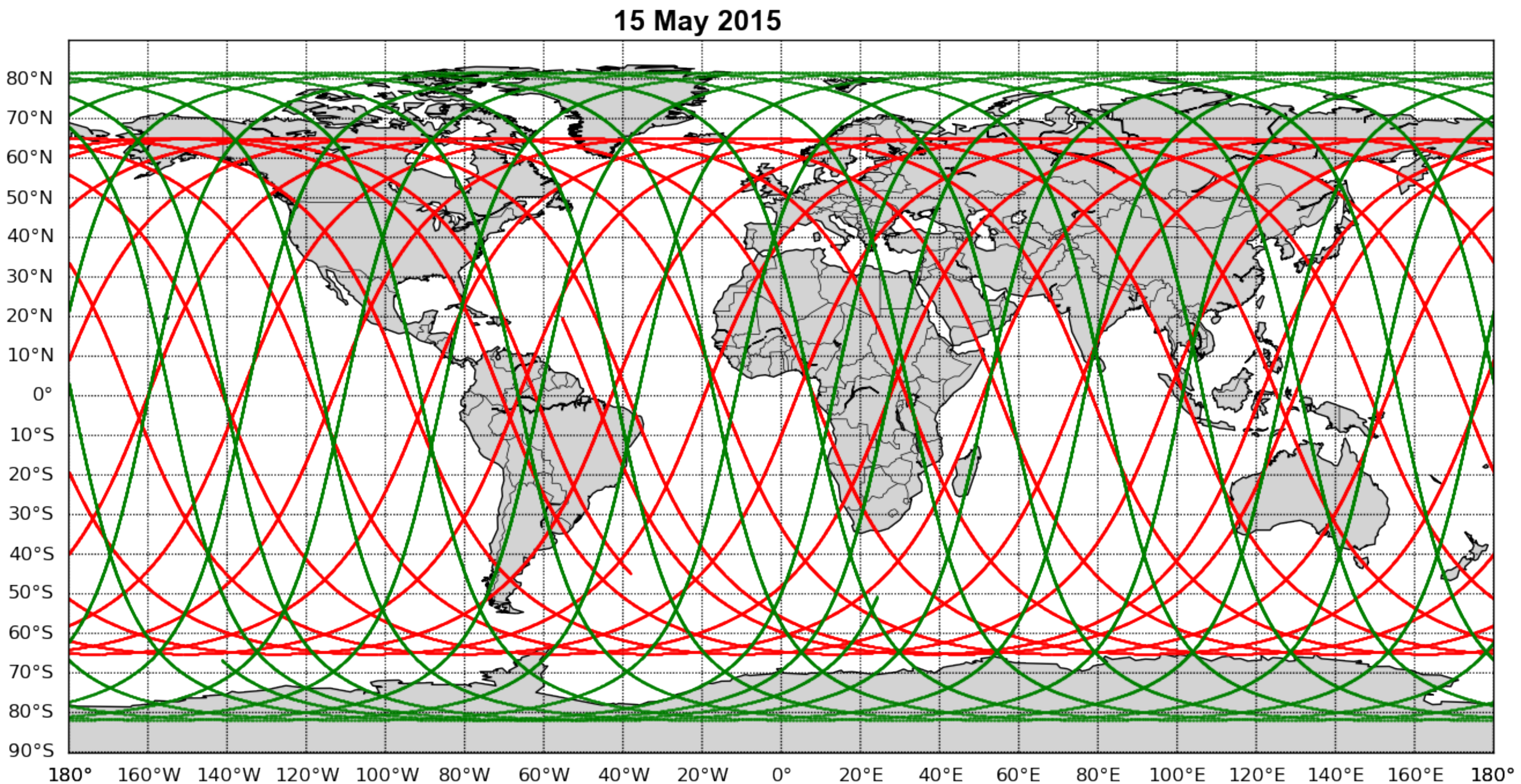
The structure of the underlying rainfall is finer than the sensor can resolve (think of a low-resolution digital camera)

One Day Orbit Tracks GPM-core CloudSat



About 15-16 orbits per day, from nominal altitude (405-km for GPM-core, 800-km for CloudSat)

One Day Orbit Tracks GPM-core CloudSat



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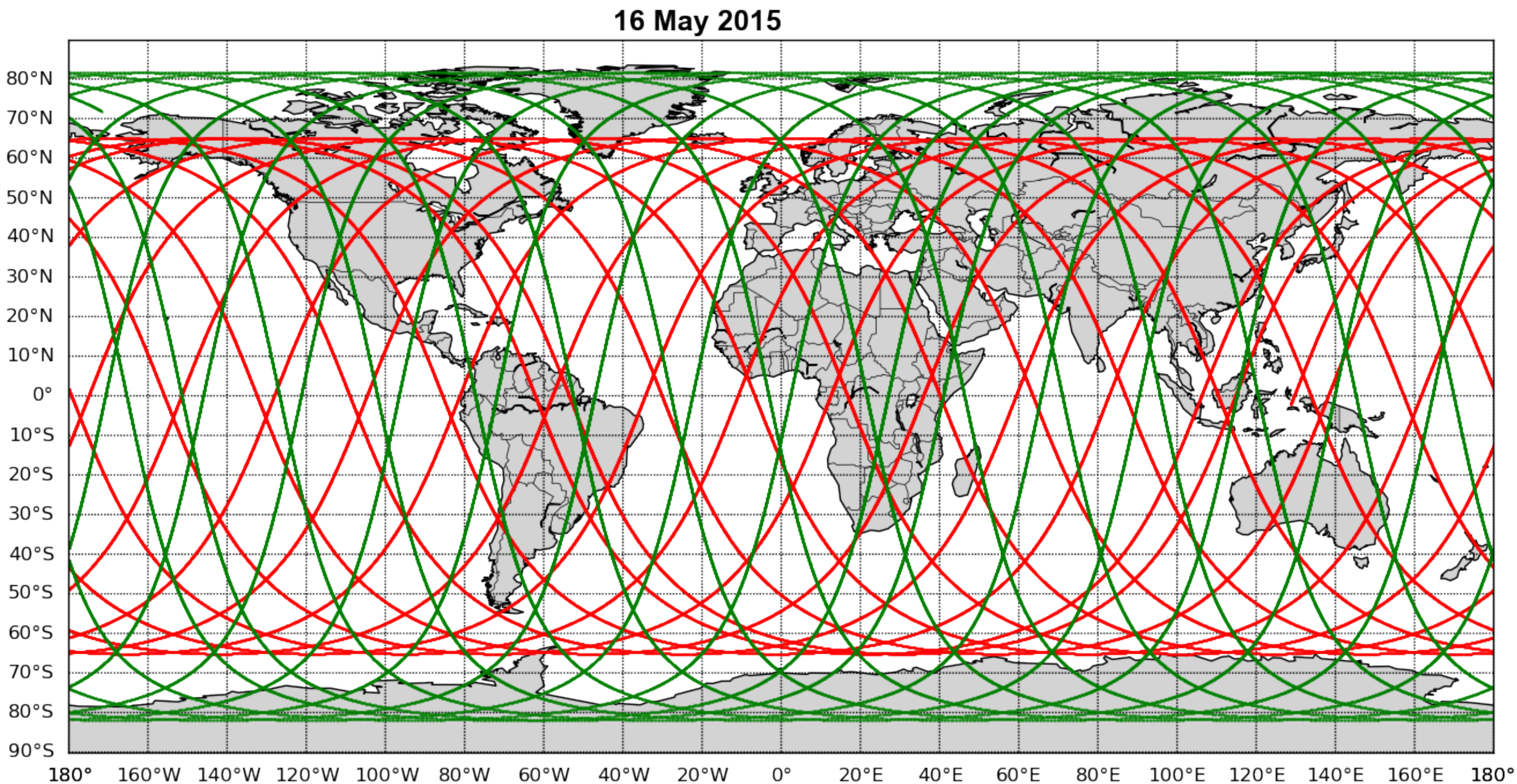

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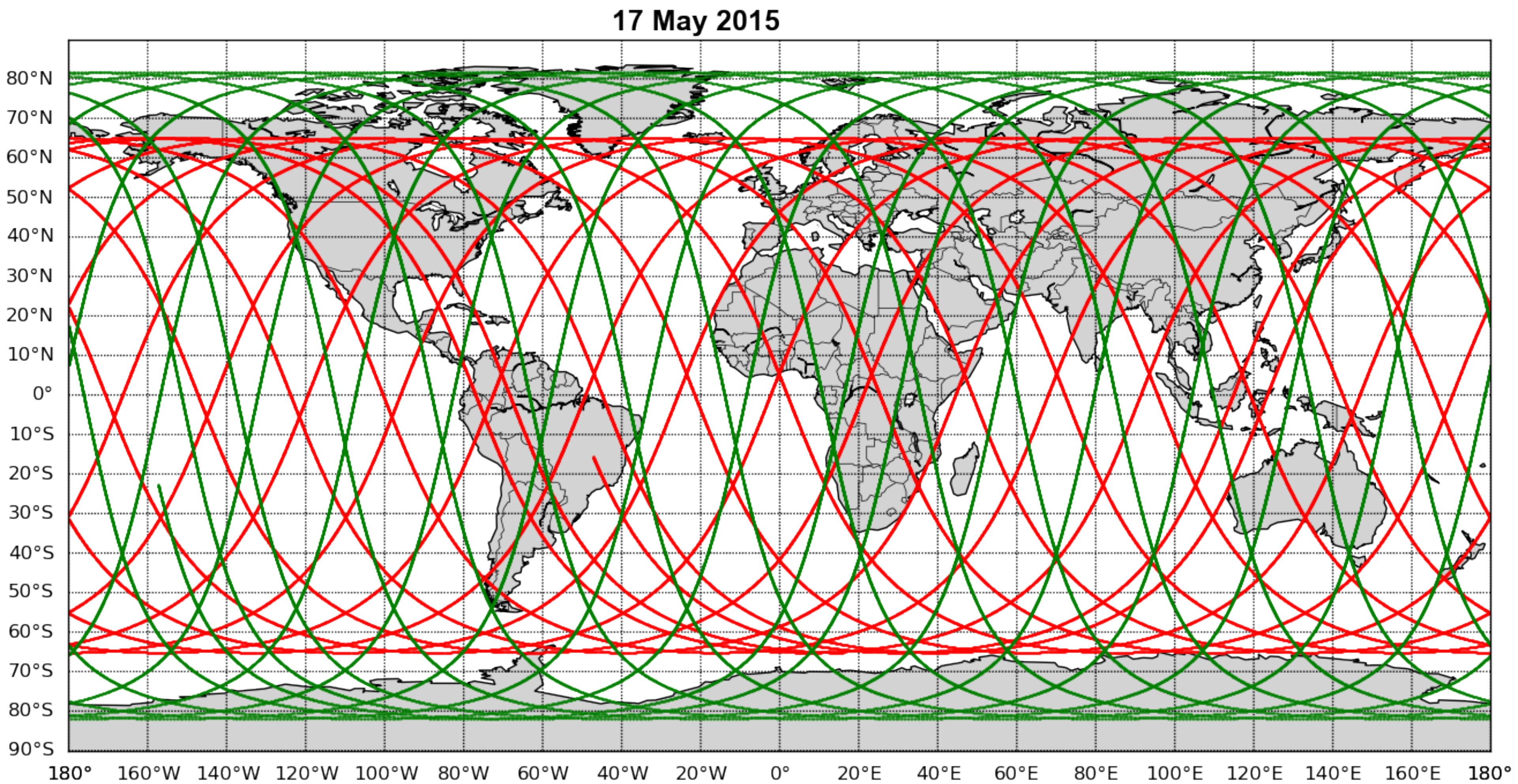
One Day Orbit Tracks GPM-core CloudSat



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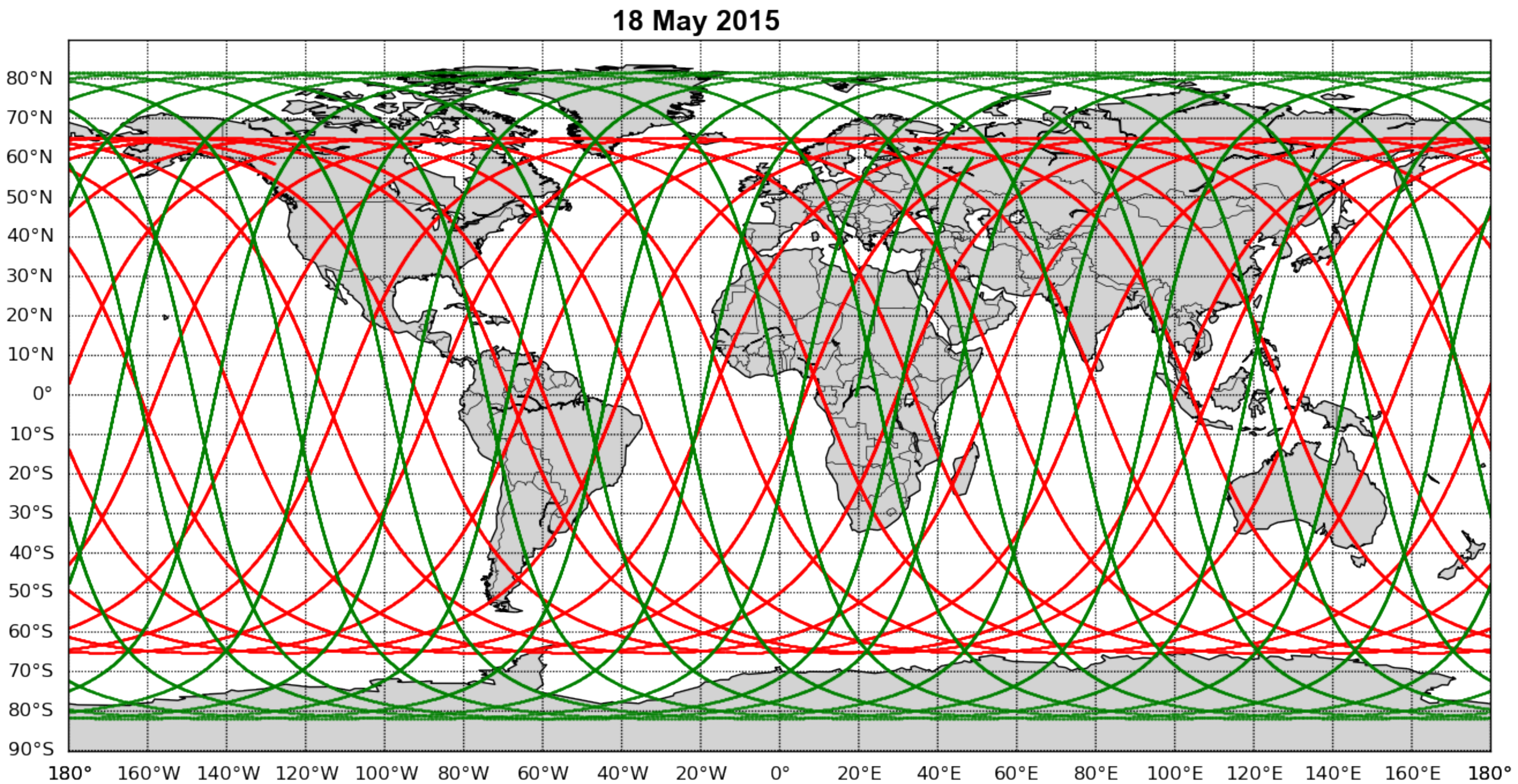
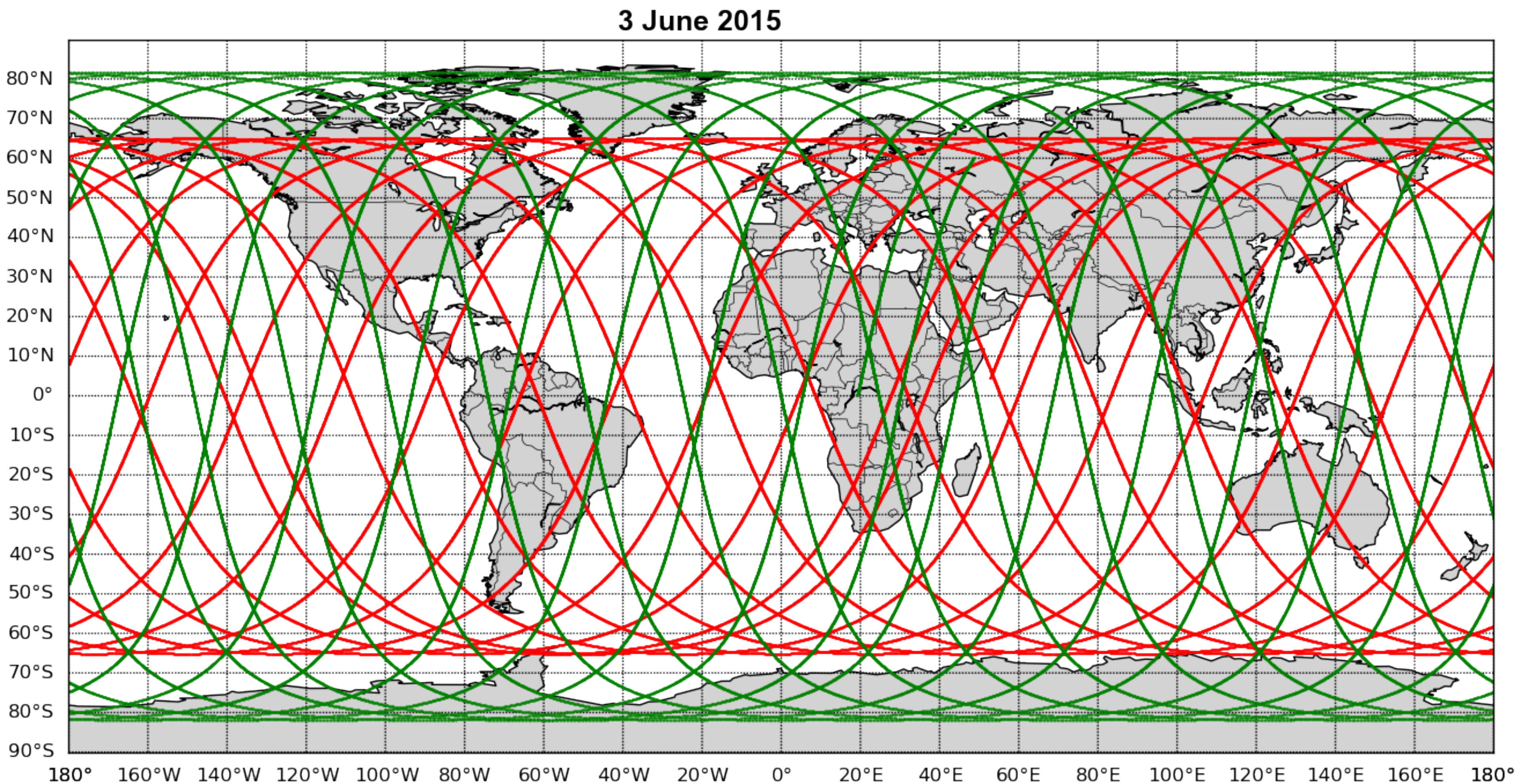
One Day Orbit Tracks GPM-core CloudSat



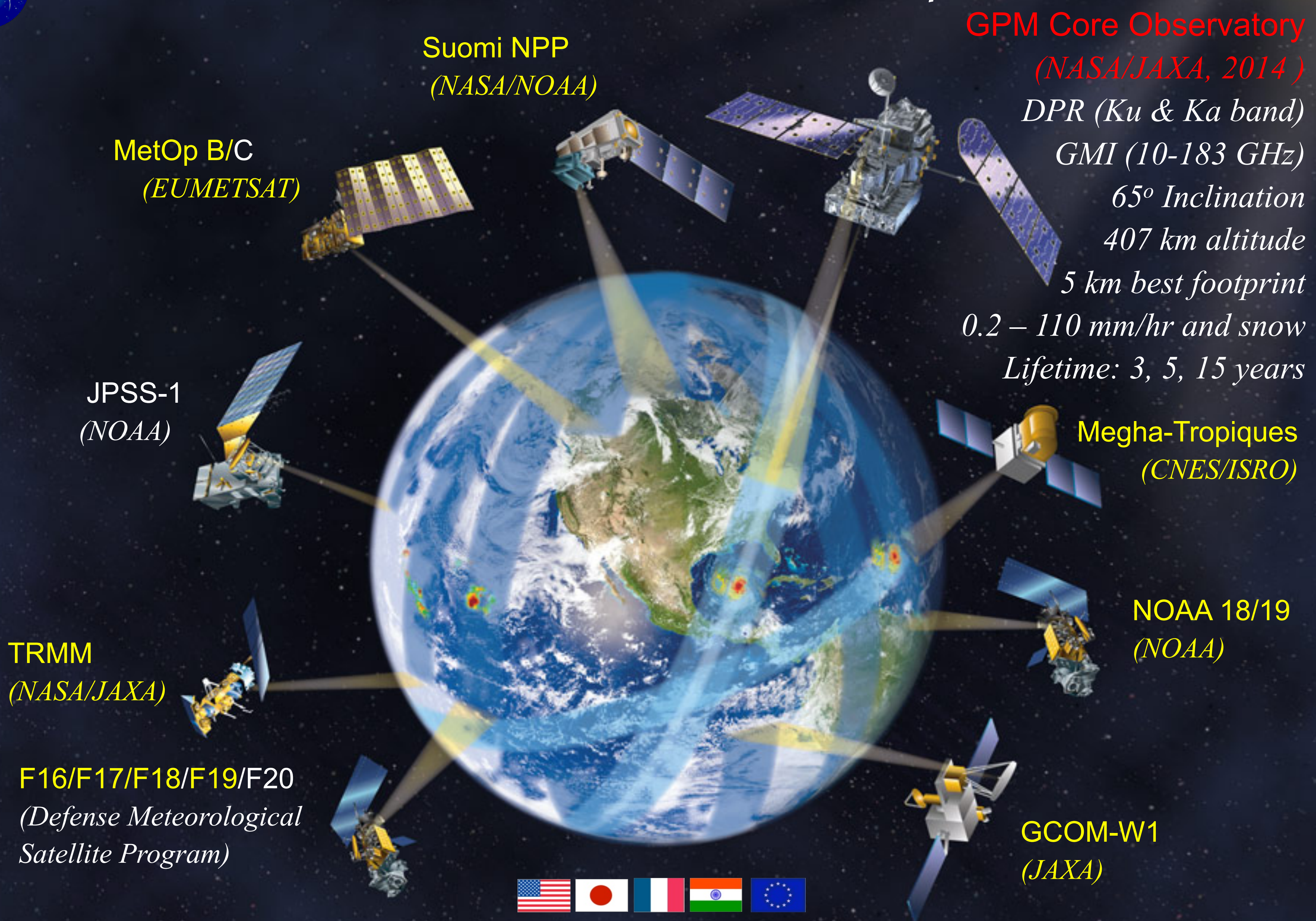
About 15-16 orbits per day, from nominal altitude (405-km for GPM-core, 800-km for CloudSat)

One Day Orbit Tracks GPM-core CloudSat



16 days later (after May 18). Note how CloudSat's orbit progression starts all over, but not GPM. GPM is in an asynchronous orbit – it does not cross the equator at the same local time each orbit.

GPM Constellation Concept



Next-Generation Unified Global Precipitation Products Using GPM Core Observatory as Reference

Precipitation rates everywhere in the world every three hours

Outline

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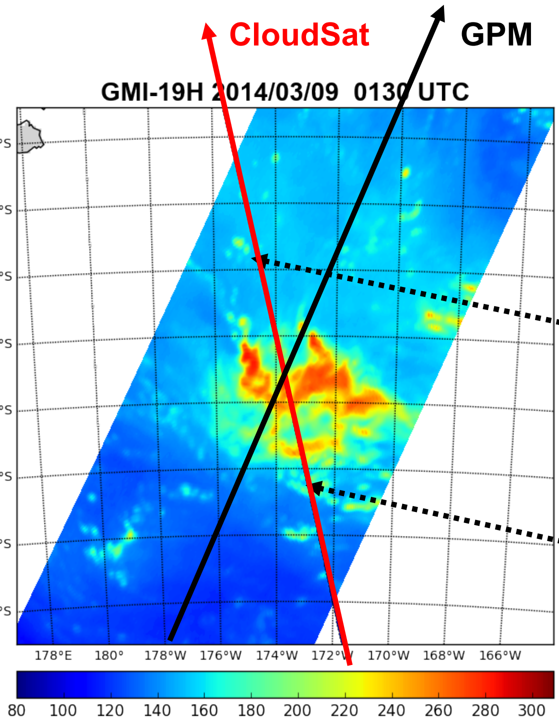
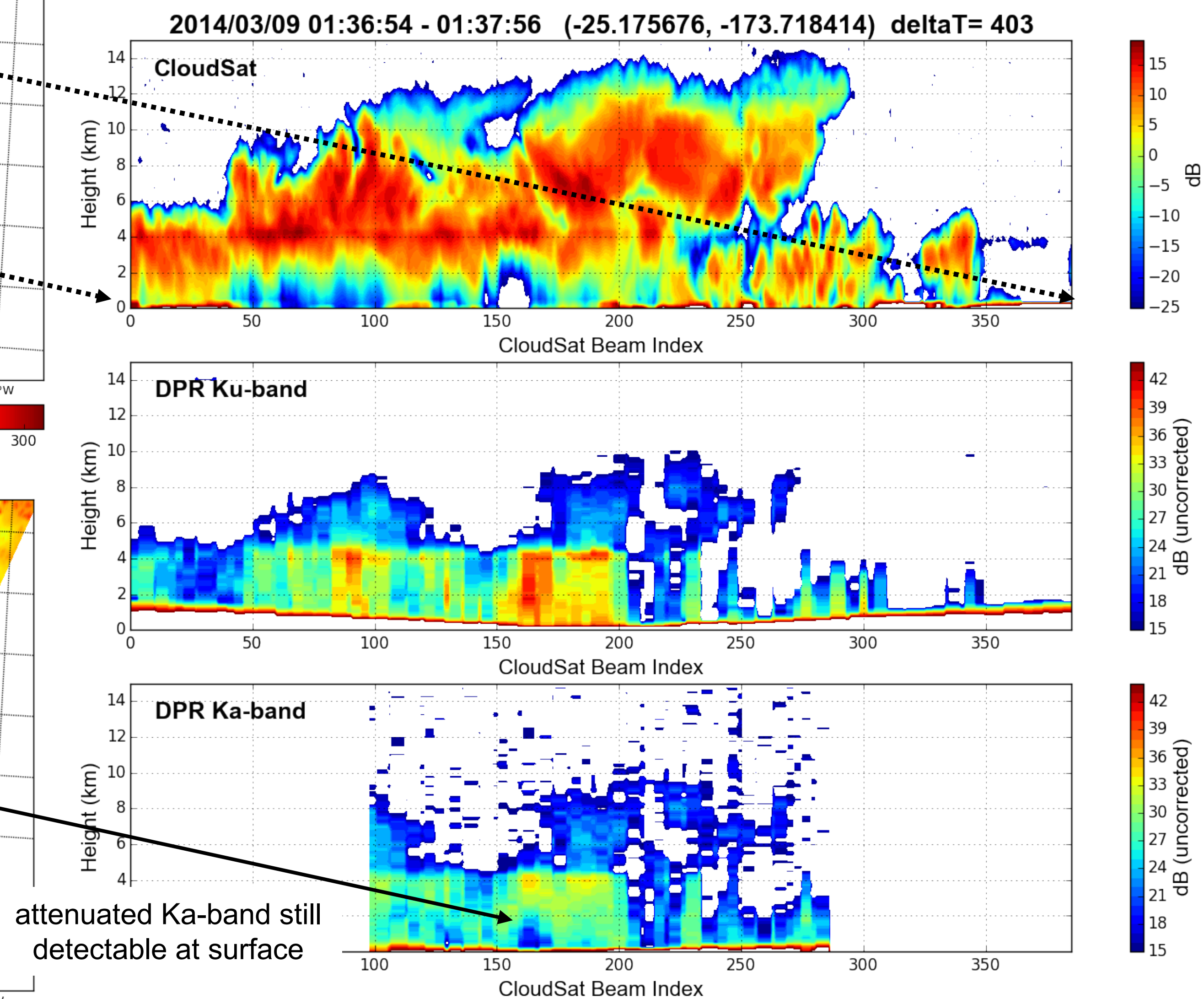
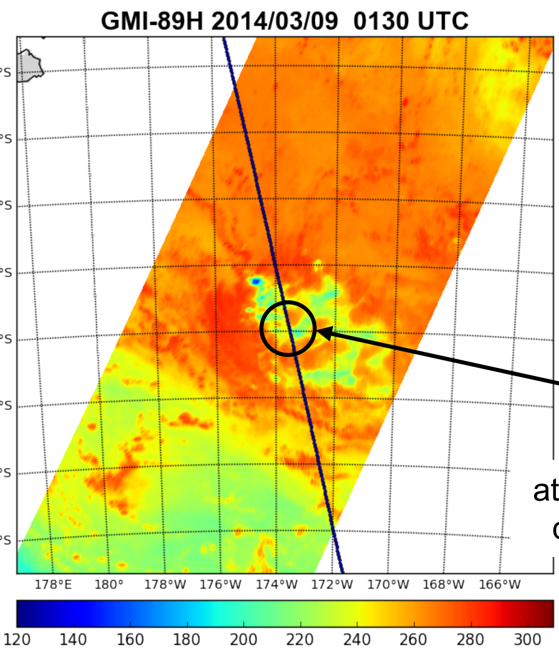
What Types of Clouds Can GPM Sense?



2014/03/09 0137 UTC
Southern Pacific Ocean: Deep Convection





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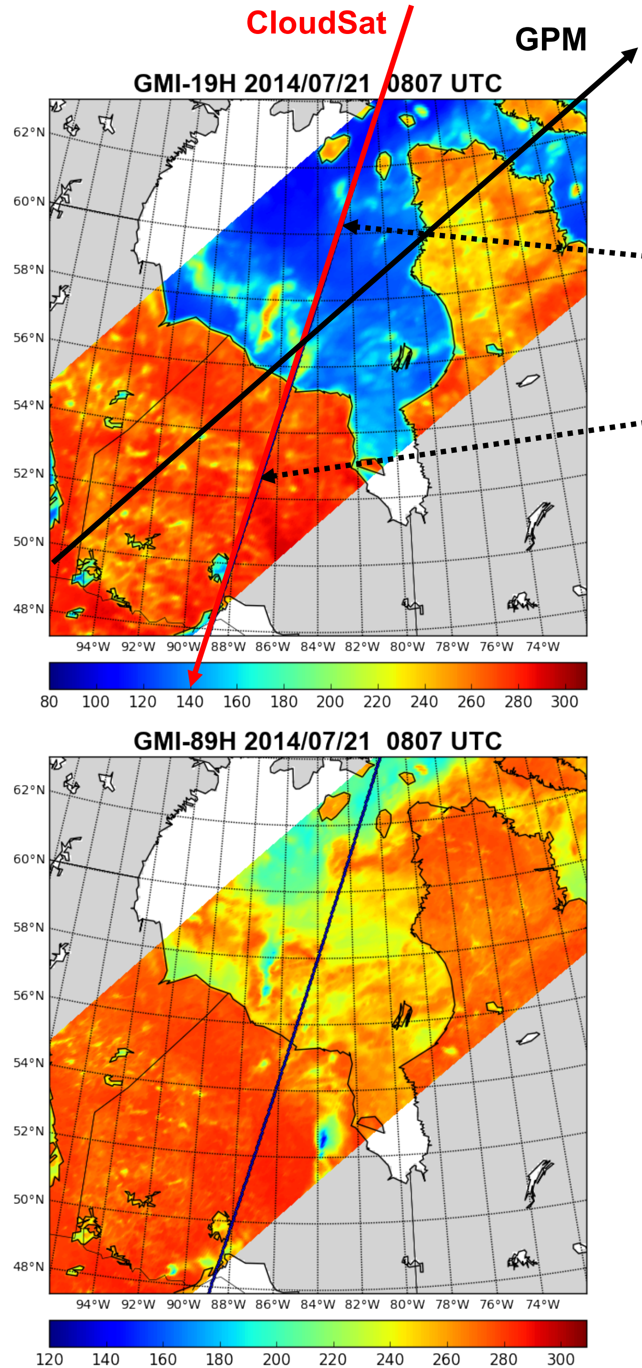
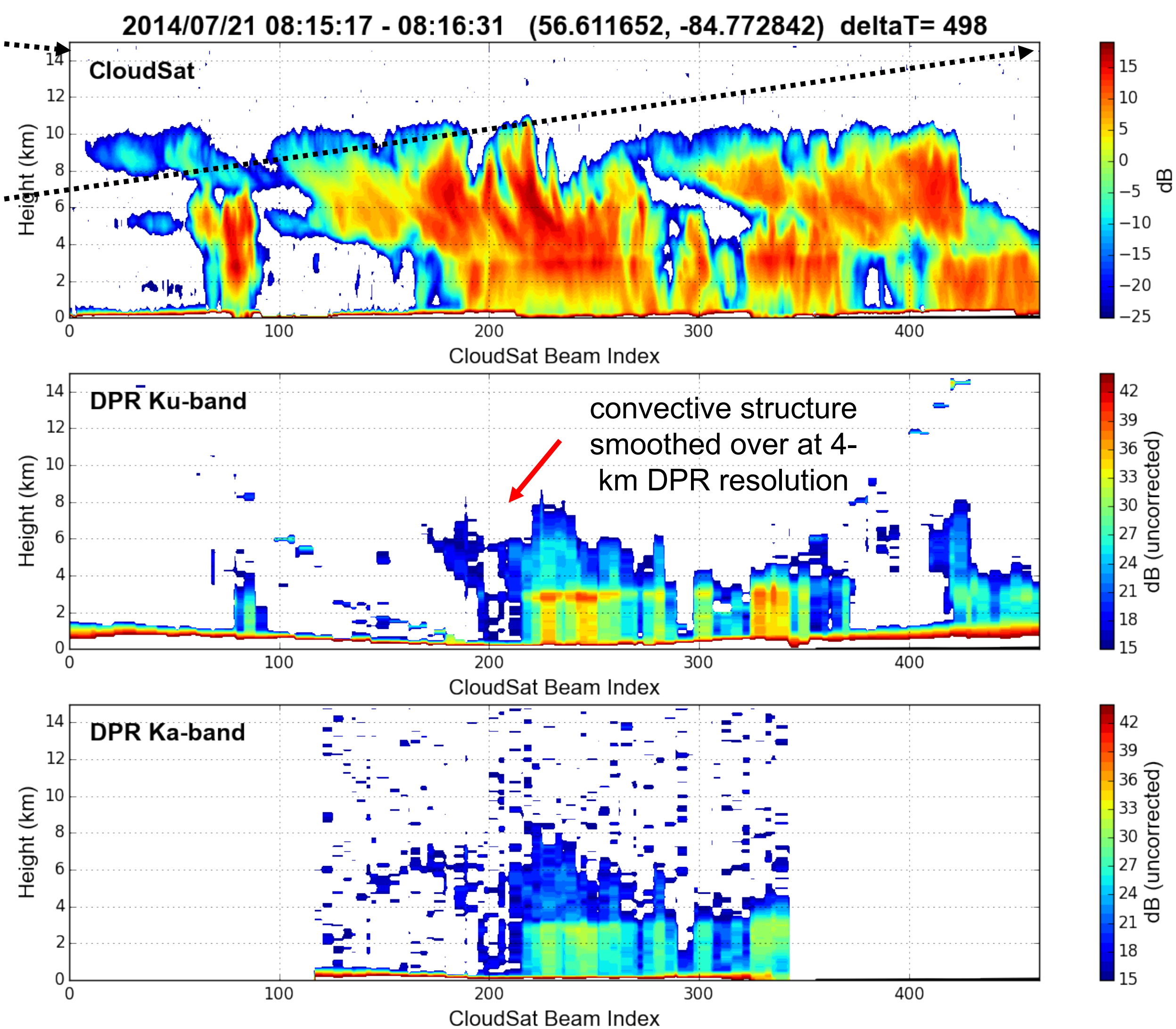
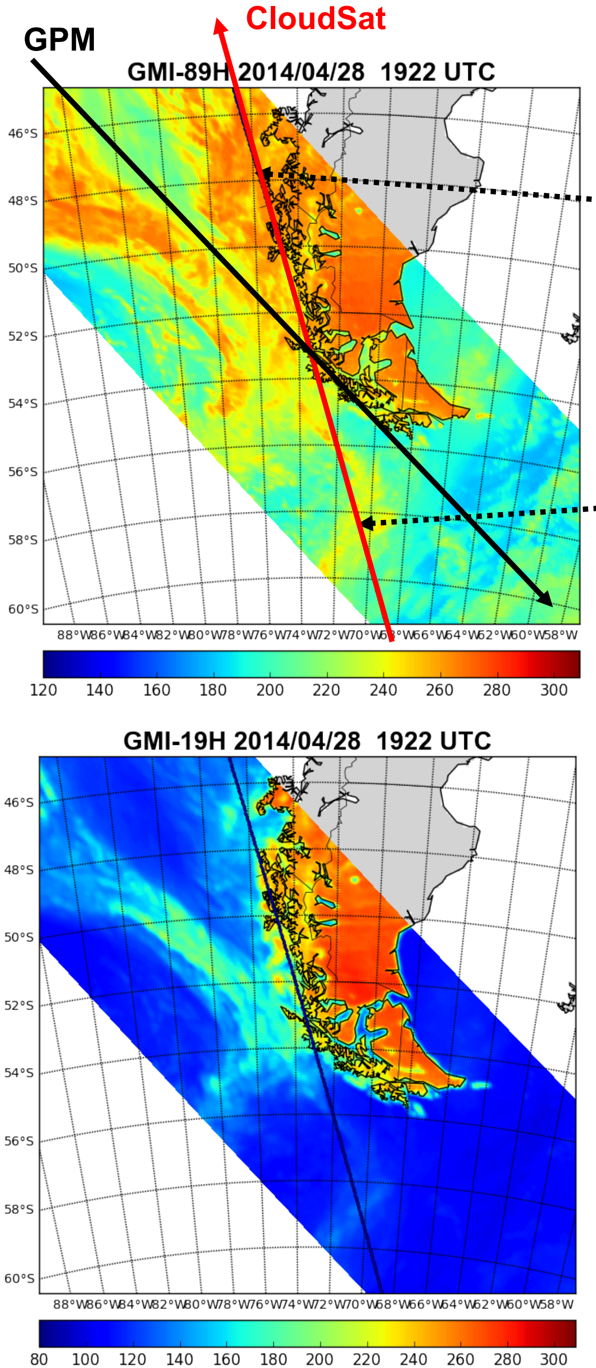


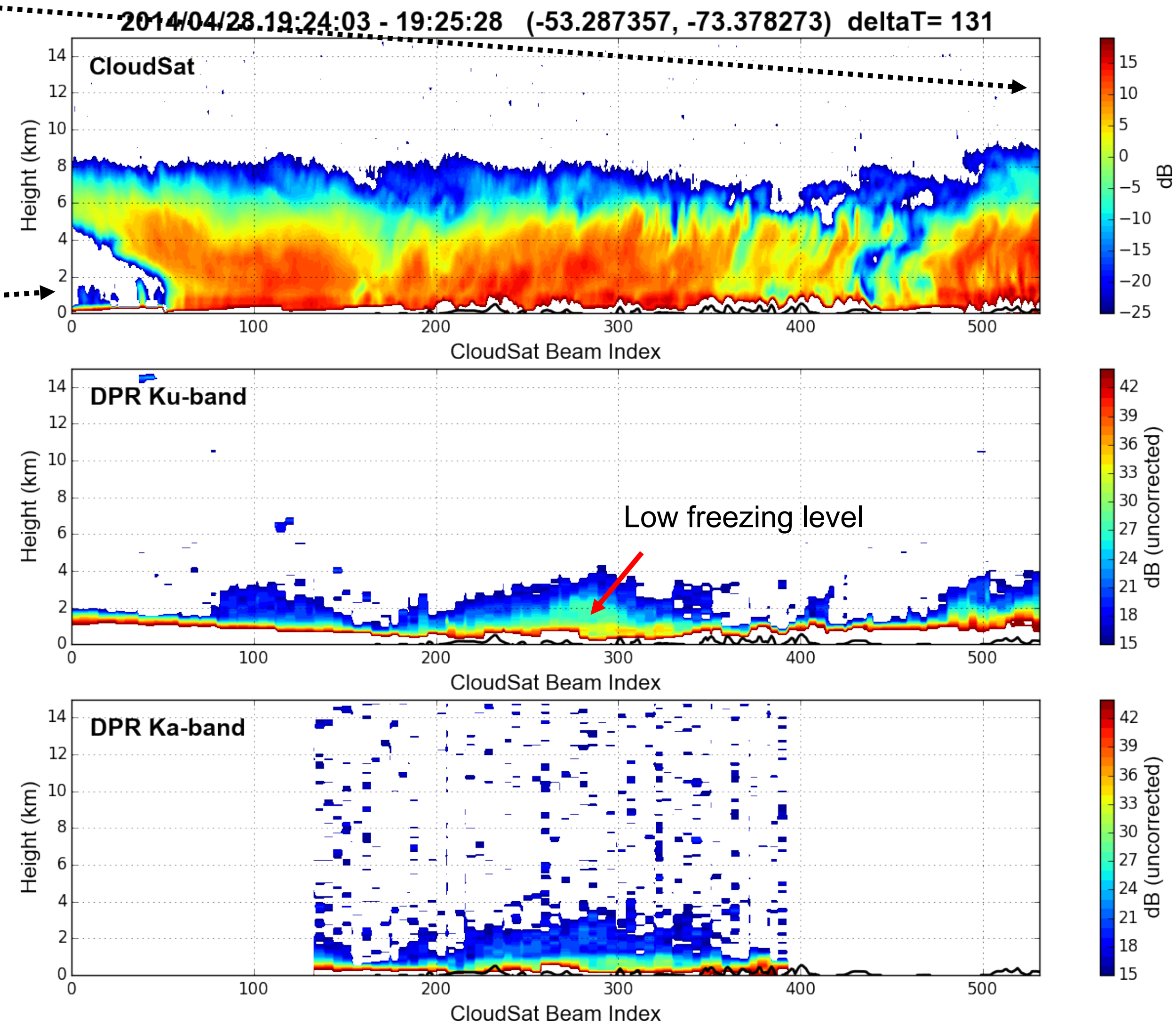
2014/07/21 0816 UTC
Hudson Bay, Canada, Mostly Convective



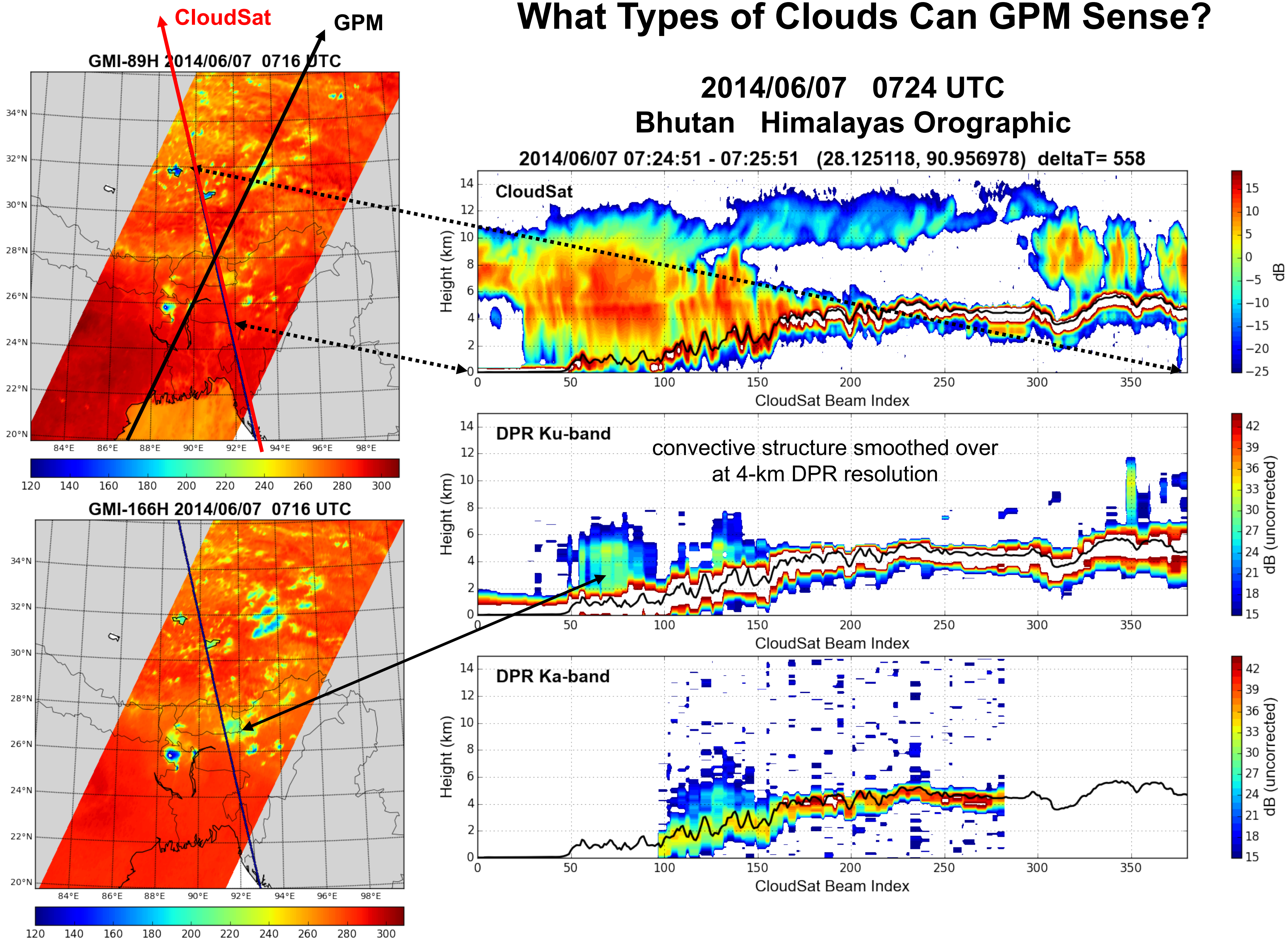
What Types of Clouds Can GPM Sense?

2014/04/28 1924 UTC
Edge of SW Chile Coast Cold Maritime Drizzle

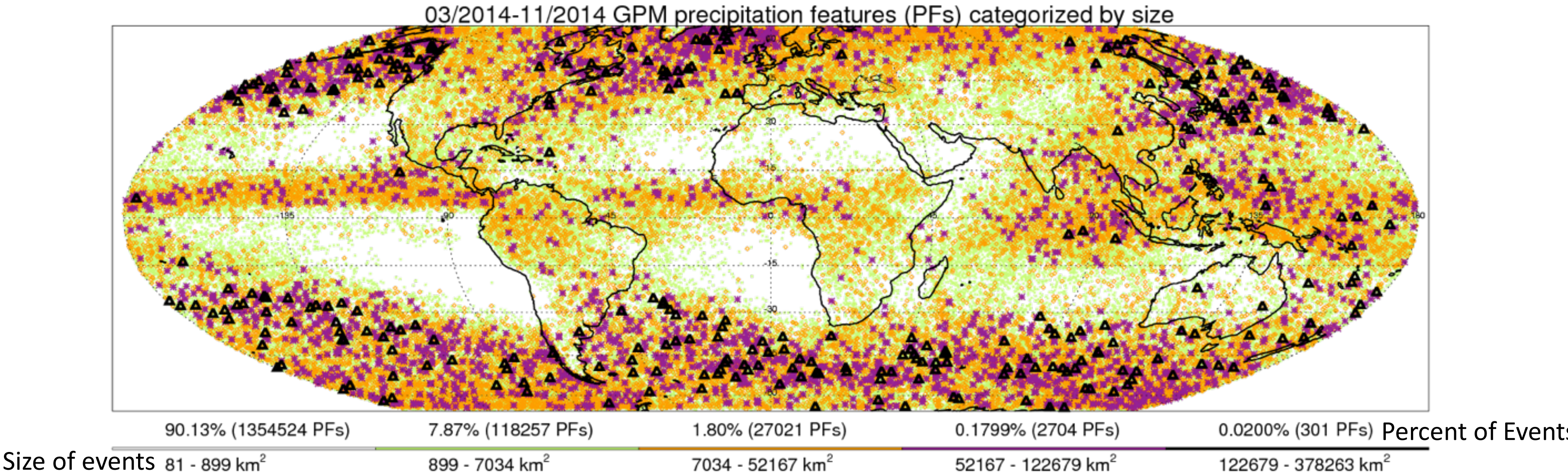




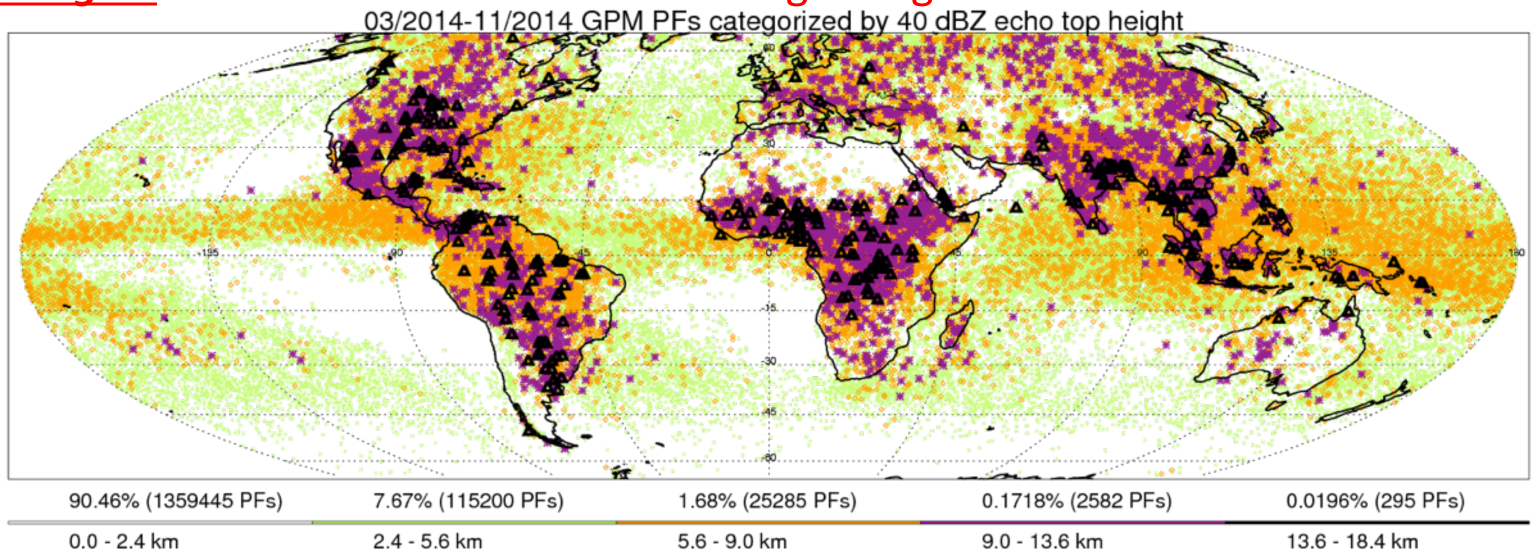
What Types of Clouds Can GPM Sense?



The most ***extensive*** precipitation systems are found over mid and high latitude ocean

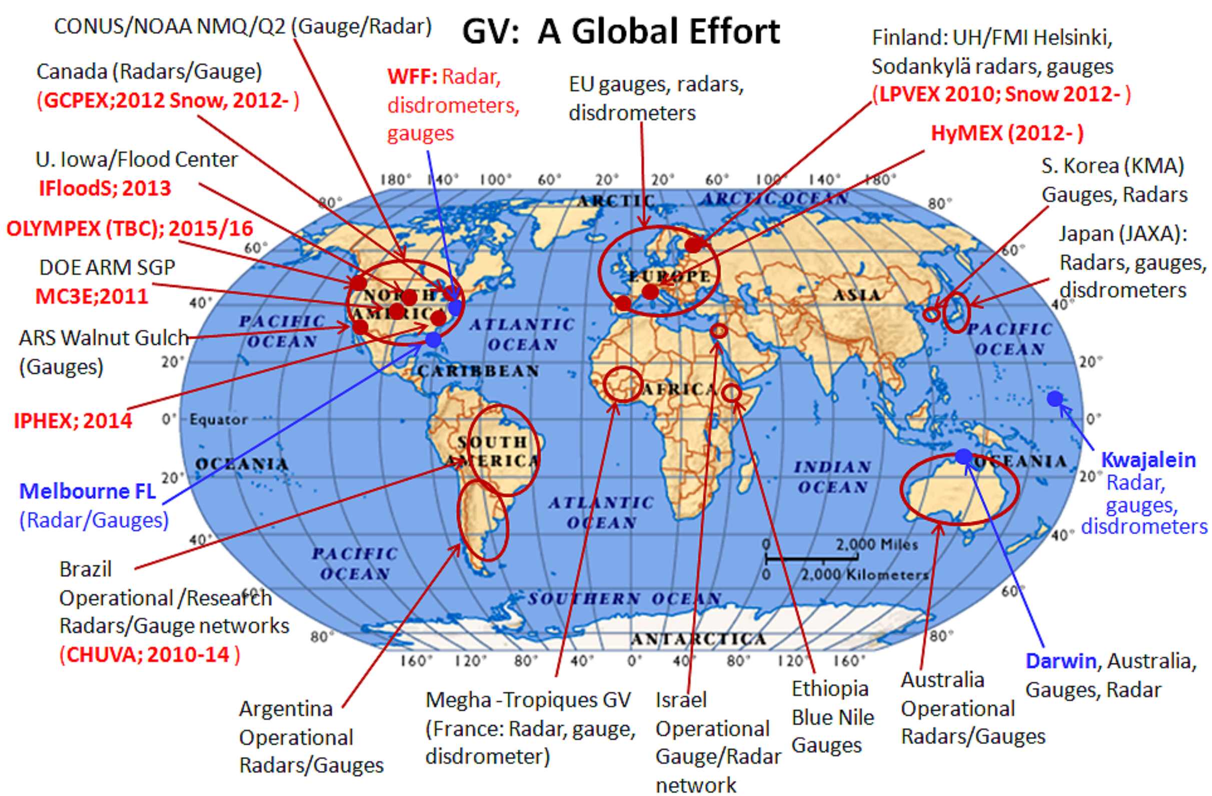


The ***strongest*** storms such as hailstorms and lightning storms are dominant over land



Credit: Chuntao Liu, Texas A&M – Corpus Christi

Field Campaigns led or co-led by GPM:



Olympic Mountains Experiment (OLYMPEX) Nov-Dec 2015

PI's: Lynn McMurdie, Bob Houze
Univ. of Washington
olympex.atmos.washington.edu

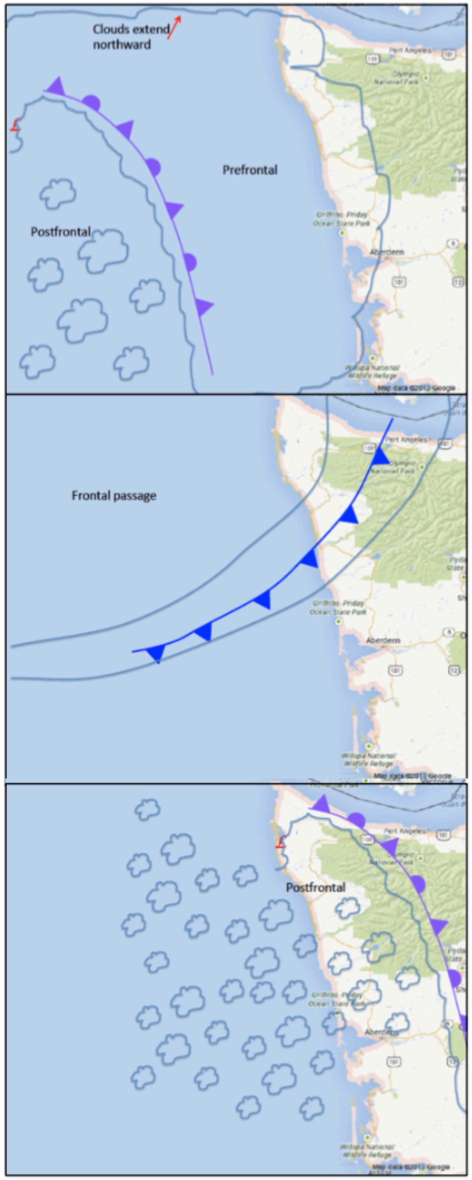
1) Physical validation of GPM satellite-based precipitation (rain and snow) estimation algorithms

2) Relation of mid-latitude frontal precipitation mechanisms and their modification by terrain to GPM rainfall estimation uncertainties

3) Quantifying the accuracy and uncertainty of the GPM precipitation data and impacts on hydrologic applications

4) Merger of numerical modeling and satellite observations to optimize precipitation estimation in hybrid weather monitoring systems of the future.

Doppler-on-Wheels



Pre-Frontal:
Warmer, steady rainfall

Frontal:
Transition from warmer to colder air mass,
less steady but more intense rainfall

Post-Frontal:
Cold air mass, showers and snow in mtns

Figure 6: Idealized depiction of the three sectors of a typical midlatitude cyclone. Cloud outlines as seen from satellite imagery shown in blue, standard frontal symbols shown in blue (cold front) and purple (occluded front): Prefrontal (top), Frontal (middle) and Post Frontal (bottom).

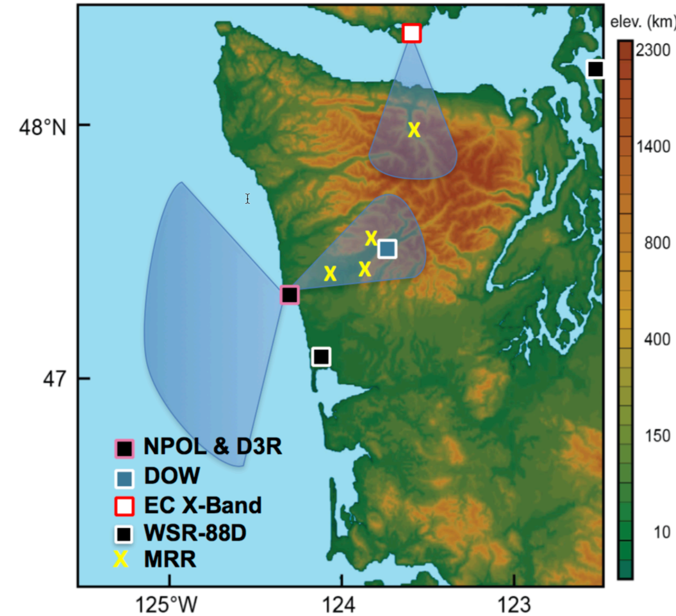
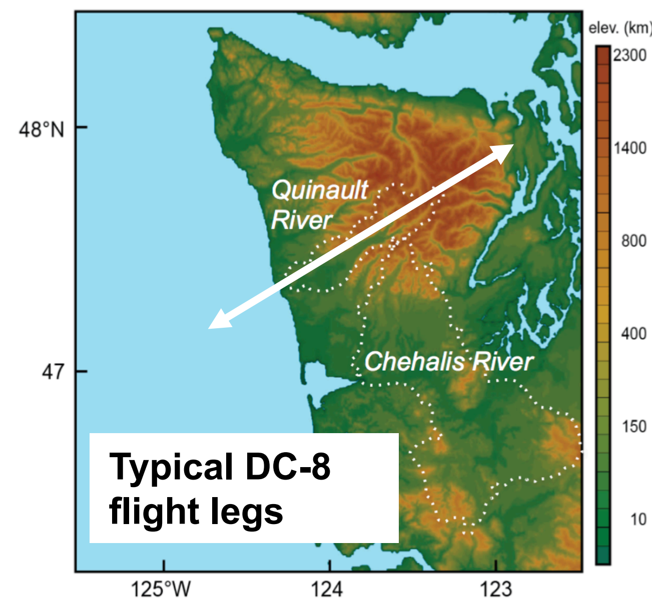


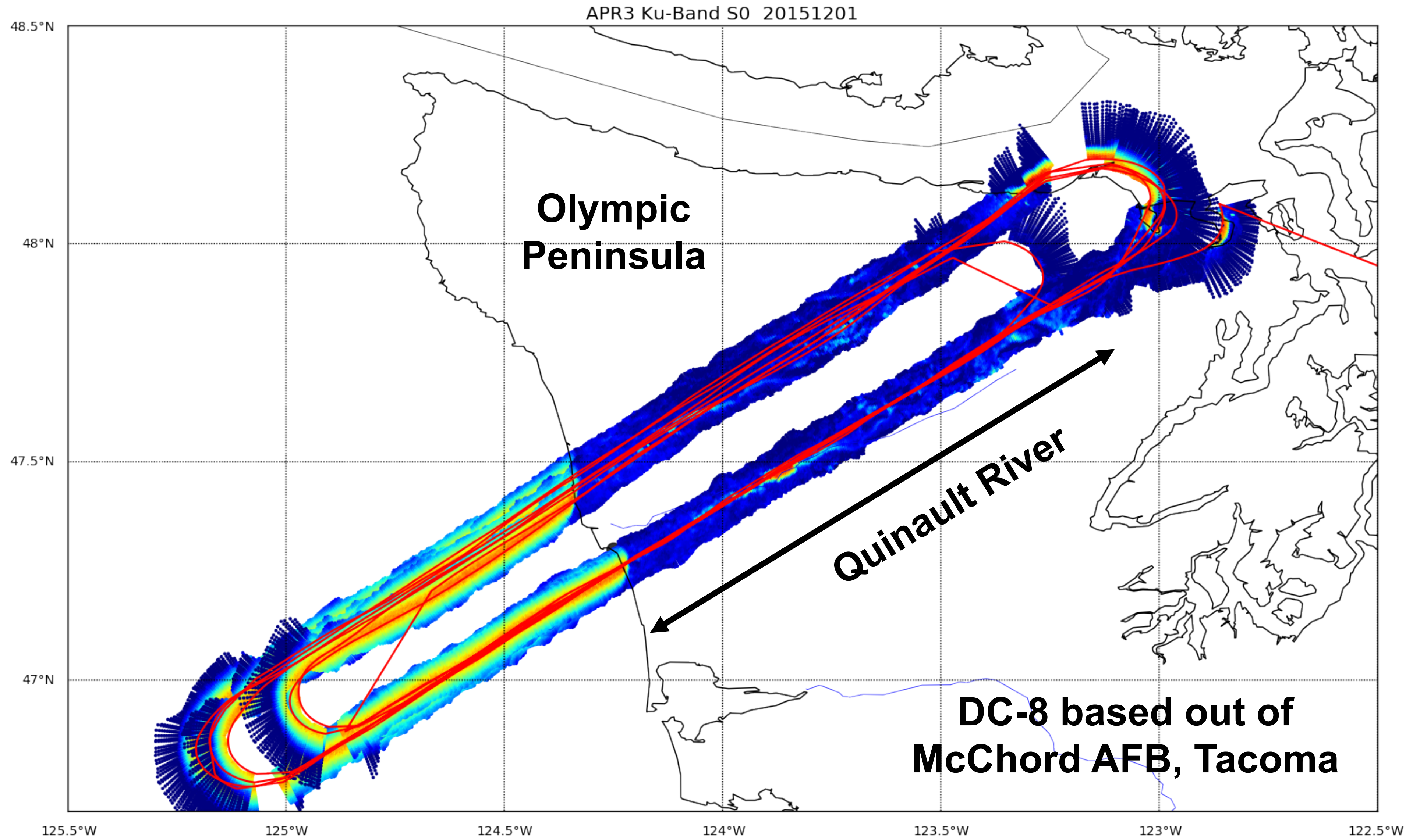
Figure 14: Locations of all the available ground radars for OLYMPEX and the RHI scanning regions for NPOL and EC X-band.



http://olympex.atmos.washington.edu

OLYMPEX APR-3 Radar onboard DC-8 Dec 1, 2015

APR-3 is the "airborne equivalent" of the GPM+CloudSat radars



OLYMPEX APR-3 Radar onboard DC-8 Dec 1, 2015

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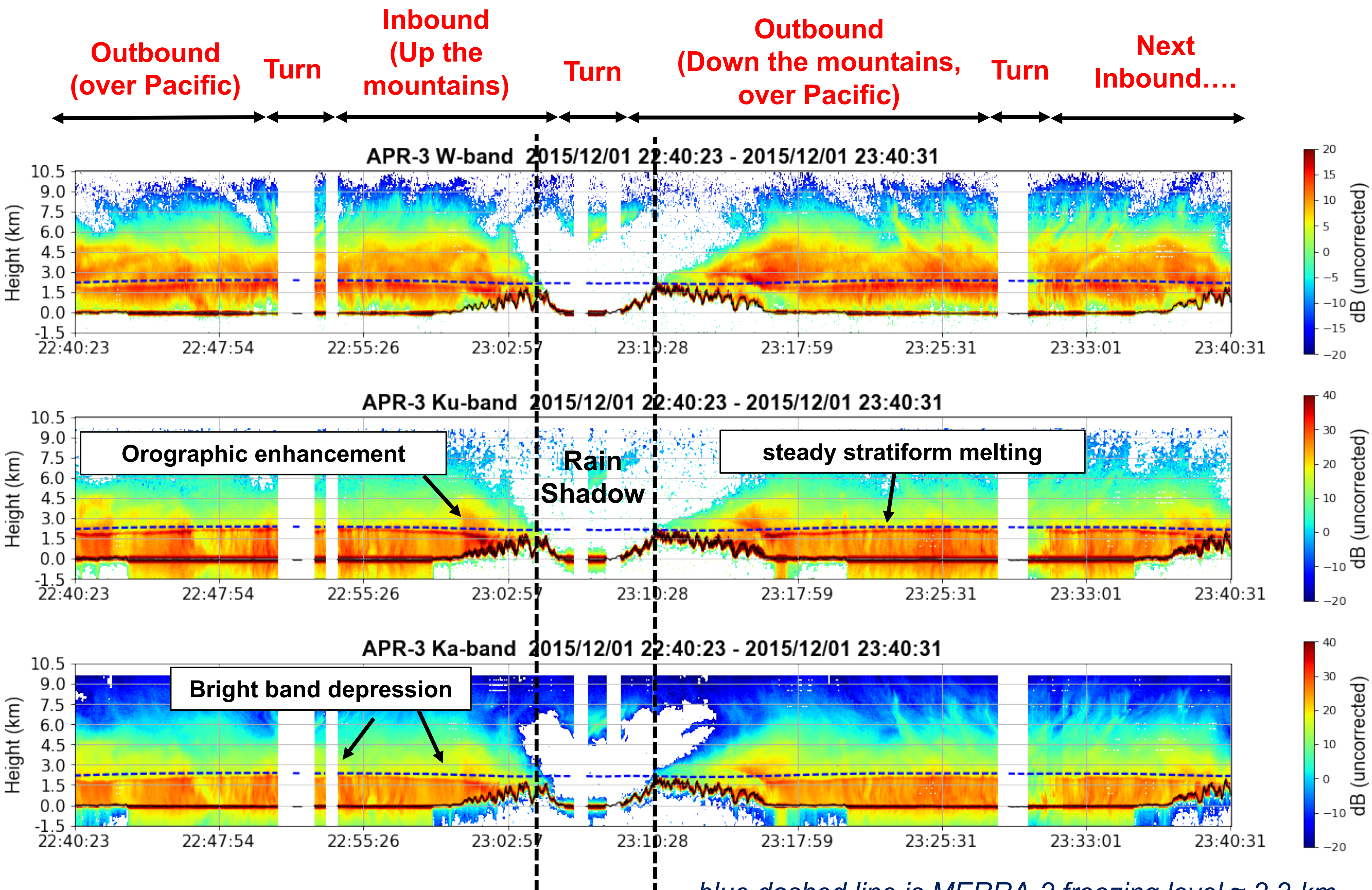

blue dashed line is MERRA-2 freezing level ≈ 2.2-km

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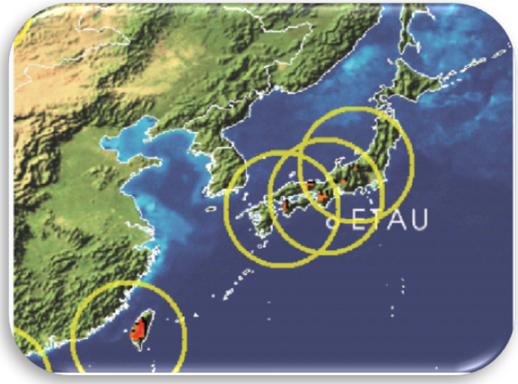
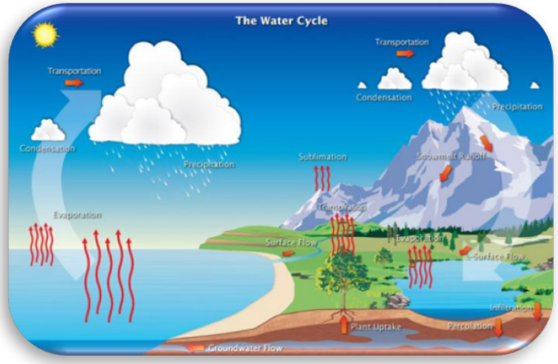
Science With Integrated Application Goals

Flooding

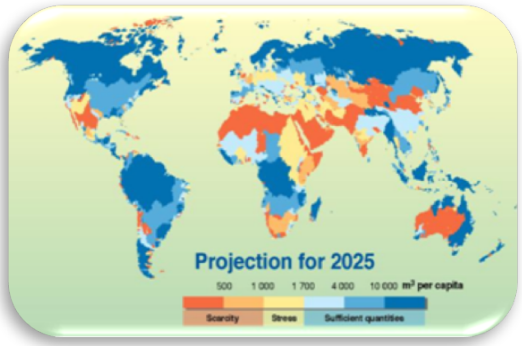
Landslides



Land surface and climate modeling



Freshwater Availability

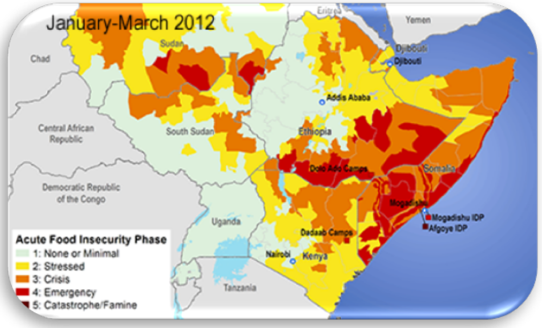


GPM Science Objectives:

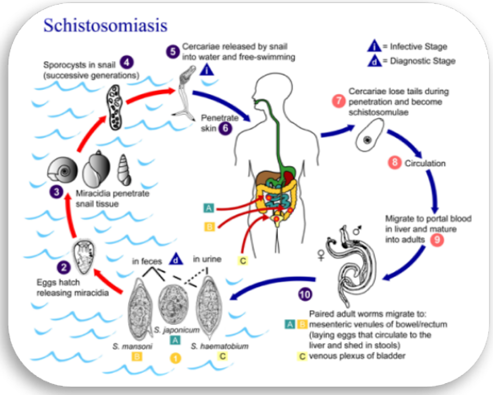
- **New reference standards for precipitation measurements from space**
- **Improved knowledge of water cycle variability and freshwater availability**
- **Improved numerical weather prediction skills**
- **Improved climate prediction capabilities**
- **Improved predictions for floods, landslides, and freshwater resources**

Extreme Events

Agriculture/Famine Early Warning



World Health



GPM Core Observatory & Data Summary

Spacecraft, Instrument, & Data Capture Status:

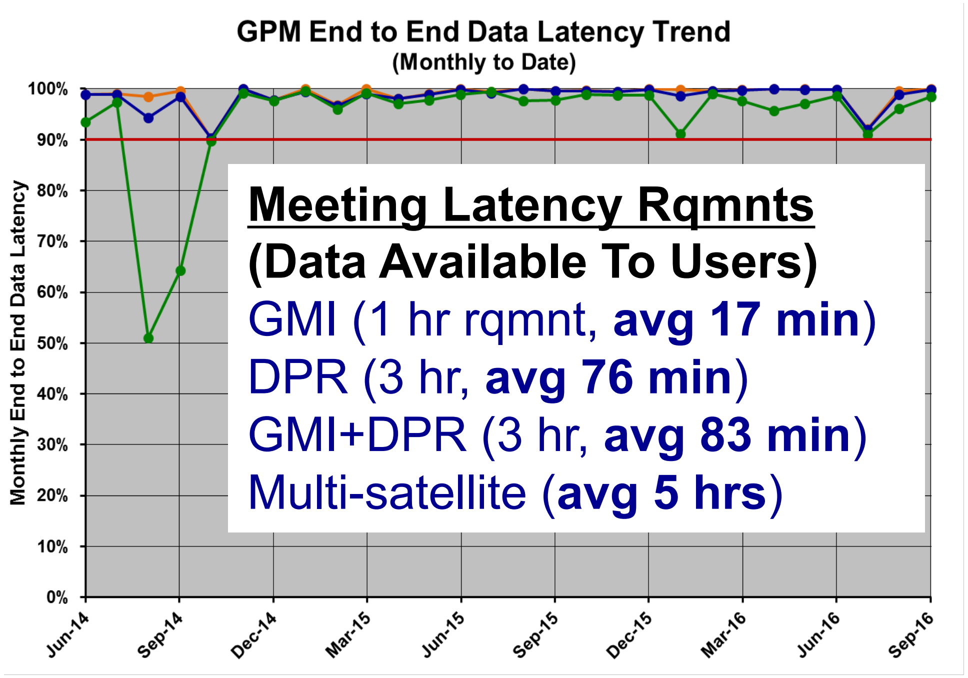
Green

Data Products:

- GPM Version 05 algorithms expected in 2017
- TRMM+GPM long-term record expected in 2018

GPM/TRMM data?

http://gpm.nasa.gov

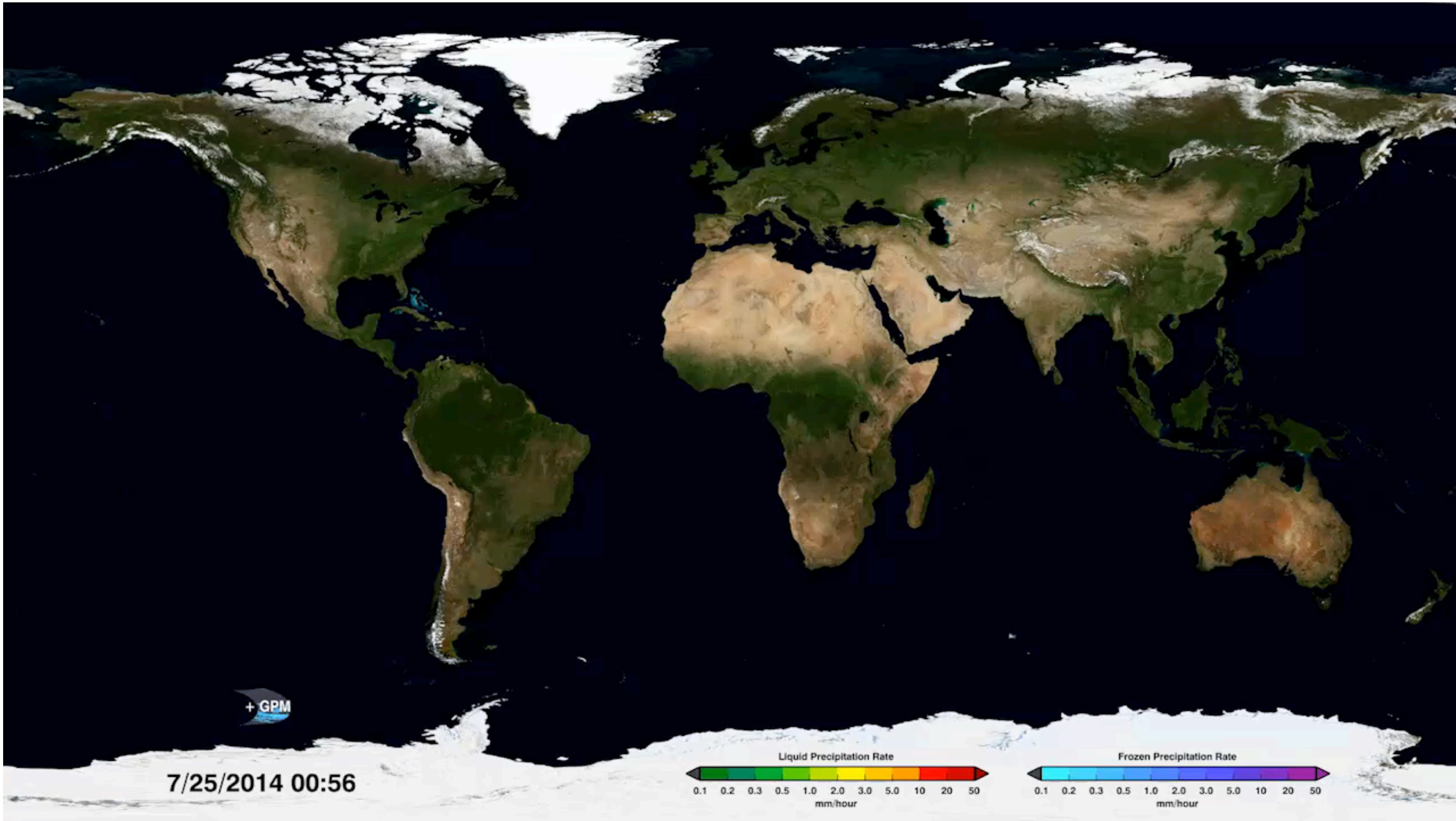


Fuel Predictions (w/controlled re-entry)

Prediction	Plus/Early	Mean/Nominal	Minus/Late
Nov 2016	08/2029 (15 years)	04/2035 (21 years)	10/2038 (24 years)

Fuel is unlikely to be the limiting factor for GPM

Integrated Multi-satellitE Retrievals for GPM (IMERG)

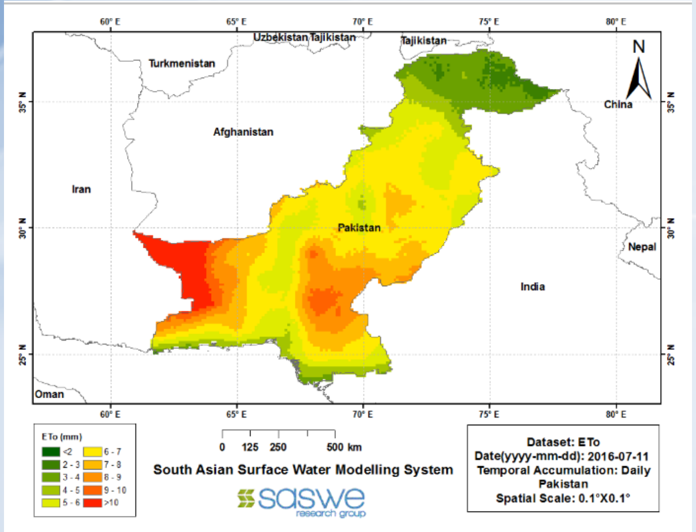


Integrated MultisatellitE (IMERG) Retrievals for GPM available (with a 4-5 hour latency from observations) every 30 min at a 0.1x0.1deg gridbox

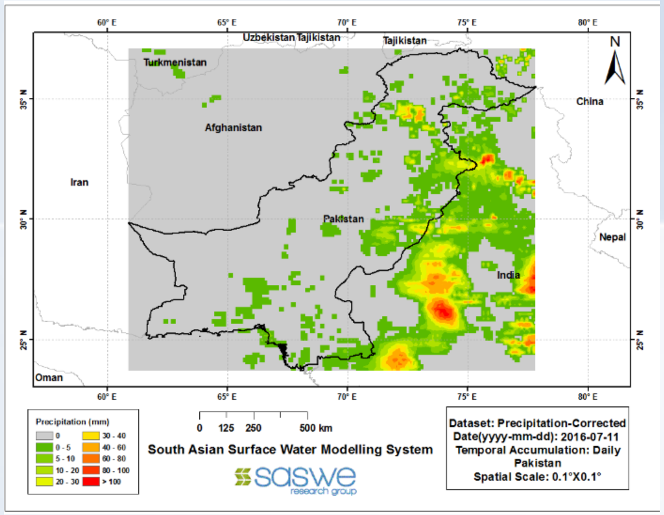
Real-world Application of IMERG

Stakeholder Agency: PCRWR (Federal)
Country: Pakistan; Goal: Water Conservation & Food Security
People Impacted: 700 farmers (2016) 10,000 (2017), 1 million (2018+)

- P-ET (irrigation demand) information pushed to farmers via SMS cellphone broadcast weekly to Pakistani farmers since April 2016.
- Precipitation from IMERG-late (dynamically corrected through a web-crawling system)
- ETo (FAO56) estimated using GFS and Satellite data at 10 km daily grids.
- Housed in UW South Asian Surface Water Modeling system (http://depts.washington.edu/saswe) + Stakeholder agency system (coming soon)
- Reference ETo validated against lysimeter tests for cash crops to advise farmers on ways to conserve water and increase crop yield.
- Project supported by UW and PCRWR



Eto Map for July 11 2016



Dynamically corrected IMERG-late map for July 11 2016

To make a burger, first you need 660 gallons of water ...

The diet of a typical American requires more than 1,000 gallons of water a day to produce. (Kirk McKoy / Los Angeles Times)

By Betty Hallock

JANUARY 27, 2014, 2:35 PM

California's severe drought has probably made a lot of us more aware of our water footprint, which is the amount of fresh water we use plus the amount used for the goods and services we consume every day.

The obvious contributors to our water footprint are washing clothes and dishes, cooking and bathing. But the biggest contributor to our water footprint is our diet.

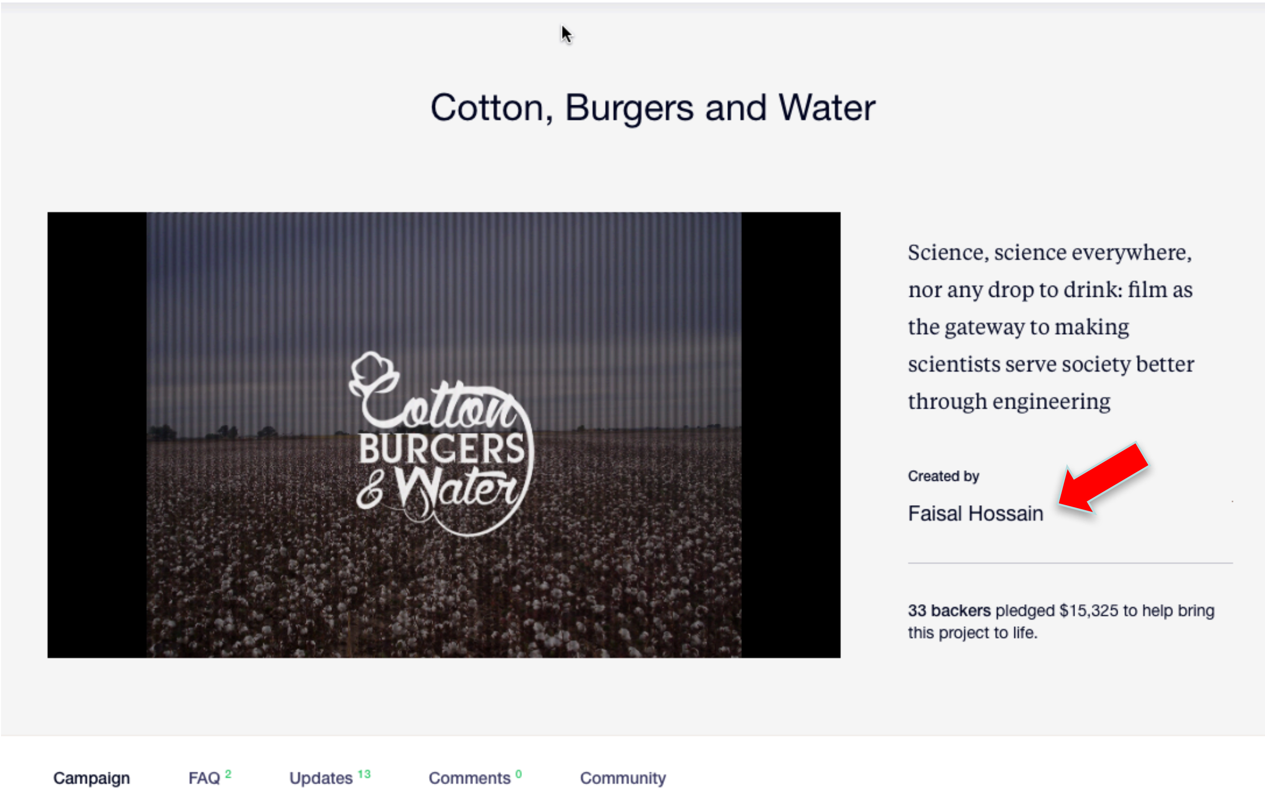
On average, the water we use in our households is about 98 gallons a day, says a U.S. Geological Survey. The industrial goods we use -- paper, cotton, clothes -- that's about another 44 gallons a day. But it takes more than 1,000 gallons of water a day per person to produce the food (and drinks) in the average U.S. diet, according to several sources. More than 53 gallons of water go into making 1 cup of orange juice, for example.

Food	#Gallons Req
1 slice bread	11
1# wheat	132
1 gal wine	1008
1 gal beer	68
1 gal milk	880
1# beef	1799
1 apple	18
1 cup apple juice	59
1 cup coffee	37

http://www.latimes.com/food/dailydish/la-dd-gallons-of-water-to-make-a-burger-20140124-story.html

Cotton, Burgers & Water tells us the story of a Pakistani cotton farmer and a researcher based in the US. Our two protagonists are from two different parts of the world and their surroundings are quite different and yet they are bound by a common theme - cotton and water.

KICKSTARTER



https://www.youtube.com/watch?v=rIWus8OVocc

https://www.kickstarter.com/projects/fhossain/cotton-burgers-and-water

Outline

Introduction to NASA's current precipitation and cloud radar systems

Orbital characteristics and precipitation constellation concept

Examples from different types of weather systems

Applications

Where the technology is leading for next-generation precipitation and cloud observing systems

Looking Ahead

During my presentation, GPM collected another 600,000 observations or so…..

There was 16 years of TRMM before GPM….

CloudSat, while hobbling, is still functioning....

POTENTIAL OF SMALL SATELLITE RADARS & EMERGING TECHNOLOGIES FOR OBSERVATIONS OF CLOUDS AND PRECIPITATION

Simone Tanelli

Contributors:

Gregory Sadowy, Eva Peral, Mauricio Sanchez-Barbetty, Shannon Statham, Ziad Haddad, Ousmane Sy, Eastwood Im, Stephen Durden, F. Joe Turk, Shannon Brown, Pekka Kangaslahti, Graeme Stephens, Al Nash,

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Nobuhiro Takahashi, ISEE/NICT

Lihua Li, GSFC

Almost all slides shown in this review package have been previously presented or published in public settings

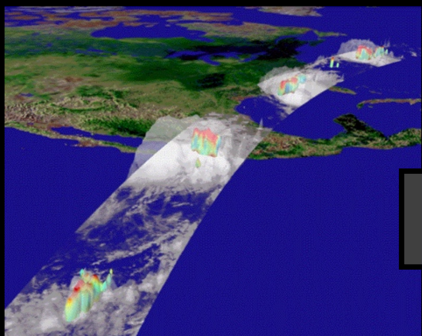
CaPPM concept working group meeting - Oct 2017, San Diego, CA, USA

Spaceborne "Tropospheric Radar" landscape (2017)

Pre-Decisional Information- For Planning and Discussion Purposes Only

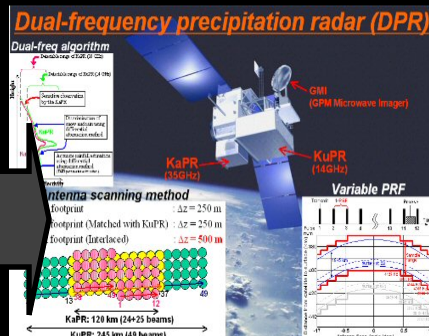
The 5 missions with Spaceborne C&P Radars

TRMM/PR – NICT/JAXA
Ku, Scanning , Tropical Rain



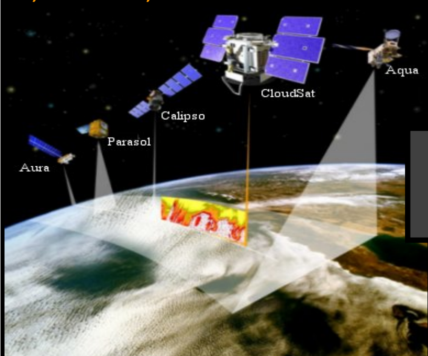
1997-2015

GPM/DPR – NICT/JAXA
Ku/Ka, Scanning, Precipitation



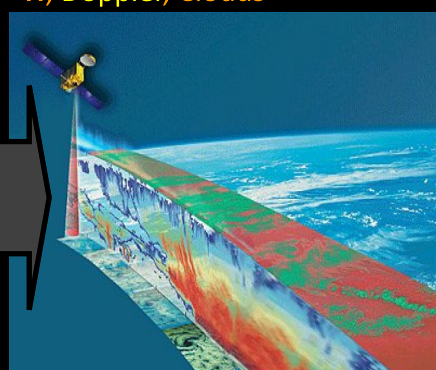
2014-Today

CloudSat/CPR
JPL/NASA/CSA
W, -30dBZ , Clouds



2006 -Today

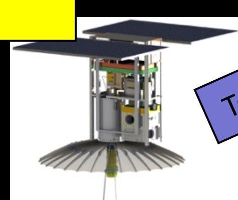
EarthCARE/CPR
NICT/JAXA
W, Doppler, Clouds



NET 2019

Next up: Launch NET Mar 2018

RainCube
JPL/NASA InVEST Tech Demo
Ka, Precipitation, 6U CubeSat



Temporal

NET 2018

Some concepts under development or proposed by the international community

PHDsat (2002)
Ka/Ku, Scanning Doppler

SnowSat / PPM
W/Ka, Doppler

Temporal

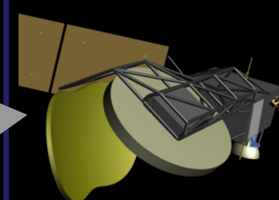
NIS (2004)
W/Ka, Scanning,
Doppler, GEO

Dynamics

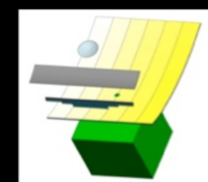
StormSat on ISS (2016)
Ka/, DPCA Doppler
Wide Swath Winds
W Conical Scanning

ES DS 2007:
ACE Mission Concept Radar
Ka/W, Doppler, Scanning (Ka)

ACERAD

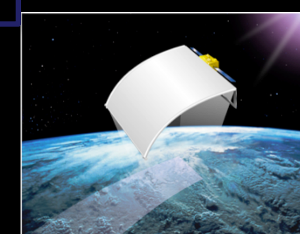


ReflectArray ACE radar



Water Vapor in Cloud

VIPR
183 GHz line
Water Vapor



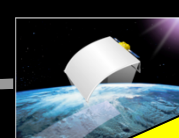
StereoRadar
Dual Beam

Precip Mapping

Scanning W on ISS
W Scanning
Wide Swath
Ka/Ku Scanning

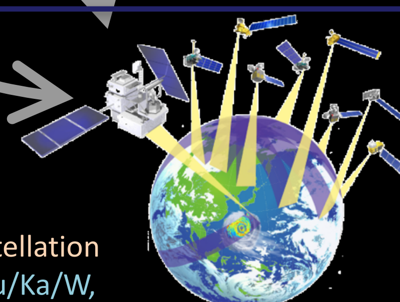
ED DS 2017:
CaPPM 3CPR
Ku/Ka/W, all Doppler,
all Scanning

IIP 2016: MASTR
Ku/Ka/W, Scanning,
SmallSat



New Entry

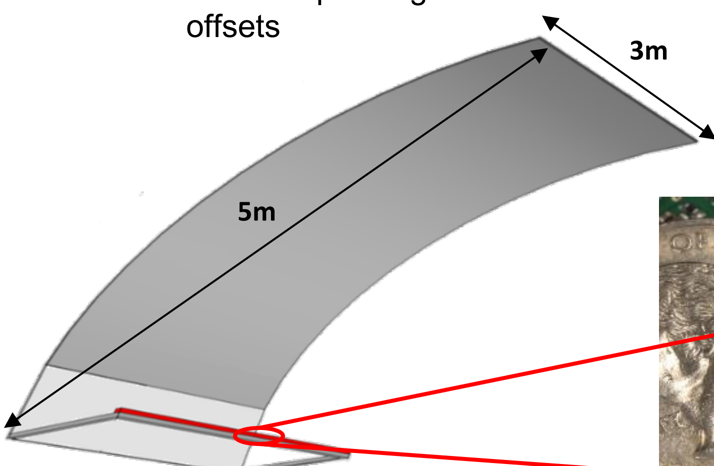
ES DS 2017:
Radar Constellation
Core S/C: Ku/Ka/W,
Trains: RainCube



3-band Cloud and Precipitation Radar (3CPR)

- Cylindrical parabolic antenna provides high gain and cross-track scanning capability at Ku-band (13.4 GHz), Ka-band (35.6 GHz) and W-band (94 GHz)
- No need for heavy, lossy slotted waveguide arrays (as used in GPM)
- Some issues to be addressed including:
  - Reflector illumination over scan
  - Pattern / pointing distortion due to feed point offsets

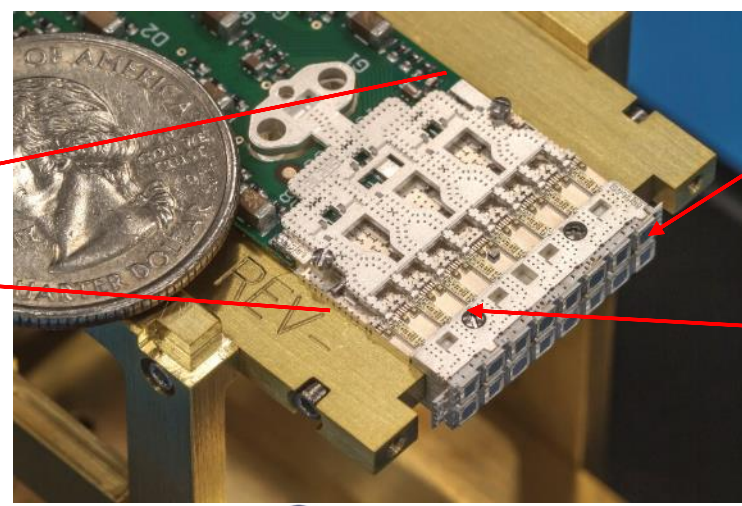
- Feed technology exists for Ku and Ka bands
  - Ka-band TR 8-pack demo at JPL
  - More recent Ka-band developments from GSFC / NGES (*Racette, et al*)
- Focus on new technology required to enable W-band scanning
- NASA ESTO Instrument Incubator program funding development of sub-scaled reflector with electronically-scanned W-band feed array

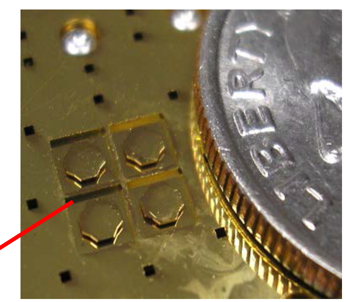


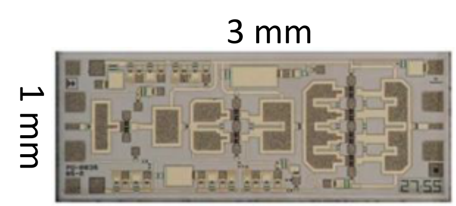
Cylindrical parabolic reflector with active array linear feeds for Ku/Ka/W band

Only W-band shown

Scanning Array Tile





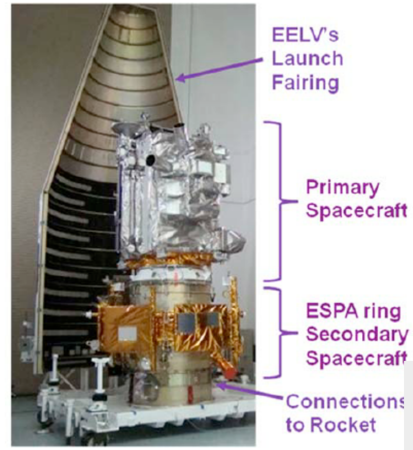


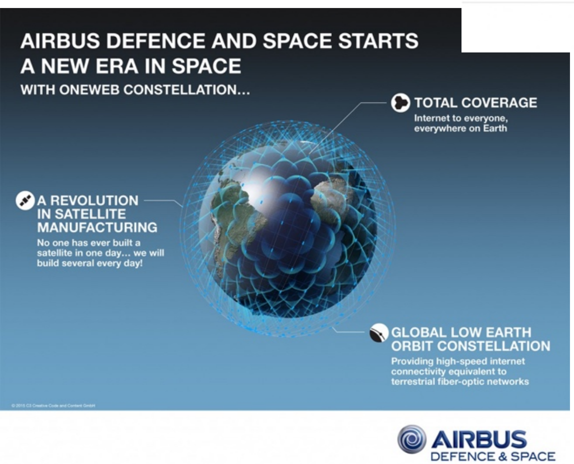
GaN TR MMICs

Raytheon

NUVOTRONICS

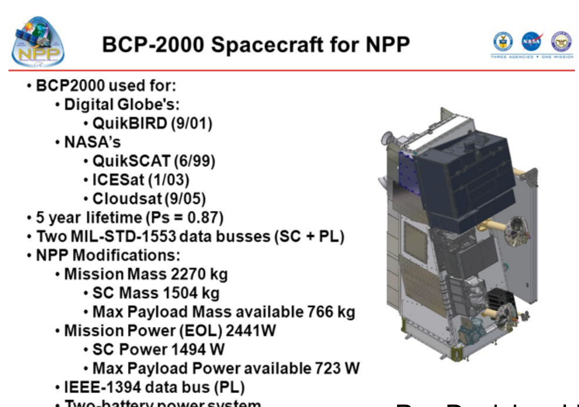
Examples of Small Satellites

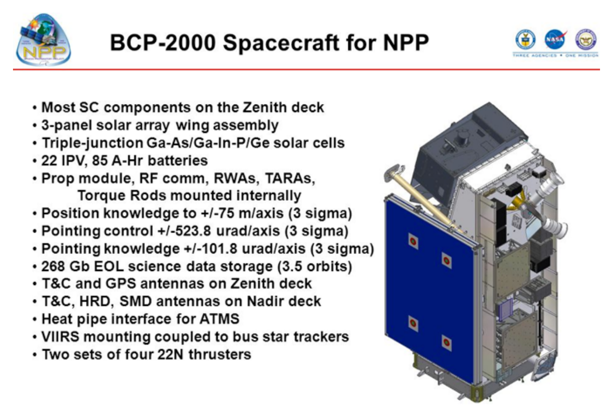




50-200 W Payloads

300-700 W Payloads



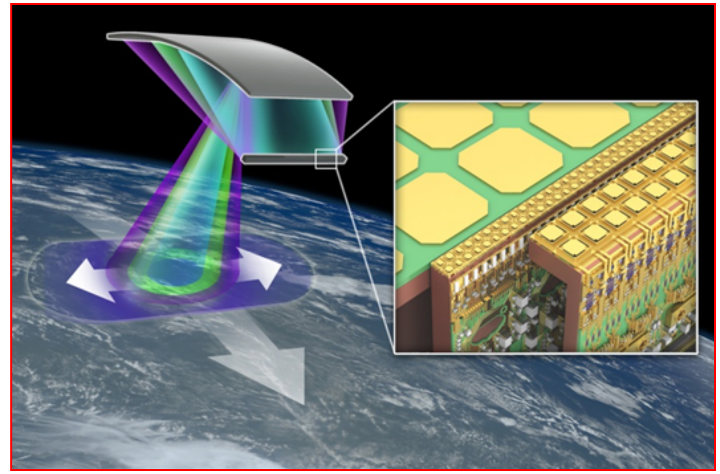


All images on this slide are from the web. Not provided by the respective vendors upon explicit request.
These are only examples to illustrate the general class.

Multi-Application SmallSat Tri-Band Radar (MASTR)

Clouds and Precipitation

- Addressed separately by active instruments so far (i.e., TRMM, GPM & RainCube at Ku and Ka band, vs CloudSat and EarthCARE at W-band).
- Three-frequency single aperture radar enables holistic view of the cloud-precipitation process
  - e.g., J. Leinonen, et al. 2014, ACE decadal survey mission concept (Ka- / W-band), Cloud and Precipitation Processes Mission (CaPPM) concept. (Ku-, Ka-, W-band) responses to Decadal Survey 2017.
- Technology maturity over the last decade enables scanning at W-band as well as tri-band integration



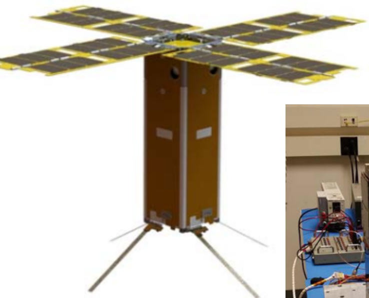
Altimetry and Scatterometry

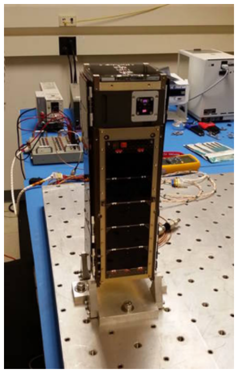
- Once an RF front end for a Ku/Ka-/W- real aperture scanning radar is available, making it suitable for other applications is possible.
  - For altimetry it is "only" a matter of opening up the bandwidth ;
  - For scatterometry more significant changes are necessary, but still possible (i.e., changing viewing geometry and tightening calibration requirements)

MASTR is tri-band (Ku-, Ka-, W-band) **scalable** phased array radar.
Designed to work as a Cloud and Precipitation Radar,
an Altimeter, or a Scatterometer (in a Spinning platform).
A modular, scalable architecture enables technology maturation via an airborne **demonstration.** A compact profile allows multiple implementations depending of mission requirements, power, and budget available (ranging from SmallSats to large platforms).

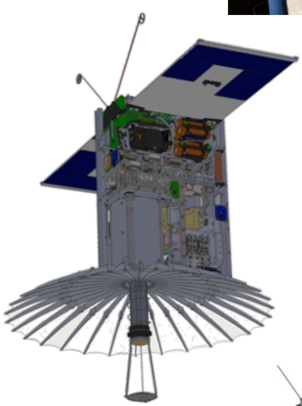
Courtesy: M. Sanchez-Barbetty

…and the Cubesats

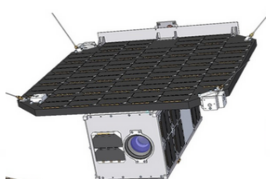


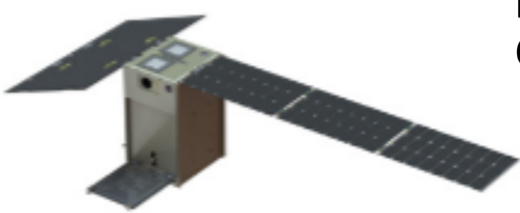


Many 3U and smaller cubeSats have been launched successfully and demonstrated high precision formation flying. Most so far have limited Earth Science value, but IceCube has demonstrated sub-mm radiometry. TROPICS incoming.



Few 6U have launched, but many in development, several with specific Earth Science remote sensing missions (TEMPEST—D, MASC, RainCube, etc,)

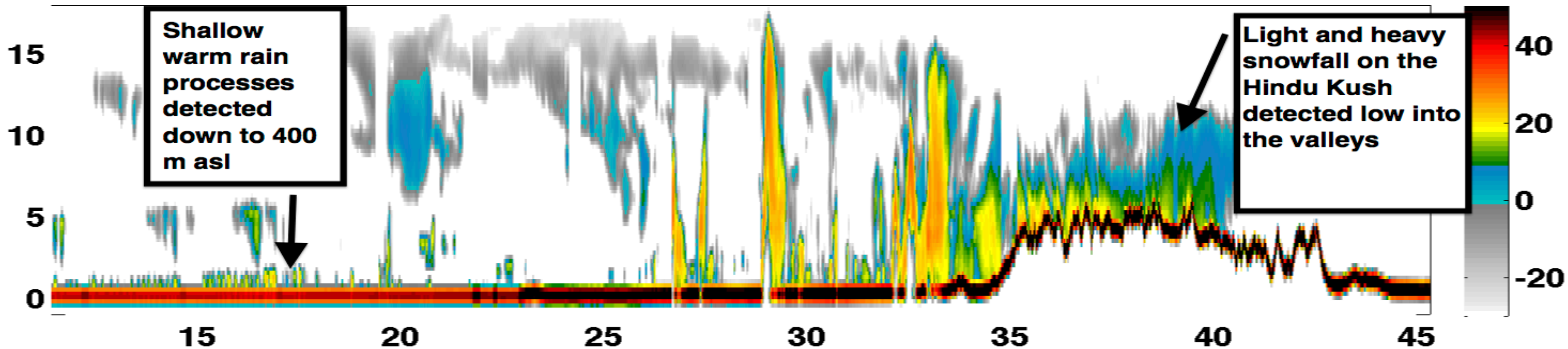




Even fewer larger than 6U have launched, but several planned or in development spanning 8, 12 and 16 U. Concepts also for larger ones.

What is RaInCube?

Constellation of Ka-band *Radar In Cubesat* that will *profile precipitation* down to near-surface, at all latitudes and at various sub-daily scales, to provide the temporal resolution in precipitation profiling that is necessary to *validate and improve weather and climate models*.

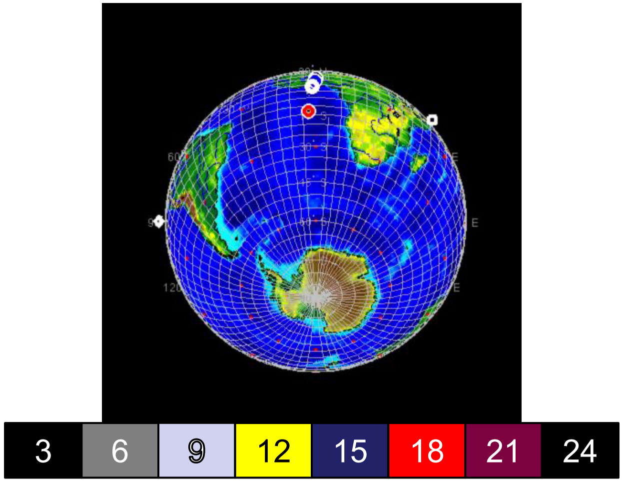


Radar performance requirements

- Horizontal resolution: **5 km**
- Range resolution: **250 m**
- Sensitivity: **10 dBZ** requirement (0 dBZ goal)
- Range sidelobe suppression **better than 70 dB @ 500m**

Constellation of 4-6 CubeSats on 2-6 orbital planes in LEO

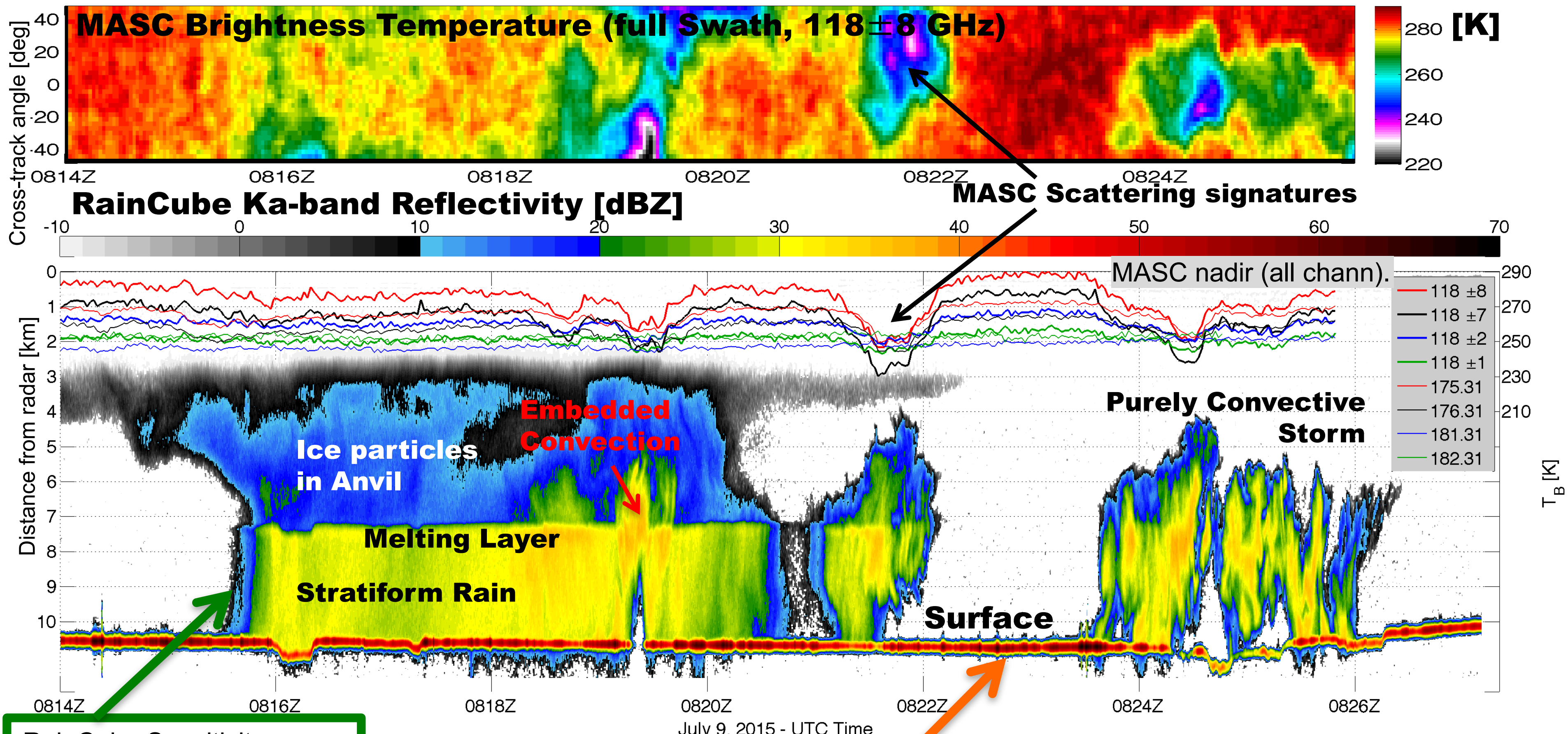
- Observe the same region at different times of the day during the same month
- Observe the same cloud at very short intervals (15-60s)



Airborne C&PR role in NASA

Radar-Sounder observations of precipitation in PECAN

Pre-Decisional Information- For Planning and Discussion Purposes Only



RainCube Sensitivity and Resolution : confirmed

RainCube Pulse Compression performance: confirmed

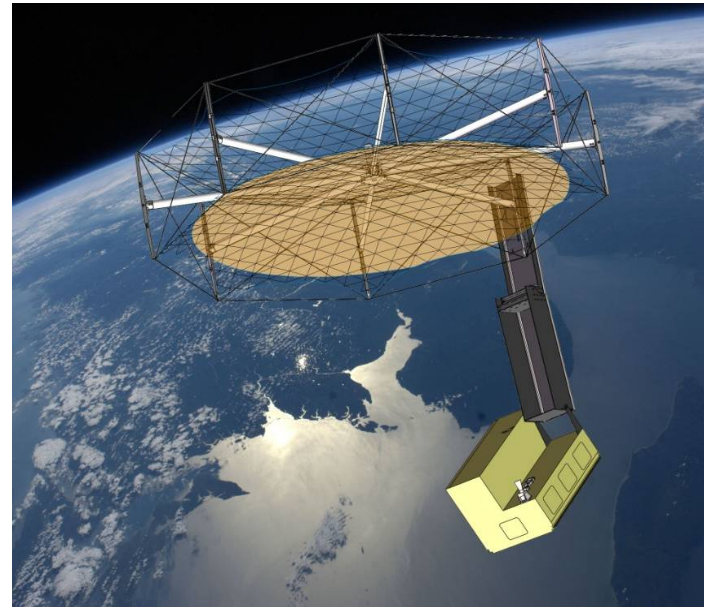
- No faults or glitches from first flight to last flight.
- Fine calibration and science analysis: in progress.
- Coordinated operations with ground based weather radars

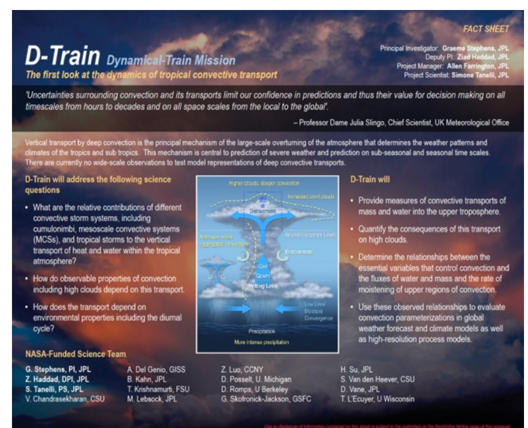
Acknowledging:

- AFRC: excellent coordination and rapid implementation
- PECAN Science Leadership: outstanding flexible and creative collaboration
- OU ARRC: coordinated deployment of X-band ground based weather radars
- Weather Focus Area Leads: additional flight hours to PECAN for RainCube and MASC

From Tech Demo to Science Mission

- The RainCube Tech Demo in a 6U CubeSat adopts a 0.5 m antenna.
- In order to achieve the horizontal resolution of 5 km a 0.8 m antenna is necessary.
- A 1-m antenna for cubesats is being implemented under ESTO ACT program by JPL & Tendeg.
- Larger deployable antenna designs viable for Ka-band are also being studied.
- Alternatively, the miniKaAR can be implemented within an “ESPA-class” SmallSat with a 0.9-m rigid, non-deployable, reflector and very large margins on volume, power and mass.
- In the end, what size antenna is truly necessary depends on the type of convection that is targeted.





FACT SHEET

D-Train *Dynamical-Train Mission*

The first look at the dynamics of tropical convective transport

Principal Investigator: **Graeme Stephens, JPL**
Deputy PI: **Ziad Haddad, JPL**
Project Manager: **Allen Farrington, JPL**
Project Scientist: **Simone Tanelli, JPL**

'Uncertainties surrounding convection and its transports limit our confidence in predictions and thus their value for decision making on all timescales from hours to decades and on all space scales from the local to the global'.

– Professor Dame Julia Slingo, Chief Scientist, UK Meteorological Office

Vertical transport by deep convection is the principal mechanism of the large-scale overturning of the atmosphere that determines the weather patterns and climates of the tropics and sub tropics. This mechanism is central to prediction of severe weather and prediction on sub-seasonal and seasonal time scales. There are currently no wide-scale observations to test model representations of deep convective transports.

D-Train will address the following science questions

- What are the relative contributions of different convective storm systems, including cumulonimbi, mesoscale convective systems (MCSs), and tropical storms to the vertical transport of heat and water within the tropical atmosphere?
- How do observable properties of convection including high clouds depend on this transport.
- How does the transport depend on environmental properties including the diurnal cycle?

D-Train will

- Provide measures of convective transports of mass and water into the upper troposphere.
- Quantify the consequences of this transport on high clouds.
- Determine the relationships between the essential variables that control convection and the fluxes of water and mass and the rate of moistening of upper regions of convection.
- Use these observed relationships to evaluate convection parameterizations in global weather forecast and climate models as well as high-resolution process models.

NASA-Funded Science Team

G. Stephens, PI, JPL	A. Del Genio, GISS	Z. Luo, CCNY	H. Su, JPL
Z. Haddad, DPI, JPL	B. Kahn, JPL	D. Posselt, U. Michigan	S. Van den Heever, CSU
S. Tanelli, PS, JPL	T. Krishnamurti, FSU	D. Romps, U Berkeley	D. Vane, JPL
V. Chandrasekharan, CSU	M. Lebsock, JPL	G. Skofronick-Jackson, GSFC	T. L'Ecuyer, U Wisconsin

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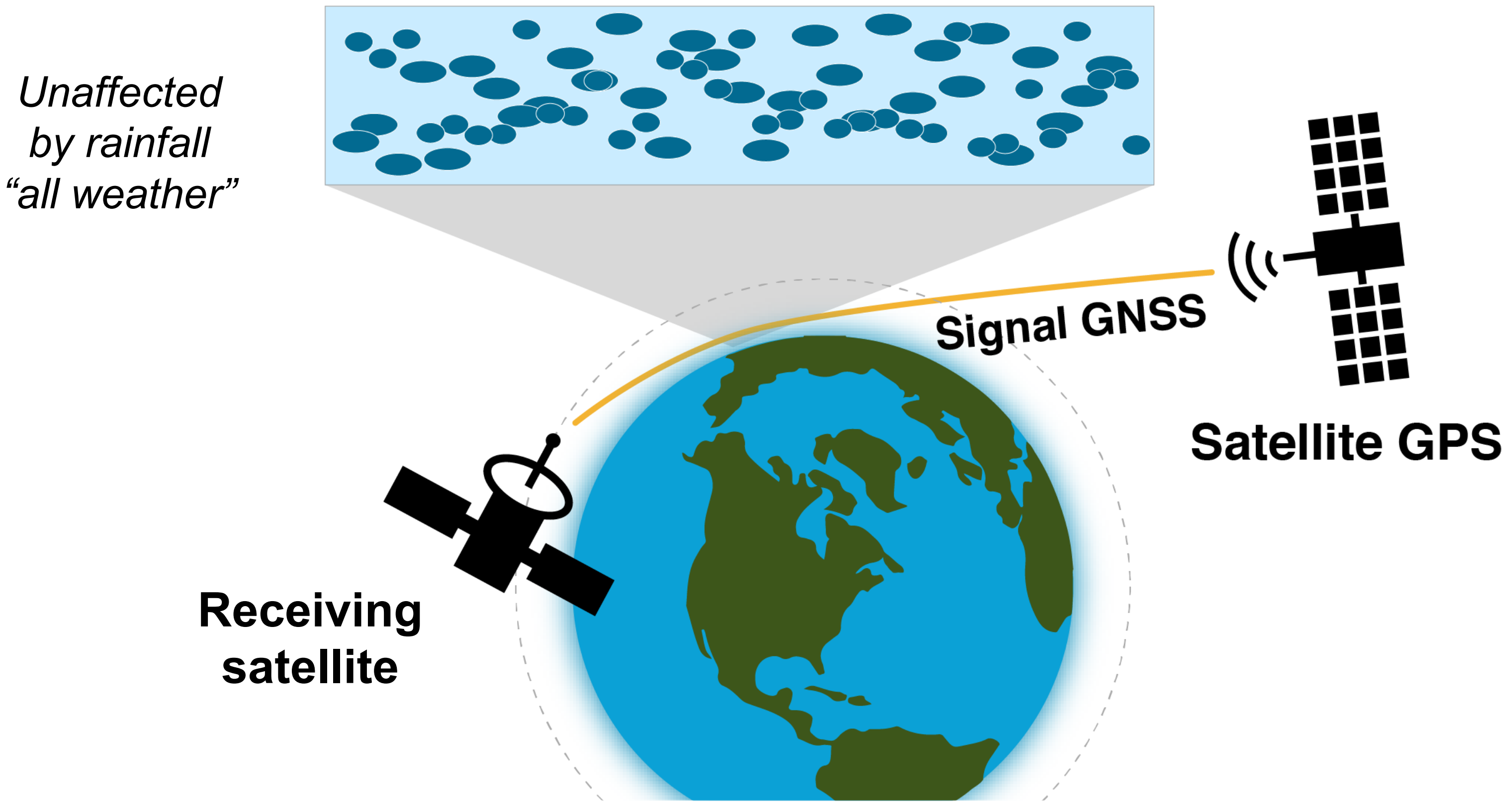
Global Navigation Satellite System (GNSS) Radio Occultations (RO)

- Current RO observing system came of age in 2006 with the deployment of the 6-satellite COSMIC constellation, COSMIC-2A to follow in 2017
- Provide high-resolution vertical refractivity structure from which vapor structure is inferred; coarse horizontal (limb type measurement)
- Have demonstrated very high impact when assimilated into forecast models

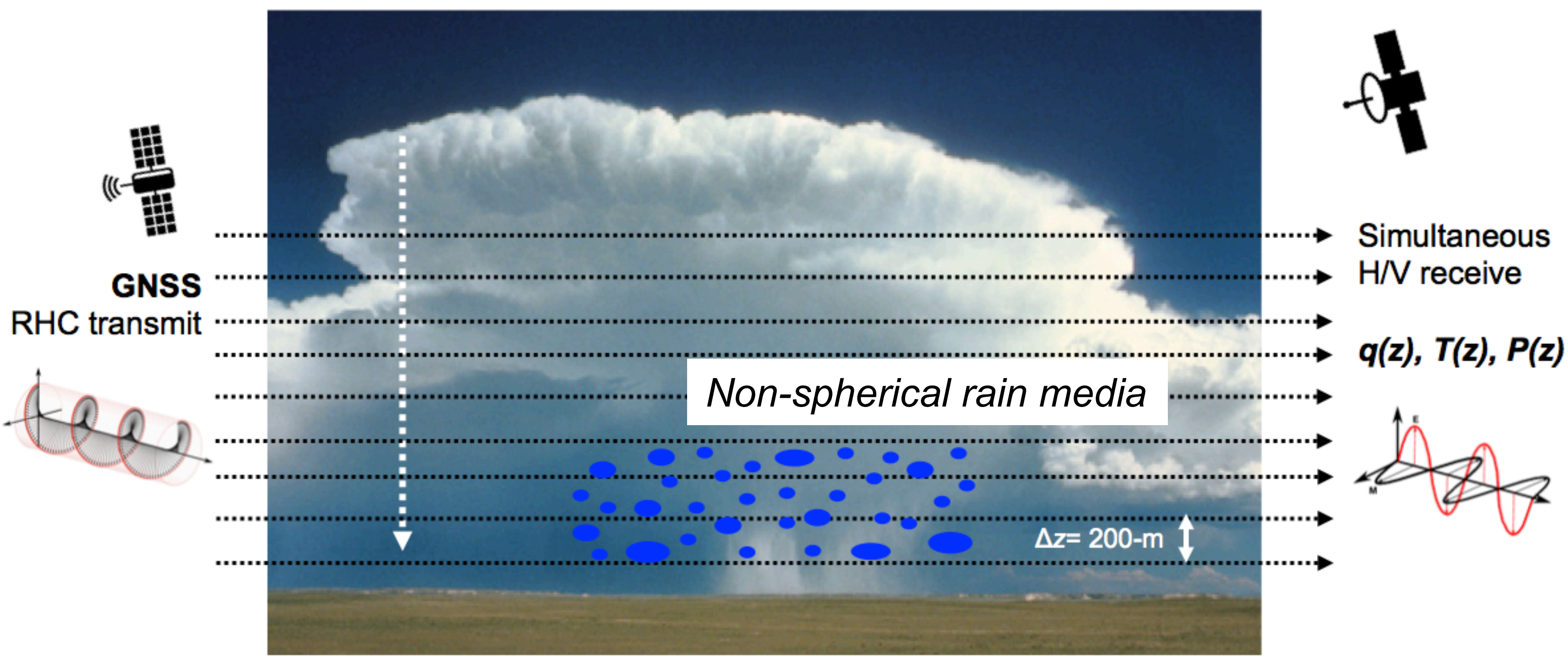


Polarimetric Radio Occultations Concept (JPL/UAB-Spain)

Typical GPS signals are transmitted in RHCP two bands near 1.4 GHz….essentially, no loss of intensity even when passing through heavy precipitation

However, the same propagation through heavy precipitation induces a *cross-polarized* component, measured as a differential phase delay by accurate GPS clocks.

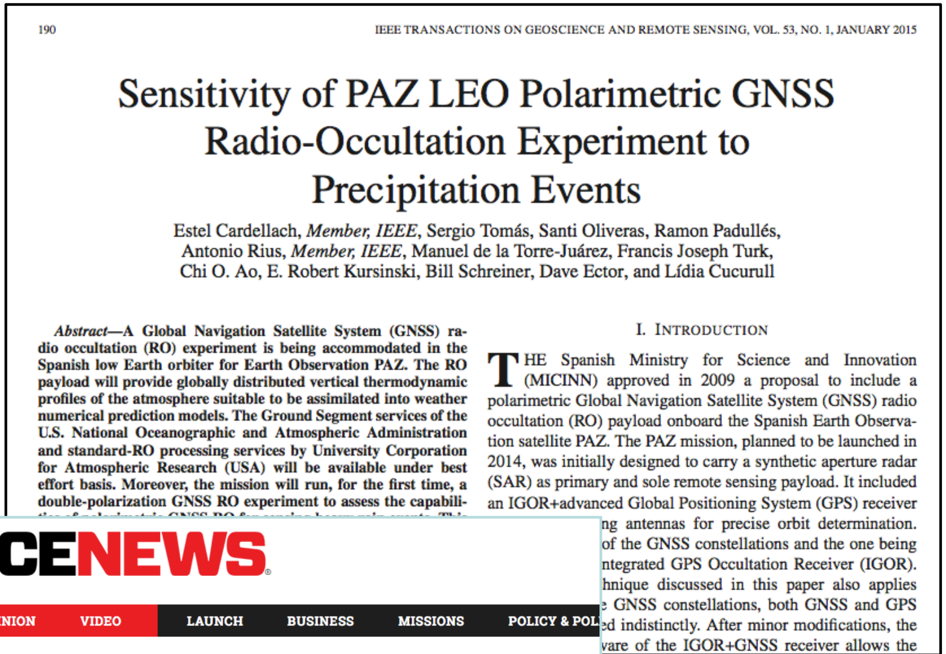
If feasible, such a measurement has potential to extend the capabilities of normal RO, with *simultaneous* measurements of the profile of water vapor (q) and temperature (T), with an **indication** of precipitation intensity along each ray.



Radio Occultations Through Heavy Precipitation (ROHP) Demonstration

Secondary payload on PAZ (Spanish X-band SAR)

Space-X Falcon-9 launch scheduled for late Jan 2018



Sensitivity of PAZ LEO Polarimetric GNSS Radio-Occultation Experiment to Precipitation Events

Estel Cardellach, *Member, IEEE*, Sergio Tomás, Santi Oliveras, Ramon Padullés, Antonio Rius, *Member, IEEE*, Manuel de la Torre-Juárez, Francis Joseph Turk, Chi O. Ao, E. Robert Kursinski, Bill Schreiner, Dave Ector, and Lídia Cucurull

***Abstract*—A Global Navigation Satellite System (GNSS) radio occultation (RO) experiment is being accommodated in the Spanish low Earth orbiter for Earth Observation PAZ. The RO payload will provide globally distributed vertical thermodynamic profiles of the atmosphere suitable to be assimilated into weather numerical prediction models. The Ground Segment services of the U.S. National Oceanographic and Atmospheric Administration and standard-RO processing services by University Corporation for Atmospheric Research (USA) will be available under best effort basis. Moreover, the mission will run, for the first time, a double-polarization GNSS RO experiment to assess the capabili-**

I. INTRODUCTION

THE Spanish Ministry for Science and Innovation (MICINN) approved in 2009 a proposal to include a polarimetric Global Navigation Satellite System (GNSS) radio occultation (RO) payload onboard the Spanish Earth Observation satellite PAZ. The PAZ mission, planned to be launched in 2014, was initially designed to carry a synthetic aperture radar (SAR) as primary and sole remote sensing payload. It included an IGOR+advanced Global Positioning System (GPS) receiver ...ng antennas for precise orbit determination. ...of the GNSS constellations and the one being ...ntegrated GPS Occultation Receiver (IGOR). ...hnique discussed in this paper also applies ...e GNSS constellations, both GNSS and GPS ...ed indistinctly. After minor modifications, the ...vare of the IGOR+GNSS receiver allows the

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ROHP-PAZ is a mission of opportunity: The Spanish Earth Observation PAZ satellite, planned to be launched in 2013, was initially designed to carry a Synthetic Radar Aperture (SAR) as primary and sole payload. It included an IGOR+ advanced Global Navigation Satellite System (GNSS) receiver for precise orbit determination. The design of this particular GNSS receiver allows the tracking of occulting signals, that is, signals transmitted by navigation satellites setting below the horizon of the Earth (or rising above it). The Spanish Ministry for Science and Innovation (MICINN) approved a proposal aimed to modify the original plans of PAZ, by including a polarimetric GNSS Radio-Occultation (RO) payload. This means to enable the radio occultation capabilities of IGOR+, together with the acquisition and installation of a GNSS antenna oriented towards the limb of the Earth.

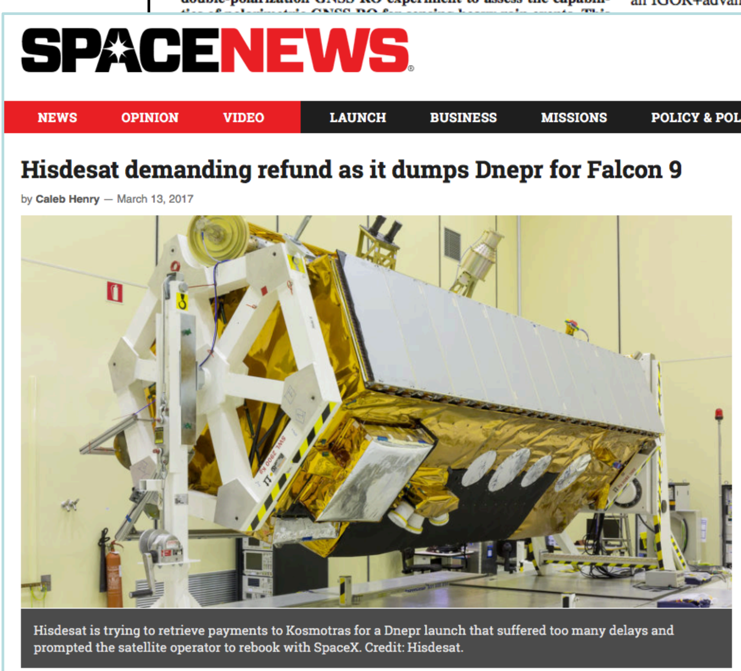
Artistic view of the PAZ satellite, which will host the Radio Occultation and Heavy Precipitation (ROHP-PAZ) experiment payload.

The Radio Occultation technique originated in Planetary sciences for the study of other Planets' atmospheres, and measures the bending caused by the atmospheric refractivity gradients on the propagation of the radio link. This bending can be used to infer vertical radio-refractivity profiles from which ionospheric total electron content can be inferred as well as thermodynamic variables such as atmospheric pressure, temperature, water vapor pressure from the stratosphere down to the boundary layer with a vertical resolution close to 300 m. RO thermodynamical profiles are assimilated operationally into several global numerical weather prediction models (NWP) [Healy et al., 2005]. Latest results show that ROs improve the weather forecast, reducing the NWP model biases and becoming the operational observation system of fifth-highest impact among the 24 available systems [Cucurull and Derber, 2008, Cardinali, 2009]. The use of GPS RO is thus a key component of the operational observing system [NRC, 2007].

Since 1995, GNSS RO has now been flown on a number of missions, among them: GPS/MET, Oersted, CHAMP, SAC-C, or GRAS/METOP. Since 2006, the main source of RO data is a constellation of 6 Low-Earth Orbiters, the Taiwan/USA FORMOSAT-3/COSMIC mission, in the form of globally distributed profiles. However, the number of RO profiles risks to dramatically drop after the decommissioning of the COSMIC constellation. With a mission life-expectancy of 5 years, COSMIC already begun to degrade in 2011. PAZ is planned to be launched when this happens and before a possible new RO constellation is deployed.

Moreover, ROHP-PAZ is a proof-of-concept experiment: for the first time ever, GNSS RO measurements will be taken at two polarizations, to exploit the potential capabilities of polarimetric radio occultation for detecting and quantifying heavy precipitation events. If the concept is proved, PAZ will mean a new application of the GNSS Radio-Occultation observations, by providing coincident thermodynamic and precipitation information with high vertical resolution within regions with thick clouds.

This might help understanding the thermodynamic conditions underlying intense precipitation, which is relevant because these events remain poorly predicted with the current climate and weather model parametrization. A better understanding of the thermodynamics of heavy precipitation events is necessary towards improving climate models and quantifying the impact of climate variability on precipitation [Wentz et al., 2007, Allan and Soden, 2008]. The particular advantage of GNSS polarimetric RO is that their signals are in the microwave spectrum which, unlike infrared sensing technology, is little influenced by clouds, not even by the thick clouds that are typically associated with heavy precipitation.



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Hisdesat demanding refund as it dumps Dnepr for Falcon 9

by Caleb Henry — March 13, 2017

Hisdesat is trying to retrieve payments to Kosmotras for a Dnepr launch that suffered too many delays and prompted the satellite operator to rebook with SpaceX. Credit: Hisdesat.

JPL and UAB Science Team

www.ice.csic.es/paz

WrapUp - Current Status

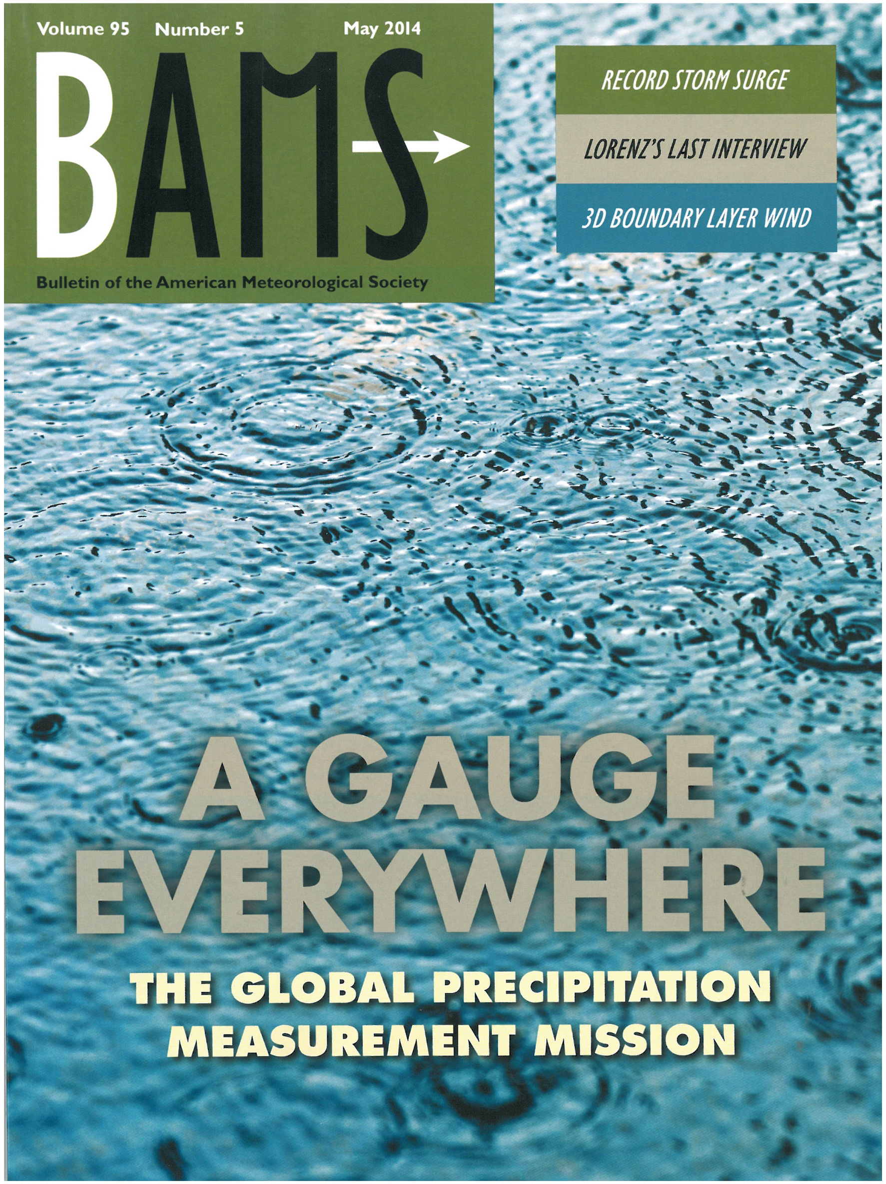
GPM-core spacecraft is healthy and recent solar projections indicate that it has sufficient fuel to operate until the 2030s

Constellation of US polar satellites is aging (Defense Meteorological Satellite Program, DMSP), and a microwave imager is not part of NOAA's Joint Polar Satellite System (JPSS)

EUMETSAT's EPS (early 2020s) will have an operational microwave imager series; NASA is currently forbidden from using CMA FY-3 data

Technological advances allowing reduced size, weight, and power requirements are planned as various tech demos or NASA Earth Ventures missions in the coming decade

Future space-based cloud/precipitation observations may be a mixture of national operational weather satellite systems (polar and geostationary), complemented by various low-cost, smallsat-hosted radar and/or radiometric systems, other (eg, GPS radio occultations)



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Thank you for the invitation to visit and meet with the students and faculty.

There was quite a bit of material presented here, and contact me if you have questions, ideas, comments, etc.

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